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Location Management in Internet Protocol-Based Future LEO Satellite Networks: A Review

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ABSTRACT Future integrated terrestrial, aerial, and space networks will involve thousands of low-Earth-orbit (LEO) satellites, which will form a network of mega-constellations. These mega-constellations will play a significant role in providing communication and Internet services anywhere, at any time, and for everything. Due to the large scale and highly dynamic nature of future LEO satellite networks (SatNets), their management will be a complicated process, especially the aspect of mobility management and its two components: location management and handover management. In this article, we present a comprehensive and critical review of the state-of-the-art research in location management for LEO SatNets. First, we give an overview of the Internet Engineering Task Force (IETF) mobility management standards (e.g., Mobile IPv6 and Proxy Mobile IPv6) and discuss the limitations of their location management techniques for future LEO SatNets. We highlight the mobility characteristics of future LEO SatNets and their challenging features, and we describe two unprecedented future location management scenarios. A taxonomy of existing location management solutions for LEO SatNets is also presented with solutions classified according to three approaches. The "Issues to consider" section draws attention to critical points related to each of the reviewed approaches that should be considered in future LEO SatNets location management. To identify the research gaps, the current state of LEO SatNets location management is summarized. Noteworthy future research directions are recommended. The article provides a road map for researchers and industry to shape the future of location management for LEO SatNets.

INDEX TERMS Satellite networks, mega-constellation, LEO, mobility management, location management.

ABBREVIATIONS

3GPP	3rd Generation Partnership Project
AP	access point
APSO	accelerated particle swarm optimization
AR	access router
BA	binding acknowledgment
BCE	binding cache entry
BS	base station
BU	binding update
CN	corresponding node
CoA	care-of-address
DAD	duplicate address detection
DCPP	dynamic controller placement problem
DCT	dynamic classified timeout
DMM	distributed mobility management
EID	end identifier
ETR	egress tunnel router
FAR	foreign access router
FBU	fast binding update
FES	fixed Earth station
FMIPv6	fast handovers for Mobile Internet Protocol version 6
FNA	fast neighbour advertisement
GEO	geostationary orbit
GS	ground station
GSL	ground-to-satellite link

HA	home agent
HAPS	high altitude platform system
HIP	Host Identity Protocol
HMAA	home mobile agent anchor
HMIPv6	Hierarchical Mobile Internet Protocol version 6
ICN	information centric network
ID	identifier
IETF	Internet Engineering Task Force
ILNP	Identifier Locator Network Protocol
ILP	integer linear programming
IoE	Internet of Everything
IoT	Internet of Things
IP	Internet Protocol
IRTF	Internet Research Task Force
ISLs	inter-satellite links
ITR	ingress tunnel router
LA	location area
LCoA	on link care-of-address
LEO	low-Earth orbit
LISP	Locator/Identity Separation Protocol
LM	location manager
LMA	local mobility anchor
MAA	mobile agent anchor
MAG	mobile access gateway
MAP	mobility anchor point
MEO	medium-Earth orbit
MIP	Mobile Internet Protocol
MIPv4	Mobile Internet Protocol version 4
MIPv6	Mobile Internet Protocol version 6
MN	mobile node
NOCC	network operation and control centre
OBP	on-board processor
PAR	previous access router
PBA	proxy binding acknowledgment
PBU	proxy binding update
PMIPv6	Proxy Mobile Internet Protocol version 6
PRAdv	proxy router advertisement
QoS	quality of service
RCoA	regional care-of-address
RLOC	routing locator
RMRS	rapid mapping resolution system
RS	router solicitation
SatNet	satellite network
SCPP	static controller placement problem
SDN	software defined network
SDSN	software defined satellite network
TCAM	ternary content addressable memory
TCP	Transport Control Protocol
TD	topology discovery
TGMS	terrestrial gateway mapping server
TSMM	timeout strategy-based mobility management
VAC	virtual agent cluster
VAD	virtual agent domain
VAP	virtual attachment point
VHetNet	vertical heterogeneous network.

I. INTRODUCTION

With the emergence of the Internet-of-Everything (IoE) paradigm, which involves people, data, intelligent processes, sensors, and devices [1], wireless communication networks are going through an unprecedented revolution to meet the requirements of IoE global deployment. It is anticipated that future networks will have to ensure the provision of communications and computation services and security for a tremendous number of devices with broad and demanding requirements in a ubiquitous manner. This fuels the need for providing broadband Internet connectivity everywhere on Earth and even within its surrounding space. Although terrestrial communication networks have witnessed several significant advances, the coverage of communication networks is still patchy, particularly in rural and difficult-to-serve areas (e.g., seas, oceans, polar regions, and high altitudes). During the COVID-19 pandemic, many people and companies realized that work can be done remotely without going to working places. This might encourage an exodus of people from big cities to rural areas, even after the pandemic is over. Such a change in population distribution would require the provision of the Internet in more scattered spots. Besides providing coverage to rural and difficult-to-serve areas, the large footprint of satellite networks can boost the communication capacity for a huge number of terrestrial users on a flexible basis. This makes satellites ideal for providing broadcasting or multicasting services. In addition, satellite networks can offer critical and emergency services during and after natural disasters.

Recently, several industrial groups and standardization organizations, including the 3rd Generation Partnership Project (3GPP), have proposed integrating satellite networks with 5G and beyond to support seamless and ubiquitous broadband coverage that would be available at any time [2]. Driven by growing demands for Internet and communications services, the development of satellite networks has developed rapidly during the last ten years [3]. This has been the case especially for low-Earth-orbit (LEO) satellite networks (SatNets), such as the Iridium NEXT system and the upcoming SpaceX mega-constellations. The objective is to cover the entire Earth with LEO satellites equipped with on-board processor (OBP) devices. Such SatNets can be considered as an extension of terrestrial IP networks or as a standalone satellite network, where satellites are the data sources, processors, and consumers [4].

Due to their low altitudes (160-2,000 km), LEO satellites provide low-latency communications in comparison to medium-Earth-orbit (MEO) and geostationary-orbit (GEO) satellites. However, the high speed of low-Earth orbits necessitates frequent handovers in communications with ground stations and users, aerial network entities, and other LEO satellites [4]. For example, an LEO satellite at 500 km altitude travels at 7.6 km/s and it takes around ninety-five minutes to orbit the Earth resulting in a handover every five minutes approximately. In addition, LEO satellite channels

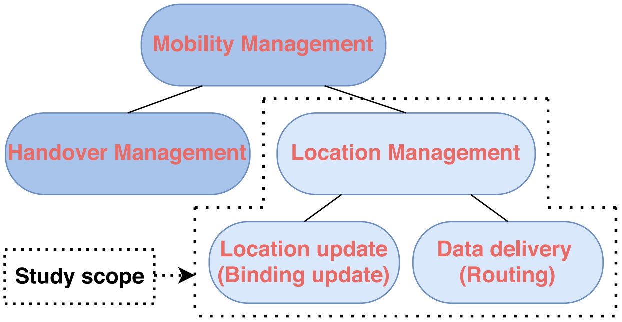


FIGURE 1. The scope of this study.

have severe spreading in delay and Doppler shifts on the transmitted signal (e.g., with different elevation angles, the Rician K factor may be reduced to as low as 2 dB, and the delay spread may reach 100 ns). Moreover, a gateway on Earth has a very limited communication period with an LEO satellite. Therefore, there is a pressing need for efficient mobility management protocols to provide seamless communication between the satellite networks and the Internet [5].

IETF introduced Mobile Internet Protocol (MIP) (i.e., MIPv4 and MIPv6) and Proxy Mobile Internet Protocol version 6 (PMIPv6) to provide mobility management in terrestrial IP networks. IETF's IP-based mobility management protocols aim to maintain the Transport Control Protocol (TCP) connection between a mobile node (MN) and a static access point (AP) or base station (BS) while reducing the effects of location changes of the MN. This is achieved through the interrelated mobility management components, namely handover management and location management. Handover management is the process by which an MN keeps its connection active while moving from one AP to another. Location management has two components, location update which is the process of identifying and updating the logical location of the MN in the network; and data delivery (i.e., routing), which forwards the data packets directed to the MN to its new location. This study focuses on the location management side with its two components, location update (binding update) and data delivery (routing), as described in Figure 1.

Due to the differences between terrestrial networks and SatNets in terms of topology, processing power, and communication links, the application of standard IP mobility management protocols—and more specifically their location management techniques—to satellite networks has some drawbacks [3]. IETF's IP-based location management techniques were designed to manage the logical location of MNs (terminals) and deliver their data to wherever they move. However, in LEO SatNets, both terminals and BSs (satellites) move, which creates new challenges that cannot be fully addressed using existing IETF location management techniques. In addition, IETF location management techniques are intended to work in centralized units that manage both control and data traffic (i.e., routing) [6]. As a result, IETF location management techniques have poor scalability and may create processing overloads in core network devices. Moreover, even in terrestrial networks, such standards pose several problems because of the low granularity of their mobility management and their suboptimized routing. What makes things more challenging is the characteristics of future LEO SatNets, such as frequent and rapid topology changes due to their high speeds and dense deployment in a network of mega-constellations—and their complete integration with aerial, terrestrial, and deep-space networks. In addition, future LEO SatNets are expected to service highly populated areas where thousands or millions of heterogeneous user devices can communicate directly with an LEO satellite (without going through a gateway). Hence, future LEO SatNets will create unprecedented mobility scenarios that require innovative solutions.

To overcome the limitations of IETF IP-based location management, existing studies on location management for LEO SatNets have followed one of three approaches. The first approach attempts to enhance or extend the IETF IP-based location management techniques [7], [8]. The second approach is based on splitting the two roles of IP addresses (i.e., locator/identifier split) [9], [10]. The third approach uses a software-defined network (SDN) for topology (location) management [11], [12]. However, existing studies have not considered the unique characteristics of future LEO SatNets, and the adoption of the existing solutions—as they are—will not be adequate. By pointing out the advantages that existing studies have and what is required for future LEO SatNets, this study aims to steer the development of location management needed for future SatNets.

A. EXISTING SURVEYS AND TUTORIALS

A number of excellent surveys and tutorials related to mobility management have been published over the past several years. These include discussions of IETF's mobility management protocols and their proposed enhancements, reviews of available location/identifier split architectures and mapping systems, and various surveys on the exploitation of SDNs for mobility management purposes.

A comprehensive tutorial on mobility management in data networks was introduced in [13]. In [14], the authors discussed suitability of the existing mobility management solutions introduced by standardization bodies (e.g., IEEE, IETF, 3GPP, and ITU) to be applied to 5G and beyond networks. In [15] several mobility management issues and potential solutions were discussed in the context of 5G networks with a focus on handover management aspects. Reference [16] introduced a review on the architectures, designs, benefits, and potential drawbacks of the Host Identity Protocol (HIP), which is an inter-networking architecture and an associated set of protocols developed at the IETF. The mobility management services in mobile networks were surveyed in [17]. For networks with self-organizing and self-configuring characteristics, the applicability of IETF mobility management protocols was discussed in [18]. Several algorithms developed to address the challenges of IP-based mobility management for the Internet of Things (IoT), were reviewed in [19].

A detailed discussion of the limitations of IP addressing architecture and existing enhancements based on location/identifier split architectures were presented in [20]. In [10], the authors introduced a comprehensive survey of location/identifier split network architectures and their characteristics. Reviewing an essential component in location/identifier split solutions, [21] provided a survey of several mapping systems.

SDN is considered to be a promising approach to managing mobility. The author in [22] discussed the challenges of using SDN to manage mobility in IP-based networks. In [23], the authors discussed the topic of mobility management in 5G and 6G SDNs, where the focus was on handover management issues.

While mobility management has received considerable research attention in communication networks, this is not the case for the next generation of SatNets. Many recent surveys and tutorials on future SatNets have discussed communication and networking related issues. For example, Radhakrishnan *et al.* [24] focused on inter-satellite communications in small satellite constellations from the perspectives of physical to network layers, and the Internet-of-Remote-Things applications for satellite communication were reviewed in [25]. However, only a few reviews were published on mobility management related issues in next-generation satellite networks. The author in [26] discussed the challenges facing SDN-based integrated satellite-terrestrial networks. Another review, [27], explored the challenges that software-defined next-generation satellite networks may encounter and provided some potential solutions. Reference [28] discussed the survivability and scalability of space networks. In [29], the authors discussed several mobility management aspects of a space-air-ground integrated network environment with a focus on handover and routing issues. The aforementioned surveys with regards to mobility management are summarized in Table 1 to allow the reader to capture the focal point of each of the existing surveys.

The review of the literature above has shown that mobility management in future SatNets is still in its infancy. Although some reviews discussed the integration of SDN and future SatNets, mobility management issues—and more specifically location management—were not the focus of such papers. To address this gap, this paper discusses existing location management solutions and the challenges of applying them in future LEO SatNets.

B. PAPER CONTRIBUTIONS AND STRUCTURE

The contributions of this paper are as follows.

- We describe the mobility characteristics and challenging features of future LEO SatNets; in so doing, we highlight two unprecedented location management scenarios.
- We give an overview of IETF's location management techniques and their limitations in the context of future LEO SatNets.
- We comprehensively and critically review existing solutions for location management in LEO SatNets and categorize them into three approaches.
- For each of the reviewed approaches, we discuss "Issues to consider" for that specific approach of location management to serve future LEO SatNets.
- We summarize the current view of LEO SatNets location management.
- Important future research directions are highlighted, such as the relationship between orbit related parameters and location management, utilization of blockchain technology, adoption of a collaborative Internet architecture, investigating the new IP address proposal.

Section II presents an overview of the mobility characteristics and challenging features of future LEO SatNets, and it describes two unprecedented mobility scenarios. In Section III, we give an overview of IP-based standardized location management and its limitations in future LEO SatNets. Section IV introduces the taxonomy of the existing location management techniques for LEO SatNets. Section V reviews existing studies that proposed extensions of IETF location management techniques for LEO SatNets. Section VI discusses existing solutions that use a locator/identifier split approach in LEO SatNets. Section VII investigates SDN-based location management in LEO SatNets. At the end of Sections V–VII, an "Issues to consider" subsection is included, which highlights the main points that should be taken into consideration for future LEO SatNets location management. Section VIII discusses the advantages of existing solutions of the three location management approaches in future LEO SatNets, and suggests important future research directions. Our conclusions are presented in Section IX.

II. MOBILITY CHARACTERISTICS IN FUTURE LEO SATNETS

Satellite communication systems have been considered as a potential solution for complementing terrestrial networks by providing coverage in rural areas as well as offloading and balancing data traffic in densely populated areas [30]. With the emergence of LEO satellite mega-constellations, which involve hundreds to thousands of satellites [31], [32], the concept of satellite networks is evolving rapidly and gaining increased attention. 3GPP introduced a number of satellite use cases in 5G networks (3GPP TR 22.822 Release 16) and discussed the role of satellites in future networks [33]. For example, 3GPP introduced *Internet of Things with a Satellite Network* and *Global Satellite Overlay* use cases that both emphasize the future role of satellite networks. However, to realize such use cases there are still several challenging matters to address,

TABLE 1. Recent surveys and tutorials related to mobility management.

Year	Publication	One-sentence summary	Location management in SatNet	SDN	Location/ identifier split	IETF mobility management
2010	[16]	An in-depth look at the architecture, design, benefits, and potential drawbacks of the HIP.	No	No	Focused on one approach	NO
2012	[17]	A survey of the IP-based mobility management services and their techniques, strategies and protocols.	No	No	No	Yes
2012	[18]	Discusses some future network architectures in terms of their support for IETF mobility management protocols, including architectures of wireless mesh networks with self organizing and self configuring network characteristics.	No	No	No	Yes
2013	[21]	A survey of mapping systems used in location/identifier split proposals.	No	No	Focused on mapping systems	No
2014	[13]	A comprehensive tutorial on mobility management in data networks.	No	No	No	Yes
2014	[20]	Discusses the limitations of the IP addressing architecture and reviews the existing enhancement proposals based on location/identifier split architectures.	No	No	Yes	No
2016	[19]	A review of the developed algorithms to address the challenges of integrating IoT and IP, the attributes of IP mobility management protocols and their enhancements.	No	No	No	Yes
2016	[26]	A survey of the recent research works related to the software defined integrated satellite and terrestrial networks with challenge identification and a discussion of the emerging topics requiring further research.	No	Focused on satellite and terrestrial integration	No	No
2017	[22]	A review of the studies on IP mobility management using software defined networking.	No	Focused on mobility management in IP networks	No	No
2017	[10]	A comprehensive survey on location/identifier split network architectures and their mechanisms, and characteristics.	No	No	Yes	No
2018	[27]	An architecture of software-defined next-generation satellite networks with the exploitation of network function virtualization, network virtualization, and software-defined radio concepts.	No	Not on mobility management	No	No
2018	[28]	A survey on survivability and scalability of space networks with a discussion on IP mobility management applicability.	No	No	No	Yes
2018	[29]	A review of research works concerning space-air-ground integrated networks with a section on mobility management and routing in integrated networks.	No	No	No	Yes
2019	[23]	A review of the technology of software definition networks of 5G and 6G, including system architecture, resource management, mobility management, interference management.	No	Mobility management in 5G and 6G	No	No
2020	[14]	A review of the 5G and beyond mobility management functional requirements with a discussion on whether the existing mechanisms introduced by standardization bodies (e.g., IEEE, IETF, 3GPP, and ITU) meet these requirements.	No	No	No	Yes
2020	[15]	A review of mobility management issues and solutions in 5G networks with a focus on handover management.	No	No	No	No
2022	**Our work**	**A comprehensive and critical review of the state-of-the-art research in LEO SatNets location management.**	**Yes**	**Mobility management in SatNet**	**Focused on SatNet**	**Focused on IETF location management in SatNet**

such as mobility management. Therefore, in this section, after highlighting the challenges of future LEO SatNets and discussing their impact on location management, we discuss two unprecedented mobility management scenarios in future satellite networks with a focus on location management.

A. CHALLENGING FEATURES OF FUTURE LEO SATNETS

Several key points should be kept in mind while designing, implementing, or evaluating location management solutions for future LEO SatNets.

- A network of mega-constellations that has thousands of LEO satellites operated by different operators is expected. Therefore, it is essential to ensure interoperability between different constellations and also between different operators. This will require the development of standards for future satellite network operation and management.
- Unlike geosynchronous satellites, LEO satellites move at very high speeds, which results in frequent handovers.
- Future LEO SatNets is not only provide coverage for rural or remote areas but are also expected to serve highly populated areas by boosting terrestrial network capacity and ensuring continuous coverage for fast-moving users (e.g., trains, planes, drones). Thus, thousands of users can be connected to an LEO satellite.
- With the development of wireless communication technologies, not only large terminals but also small or handheld user devices for broadband communication will be able to communicate directly with satellites without the need for ground gateways. This will likely lead to heterogeneity in terms of the devices used to communicate with satellites and their required quality of service (QoS) (i.e., different applications have different QoS requirements).
- Future LEO SatNets will be integrated with terrestrial, aerial, and maybe deep-space networks. In terms of network management, such integration will result in more complexity and require high scalability.
- A satellite will have multiple roles, as it can function as a terminal, router, and BS.
- Although deploying satellites at low altitudes will require hundreds or thousands of satellites to provide continuous coverage all over the globe, a significant decrease in propagation delays can be achieved in comparison to legacy satellite communication. Nevertheless, the resulting delay and jitter are still considered non-negligible in certain delay-sensitive applications.
- Low-Earth-orbit altitudes are in the range of 160-2,000 km, which will decrease communication delays with terrestrial and aerial networks and users. However, the lower the orbit, the more satellites are required to provide coverage, the faster the satellites should move, and the smaller the satellite footprint will be. Both ground stations and users will have a short communication window with each passing satellite. Consequently, the frequency of handovers will increase when orbit altitude decreases.

B. IMPACT ON LOCATION MANAGEMENT

Future LEO satellite networks will be mega-constellations operated by different operators. As satellites orbit the Earth, satellite network management will need to be provisioned all over the globe. In addition, to be able to deliver data between any two users, location management and routing functionalities will need to be performed across different SatNet service providers and operators distributed in different countries. This will require the scalability of location management systems and interoperability among different location management systems.

LEO satellites are expected to provide services to a large number of users in urban and highly populated areas. An LEO satellite can act as a BS with thousands of users associated to it. However, users have to perform a handover process every 5-10 minutes due to the satellites' movement at high speeds. This raises the following questions. Do users on Earth need to keep acquiring or configuring new IP addresses every time they switch their connection from one satellite to another? How will the satellite network location management entity handle location updates and data delivery to a huge number of users (thousands of users) experiencing frequent handovers? In addition, when a satellite acts as a router, frequent routing table updates are required. Although the periodic satellite motion could support automated routing table updates, this might not be the case with satellite routers at the SatNet edge, which interacts with users on Earth or other networks (e.g., terrestrial networks or aerial networks). Moreover, when a satellite is a terminal, it might need to acquire a new IP address whenever it changes its point of association in the network.

Another important issue that impacts location management functionality in integrated terrestrial, aerial, and space networks is the placement of location management entities. Location management functionalities can be done from Earth, space, or aerial network entities (e.g., high altitude platform stations). However, each placement has some advantages and disadvantages in terms of location update delays, control traffic overhead, routing overhead, and the consumption of communication resources.

C. UNPRECEDENTED LOCATION MANAGEMENT SCENARIOS

In future broadband satellite networks, satellites will no longer be used only as a bent pipe. A satellite will be working as a mobile BS, a router, and a terminal. However, an LEO-based mobile BS moves very fast, which results in a high frequency of handovers and location update triggers for both the satellite and its connected users. Moreover, future satellite networks will have thousands of LEO satellites, which require location management solutions with high scalability. Due to these connectivity and mobility characteristics, future LEO SatNets will introduce two unprecedented location management scenarios that require new solutions. The following two points elaborate on the two envisioned scenarios.

1) *LEO Satellite–Based Mobile BSs Moving at High Speeds and Service Thousands of User Devices:* In

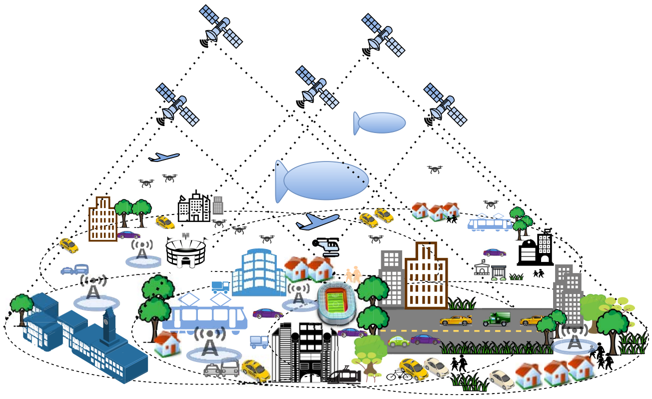


FIGURE 2. LEO satellite–based mobile BS serving thousands of users.

future networks, it is expected that satellites, especially LEO satellites, will provide wide coverage and support communication network capacity in densely populated areas, as shown in Figure 2. In this situation, an LEO satellite–based mobile BS will serve thousands of users. This will be empowered by the integration of reconfigurable intelligent surfaces with LEO satellites as well [34]. In this scenario, a wide range of user device types can be served through LEO satellites, including smart devices, machines, sensors, autonomous vehicles, and cargo drones. The mobility of LEO satellites at high speeds will result in triggering location updates not only to the satellite–based mobile BS but also to the thousands of users that are connected to the LEO satellite. Although the users might not move, changing their network access point (i.e., the LEO satellite mobile BS) will trigger location updates in classical mobility management protocols (e.g., MIPv6). This is because, in IP networks, IP addresses are used for both routing and addressing purposes. Moreover, this unnecessary and massive number of location updates will be triggered every 5–10 minutes approximately. Although satellite movement is predictable, when a user device is located in overlapping satellite coverage areas it is difficult to predict which satellite the user will hand over its connection to. Different users may make the handover decision of which satellite to choose based on different parameters in order to satisfy the user QoS requirements.

2) *An LEO Satellite Can Be Connected to Two or More Networks Simultaneously:* In future integrated networks, besides being part of the network of satellite mega-constellations, LEO satellites will be also connected to terrestrial networks, aerial networks, or both, as shown in Figure 3. When an LEO satellite is connected to terrestrial and/or aerial networks, changes in satellite position will trigger location updates in both networks if each network has its own location management system. In addition, the topology changes in LEO satellite mega-constellations will also trigger frequent location updates among satellites. In this scenario, the LEO satellite can play the role of a mobile BS, a router, or a terminal. However, the most complicated case is when an LEO satellite functions as a mobile BS to serve a large number of users through multiple backhaul connections (space, aerial, terrestrial). Managing the location updates in several networks and providing a mapping between the location systems of such networks is considered a challenging issue.

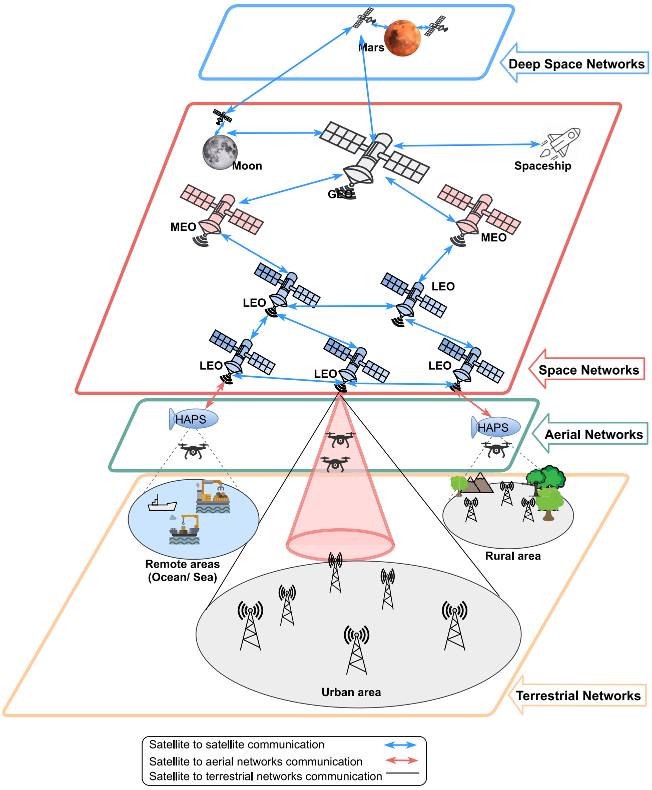


FIGURE 3. LEO satellites connected to multiple networks.

III. OVERVIEW OF IP-BASED STANDARDIZED LOCATION MANAGEMENT AND ITS LIMITATIONS IN FUTURE LEO SATNETS

In traditional terrestrial cellular networks, mobility management has been well studied. For location management, most of the research has focused on tracking and paging. Tracking in cellular networks is the process of identifying in which cell a user (i.e., MN) is located in by using the user's signal strength received by nearby cellular towers. Paging is the process of indicating a user position in a cellular network in order to establish a connection with another user calling from fixed or mobile equipment. The tracking area (location area) used in 4G and 5G usually comprises a dynamic group of cells. Location management solutions aim to find a balance among tracking area division and location updates/paging overhead. To communicate with other devices in a cellular network, the MN device must establish an end-to-end user plane path through the domain of the mobile operator. To manage the location of an idle MN, the MN performs a location update upon crossing the boundaries of a tracking area. This location update is saved in a database that can be queried to determine the location of an idle MN. To discover an idle MN's current location, the location area's cells are contacted through paging. With the upcoming densification of 5G, it is expected that there will be a considerable increase in location management signaling costs due to the increase in location updates (if the tracking areas are small) or paging (if the tracking areas are large) [35].

In IP-based networks, location management is done in a slightly different way, as the active TCP/IP connections of a MN need to be maintained while it moves from one access router to another. In the 1970s, IP protocol was introduced as an inter-networking protocol for delivering data packets in wired networks, where IP addresses are used for both identification and data packet routing. With the development of mobile wireless communication devices, there was a real need to support mobility in IP-based networks. Therefore, IETF introduced MIPv4, and this was later followed by MIPv6, PMIPv6, fast handovers for Mobile Internet Protocol version 6 (FMIPv6), and Hierarchical Mobile Internet Protocol version 6 (HMIPv6). Mobility management, in these protocols, consists of two main components, which are handover management and location management. In this study, the focus is on the location management aspect of mobility management. Location management involves locating MNs and guaranteeing data delivery [4]. There are two procedures that constitute location management: binding updates and data delivery. To address mobility in Internet networks, the IETF mobile Internet protocols bind the MNs to their corresponding new IP addresses as the MNs' locations change. A binding update is performed only when a handover has occurred (i.e., when the MN changes its network access point). The following two subsections explore the fundamental procedure of location management in IPv6 mobility management standards and investigate the limitations of applying such standards in future LEO SatNets. Figures 4, 5, 6, and 7 show the network architecture of each of the four IPv6 mobility management standards and summarize their location management procedures.

A. LOCATION MANAGEMENT PROCEDURE IN IPV6 MOBILITY MANAGEMENT STANDARDS

1) *MIPv6 [36]:* In a home network (i.e., where the MN is currently located and attached), the MN gets a permanent address, called the home address. This address is registered at the home agent (HA) in the home network and is used for both identification and routing purposes. Figure 4 shows the network architecture and the message exchange during the location management procedure of MIPv6. Since MIPv6 is a host-based mobility management protocol, the MN detects its mobility from the home network (previous network) to a foreign network by using the IPv6 neighbor discovery mechanism. A foreign network is a network that the MN can access after moving out of its home network coverage. According to the procedure of MIPv6 location management, when the MN moves out of the home network and accesses a foreign network, it will perform the following steps (the step numbers are indicated in Figure 4) [37].

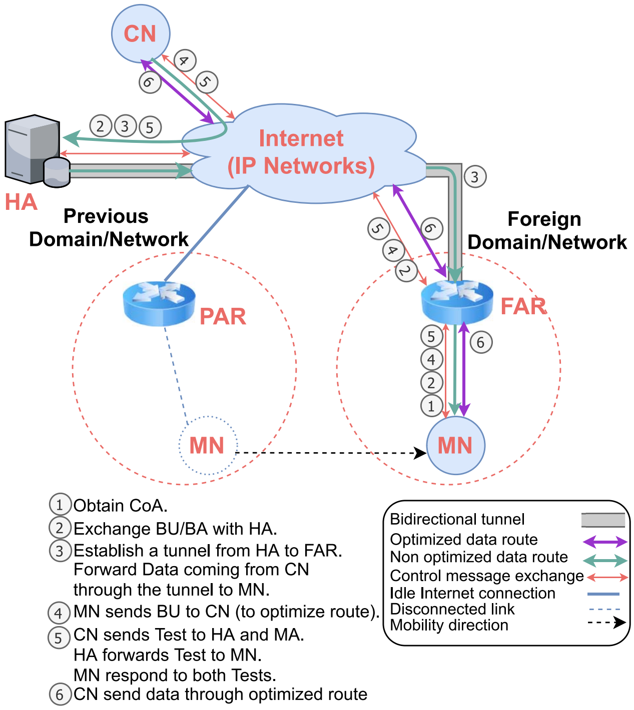


FIGURE 4. MIPv6 location management procedure.

a) Step 1: The IPv6 neighbor discovery or address auto-configuration mechanism is used to obtain a temporary IP address from the foreign network, called the care-of-address (CoA).

b) Step 2: The MN informs the HA of its current location by sending a binding update (BU) message and the HA responds with a binding acknowledgment (BA) to the MN.

c) Step 3: After completing the binding update with the HA, the HA and the access router (AR) at the foreign network (i.e., foreign access router (FAR)) will establish a bidirectional tunnel to deliver the data packets between the corresponding node (CN) and MN. In this case, the data packets have to traverse the HA, which is not necessarily the optimum route [7].

d) Step 4: The MN has the option to optimize the data forwarding route by sending BU message to the CN as well. Nevertheless, the MN will keep receiving packets through the HA until the CN starts using MN's CoA.

e) Step 5 & 6: Before using MN's CoA, the CN will send two test messages, one to the HA and one to

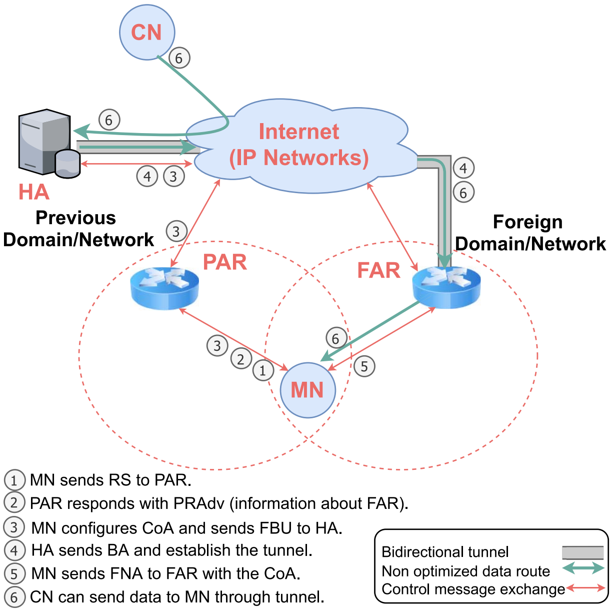


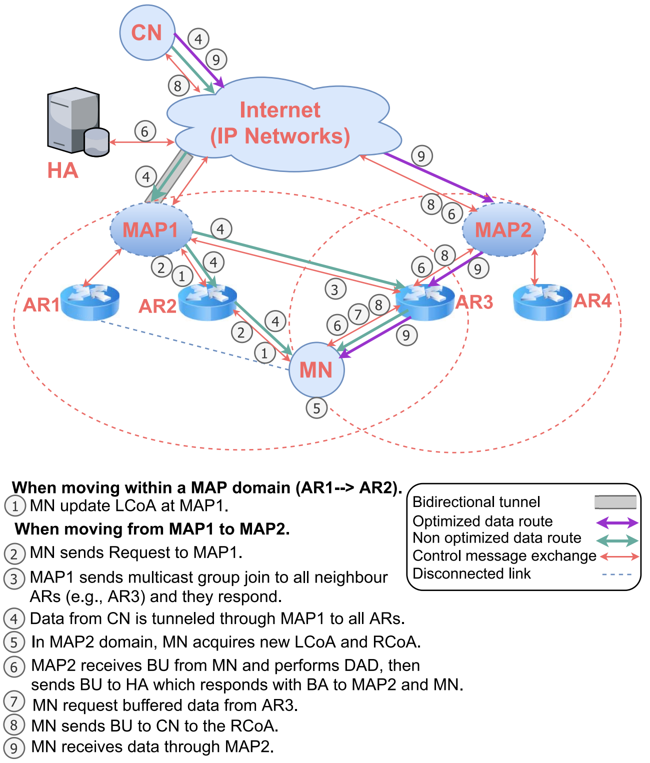
FIGURE 5. **FMIPv6 location management procedure.**

the MN. The HA has to forward the message to the MN, and then the MN has to respond to both messages through the two different paths (i.e., through the HA and directly to the CN). When the CN receives both responses, it can start using the MN's CoA, following which communication between the CN and MN can be done through the FAR without going through the HA.

In MIPv6, the handover and the location management processes are closely coupled, and every handover results in updating the CoA at HA and CN (for route optimization). This leads to a high handover delay and increases packet loss rate. Therefore, some improved protocols, such as FMIPv6 [38], HMIPv6 [39] and PMIPv6 [40], have been proposed.

2) *FMIPv6 [38]:* To reduce packet loss and handover latency, IETF proposed FMIPv6, which enables the MN to configure a CoA before moving to the new AR (i.e., FAR) coverage [4]. The FMIPv6 protocol allows an MN to request information about neighboring ARs. There are two modes of FMIPv6, namely predictive and reactive handover [41]. Figure 5 shows an example of an FMIPv6 handover, where the MN location is updated through the following steps (the step numbers are indicated in Figure 5).
    a) Step 1: The MN sends a router solicitation (RS) to the previous access router (PAR) requesting information about neighboring ARs for a potential handover.
    b) Step 2: PAR replies with a proxy router advertisement (PRAdv) containing information about neighboring ARs.
    c) Step 3 & 4: After receiving PRAdv, the MN configures a CoA and sends a fast binding update (FBU) to HA to bind MN's home address to the CoA in order to tunnel the arriving packets to the new location of the MN (i.e., FAR). The PAR sends an acknowledgment to the MN confirming that the tunnel is ready.
    d) Step 5: The MN will send a fast neighbour advertisement (FNA) as soon as it is connected to the FAR. This message confirms the use of the CoA.

    However, if the MN can not anticipate the handover, then the reactive mode will be used. In this case, the MN will configure its CoA after moving to FAR coverage, and the FBU is sent to the PAR through the FAR and is encapsulated in a FNA message. Then, the two routers PAR and FAR will exchange handover initiation or acknowledgment messages to establish a tunnel, after which the PAR starts forwarding packets to the FAR to be delivered to the MN. The reactive mode operation is clearly similar to the operation of the original MIPv6.
3) *HMIPv6 [39]:* HMIPv6 is an enhancement of Mobile IPv6 with the feature of localized mobility management for MNs [4]. To support localized mobility management, it introduces a new network entity called the mobility anchor point (MAP). In HMIPv6, an MN has two types of addresses: a regional care-of-address (RCoA) and an on link care-of-address (LCoA). The RCoA is a global address and specifies a particular domain of the Internet. The LCoA is a local address within the domain. When the MN moves between local networks inside an MAP domain (micro/intra-domain handover), it changes and updates its LCoA only at the MAP. However, moving from one MAP domain to a new MAP domain (macro/inter-domain handover), the MN has to change both addresses by registering a new local LCoA and a new RCoA at the new MAP. In this case, the new MAP registers the new RCoA to the MN's HA. Figure 6 shows the network architecture of HMIPv6 and an example of an MN moving from MAP1 domain to the MAP2 domain, where the location of the MN is updated through the following steps (the step numbers are indicated in the Figure) [42].
    a) Step 2: The MN sends a request control message to MAP1 to create a multicast group for the MN.
    b) Step 3: MAP1 creates a multicast group by sending a multicast group join request to all neighboring ARs. Then, the neighboring ARs respond to MAP1 to show their availability to receive multicast data packets.
    c) Step 4: During the handover process, any received data packet from the CN is tunneled through MAP1 to all the available ARs, where the data packet is buffered.



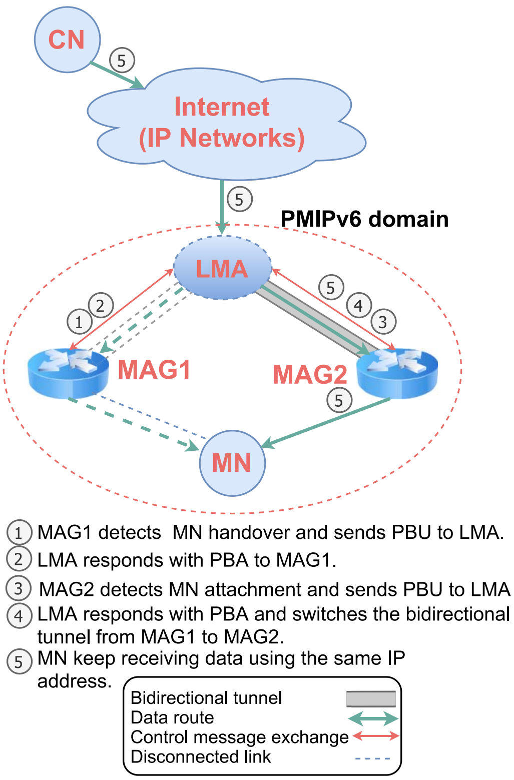
When moving within a MAP domain (AR1--> AR2).

① MN update LCoA at MAP1.

When moving from MAP1 to MAP2.

② MN sends Request to MAP1.
③ MAP1 sends multicast group join to all neighbour ARs (e.g., AR3) and they respond.
④ Data from CN is tunneled through MAP1 to all ARs.
⑤ In MAP2 domain, MN acquires new LCoA and RCoA.
⑥ MAP2 receives BU from MN and performs DAD, then sends BU to HA which responds with BA to MAP2 and MN.
⑦ MN request buffered data from AR3.
⑧ MN sends BU to CN to the RCoA.
⑨ MN receives data through MAP2.

FIGURE 6. HMIPv6 location management procedure.



① MAG1 detects MN handover and sends PBU to LMA.
② LMA responds with PBA to MAG1.
③ MAG2 detects MN attachment and sends PBU to LMA
④ LMA responds with PBA and switches the bidirectional tunnel from MAG1 to MAG2.
⑤ MN keep receiving data using the same IP address.

FIGURE 7. PMIPv6 location management procedure.

d) Step 5: When the MN travels from the MAP1 domain to the MAP2 domain, it acquires new addresses (i.e., new RCoA, new LCoA) from the MAP2 network.
e) Step 6: MAP2 receives the BU message and performs duplicate address detection (DAD). MAP2 sends a BU to the MN's HA after receiving the DAD and waits for a BA from the HA. After receiving a BA from the HA, MAP2 sends a BA to the MN.
f) Step 7: The MN sends a BU to MAP2 through AR3 and sends a message requesting AR3 to forward a multicast message. AR3 receives the request message, and subsequently forwards the buffered packets to the MN.
g) Step 8 & 9: After receiving a BA, the MN sends a BU to the CN via MAP2 to change the destination address to the new RCoA. The data packets will then be delivered to the MN through MAP2.

4) *PMIPv6 [40]:* To provide a mobility management solution with reduced signaling and delay to support an MN moving within an IPv6 domain, the IETF introduced PMIPv6. As a network-based mobility management protocol, PMIPv6 introduces two new network entities, a mobile access gateway (MAG) and a local mobility anchor (LMA) [43]. An LMA is connected to multiple MAGs, and in one PMIPv6 domain there can be multiple LMAs managing the mobility of a different group of MNs. When an MN moves within a PMIPv6 domain, the MAG performs the signaling interaction with the LMA on behalf of the MN to ensure session continuity [3]. When a new MN joins the network for the first time, it will send an RS to the first reachable MAG. Then the MAG sends a proxy binding update (PBU) to its LMA. The LMA responds with a proxy binding acknowledgment (PBA), which includes the MN's home network prefix. The LMA also creates a binding cache entry (BCE) and establishes a bidirectional tunnel with the MAG. The MN will use the home network prefix to configure its address using either stateless or stateful address configuration. When the MN moves from the coverage of one MAG to another within the same PMIPv6 domain, as described in Figure 7, only a local update of the location is required, and the data flow can be adjusted directly at the LMA based on the following steps (the step numbers are indicated in the Figure) [37].

a) Step 1: MAG1 detects that the MN is moving away from its coverage area and sends a PBU to the LMA.
b) Step 2: The LMA responds with a PBA message to MAG1.
c) Step 3: MAG2 detects the attachment of the MN and sends a PBU to the LMA.
d) Step 4: The LMA responds with a PBA message to MAG2 and switches the bidirectional tunnel from MAG1 to MAG2.

TABLE 2. Comparison of IPv6 location management standards features.

Protocol	Necessary network entity	Local/Global mobility management	Control overhead	Host/Network based	Tunneling	Route optimization	Main limitation in LEO satellites mega-constellation
MIPv6	HA	Local and global	BU and BA with HA. Extra overhead for route optimization	Host-based	Between HA and FAR	Available	• MN coupled with a HA. • New CoA every handover. • Not for large scale mobility management. • HA placement is a critical issue.
FMIPv6	HA	Local and global	RS and PRAdv with PAR. FBU and BU with HA. FNA to neighbours	Host-based	Between HA and FAR	Unavailable	• MN coupled with a HA. • New CoA every handover. • Not for large scale mobility management. • HA placement is a critical issue. • Depends on accurate prediction of handover target.
HMIPv6	HA, MAP	Local	Creates multicast group. BU and BA with MAP	Host-based	Between CN, MAP, and multicast group.	Available	• Tunneling with multiple ARs. • Requires buffering at multiple ARs. • Not for large scale mobility management. • MAP placement and domain are critical issues.
PMIPv6	LMA, MAG	Local	PBUs and PBAs between MAGs and LMA	Network-based	Between LMA and MAG	Local	• For mobility management within specific domain. • Not for large scale mobility management. • LMA and MAG placement is a critical issue.

e) Step 5: The MN keeps using the same IP address as long as it is moving between MAGs belonging to the same PMIPv6 domain.

In case the MN moves outside the PMIPv6 domain, the location management procedure of MIPv6 needs to be executed, and the home network LMA will play the role of an HA. This is because PMIPv6 supports local mobility management only.

B. LIMITATIONS OF IPV6 LOCATION MANAGEMENT STANDARDS IN FUTURE LEO SATNETS

The goal of location management is to locate mobile nodes and guarantee their data delivery while they move from one access point or network to another. The two phases of location management are binding updates and data delivery [4]. Unlike terrestrial networks, which are geographically bounded, future SatNets may operate globally. This characteristic makes the adoption of the IETF's mobility management standards infeasible. This is because the IETF's mobility management standards depend on the availability of fixed anchor nodes that manage MNs mobility in a centralized manner. Moreover, in all IP-based location management protocols, data packet routing goes through the location management anchor, thereby producing a non-optimal routing path [3]. This non-optimal data routing will be unacceptable for future LEO SatNets as it will consume link resources and increase delivery delays. Table 2 shows a comparison of the prime features of IPv6 location management standards and their main limitations in future LEO SatNets. In what follows, we explain the drawbacks of applying each of the main IP mobility management protocols (i.e., MIPv6, PMIPv6, HMIPv6, and FMIPv6) in future LEO SatNets with a focus on the protocols' location management aspect.

1) *MIPv6 in future LEO SatNets:* Both MIPv4 and MIPv6 protocols have been designed to manage mobility in Internet networks by binding the MN to its corresponding new address as its location changes. However, implementing MIPv6 in future LEO SatNets will face the challenge of high satellite speeds and frequent handovers, which will generate a large number of binding update requests from both LEO satellites and their connected end users. This, in turn, will consume a massive amount of network resources. In MIPv6 (as in MIPv4), data packet transmission is disrupted during the handover period (i.e., handover latency). This latency comprises the required time to detect the movement, configure a new address, and update the MN location [4]. Packets sent to the MN during the handover period might be lost. In future LEO SatNets, depending on the received signal strength, to detect mobility and initiate the location management procedure may involve inaccuracies because of the

signal fluctuation, which may result in unnecessary address re-configurations and location update requests. The effect of atmospheric disturbances (e.g., rain) on the received signal strength should be taken in consideration. In addition, the propagation delay will prolong the time of the new address configuration and location updates especially if the mobility control entity is located on Earth. Although MIPv6 introduced routing optimization to avoid having to send data packets through the HA, non-optimal routing should not be neglected at the initial stage. This may require the data packets to go through the HA, which can be a ground gateway, and then be sent to the destination satellite. With the long propagation delay of a ground-to-satellite link (GSL), sending data packets down to Earth and then up again to satellites might create serious packet delivery delays and increase the load on GSLs. This issue becomes worse when the HA is located far away from the current location of the satellite [3]. In addition, due to the high speed and continuous mobility of satellites, a route optimization process will be executed frequently, which generates excessive overhead across the network.

2) *FMIPv6 in future LEO SatNets:* In the FMIPv6 location management procedure, the next access router is predicted and the address configuration of the MN can be done before the handover to reduce the handover delay [4]. However, FMIPv6 introduces some interactive signaling messages between the current and the new access routers, and it also requires the establishment of a tunnel between the two routers. Although FMIPv6 with buffering and forwarding mechanisms outperforms MIPv6 in reducing handover latency and packet loss, this comes with a cost. Basically, the forwarding tunnel between the current and new access routers is established before the handover, and the data sent from the CN to the MN is forwarded through the current router to the new one [44]. In future LEO SatNets, if satellites are to function as access routes, then creating a forwarding tunnel will consume bandwidth resources of the inter-satellite links (ISLs) and satellite buffering capacity. In addition, as FMIPv6 depends on predicting the handover target (next access router), inaccurate predictions will waste network resources. In particular, tunnels might be established with the wrong target satellite and data packets might be forwarded to the wrong access routers. In the presence of multiple mega-constellations, the user will have multiple potential satellites as a handover target, which makes predicting the handover target satellite accurately a challenging task.

3) *HMIPv6 in future LEO SatNets:* The HMIPv6 protocol adds an MAP to the network to handle local handovers, which decreases the required mobility management signaling and reduces the handover delay of location updates [4]. However, the large scale movement of an LEO satellite is considered as global mobility that cannot take advantage of HMIPv6. Thus, with the large scale of future LEO SatNets, HMIPv6 will be performing inter-MAPs handovers which generates a high number of control messages for location management and prolongs latency. In addition, the placement of an MAP on a satellite or in a ground gateway has pros and cons. Co-locating the MAP in a ground gateway will face the challenge of high propagation delays and frequent change in the satellites connected to the MAP. However, placing an MAP on a satellite will require some adaptation to the mobility of the satellite fast mobility. It is important to note that in FMIPv6 MAPs are designed as static network entities.

4) *PMIPv6 in future LEO SatNets:* In PMIPv6, the network performs the mobility management process on behalf of the MN, which reduces the signaling interaction between the MN and the network access router [43]. In [45], the author compared the performance of MIPv6 and PMIPv6 in a simple LEO constellation and the results showed reduced handover latency with the implementation of PMIPv6. However, the application of PMIPv6 in future LEO SatNets may face several drawbacks, such as the high load on the LMA, the long handover delay due to the signaling that needs to pass the MAG and LMA, where one might be located on the ground. In PMIPv6, the LMA manages not only the mobility of the MN but also handles its related data traffic [3]. In future LEO SatNets, if a terrestrial gateway is the candidate LMA, directly applying PMIPv6 can cause non-optimal routing. This is because packets cannot be routed among satellites of different domains; instead packets would make a round trip through GSLs, which is unnecessary [3]. As the LMA and MAG are originally considered to be static network entities, placing either on a satellite requires an adaptation procedure to cope with the satellite's fast mobility. PMIPv6 can provide good mobility support for receivers during an IP multicast session [46]. However, when the source node is mobile (i.e., LEO satellite) in a PMIPv6-based multicast session, all the receivers need to resubscribe every time the source node changes its network access point or location.

IV. TAXONOMY OF LOCATION MANAGEMENT APPROACHES IN IP-BASED LEO SATNETS

The existing research about location management in LEO SatNets can be divided into three approaches, as shown in Figure 8.

A. *Extensions of IETF location management techniques for LEO SatNets:* As described in Section III, mobility management in IP-based networks consists of handover management and location management. The IETF IPv6 mobility management standards (e.g., MIPv6, PMIPv6, FMIPv6, HMIPv6) addressed the location management issue in terrestrial networks. Although some

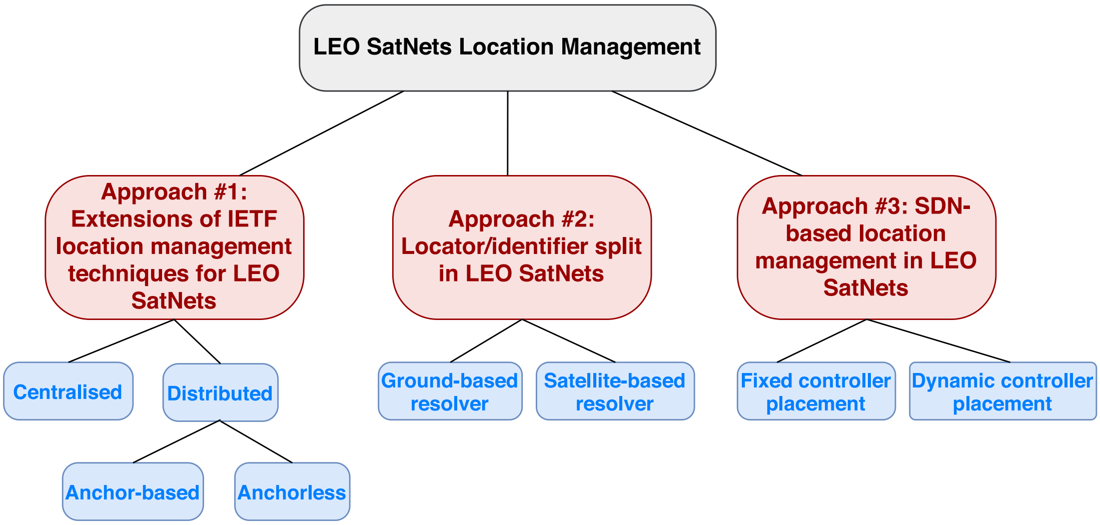


FIGURE 8. **Taxonomy of location management approaches for LEO SatNets.**

researchers have attempted to employ the location management techniques of IPv6 mobility management standards [45], [47], such techniques have many limitations when applied to satellite networks. To enhance the performance of IETF location management techniques, a number of extensions were proposed for satellite network location management, which are discussed in Section V. This approach consists of two categories where the location management is done in either a distributed or centralized manner. The distributed IETF location management techniques' extensions can be either anchor-based or anchorless, as shown in Figure 8.

B. *Locator/identifier split in LEO SatNets:* The IP dual-role (i.e., locator and identifier) is regarded as the main cause of inefficient location management. Many research works focusing on terrestrial networks have investigated the separation of the locator and identifier roles of IP, such as Identifier Locator Network Protocol (ILNP) [48]. Section VI explores existing work on the locator/identifier split approach in LEO SatNets and discusses the applicability of such solutions in future LEO SatNets.

C. *SDN-based location management in LEO SatNets:* The SDN concept was introduced to add programmability and flexibility to network management [49]. Since the centralized nature of SDNs limits network scalability, several works have integrated SDNs with a distributed mobility management (DMM) architecture to adapt to the large scale of LEO SatNets. Section VII reviews studies that have investigated the merging of SDN and DMM in LEO SatNets, and discusses the shortcomings of applying such solutions in location management for future LEO SatNets.

The following three sections critically review and compare the existing studies under each approach and highlight important points that should be considered in the context of future LEO SatNets. In Section VIII, Table 6 presents a comparison of the advantages and challenges of the three approaches from the perspective of future LEO SatNets.

V. APPROACH #1: EXTENSIONS OF IETF LOCATION MANAGEMENT TECHNIQUES FOR LEO SATNETS

To provide continuous worldwide communication and Internet services, one of the main issues in future IP-based LEO SatNets is mobility management, which is more complex than in terrestrial networks for the reasons mentioned in Section II. From the perspective of future LEO SatNets, this section explores and discusses the proposed enhancements of existing IP-based location management standards and their drawbacks. This section concludes with an "Issues to Consider" subsection, which describes some critical points that should be taken into consideration while implementing or developing IP-based location management solutions for future LEO SatNets.

A. ENHANCEMENTS OF EXISTING IP-BASED LOCATION MANAGEMENT TECHNIQUES FOR LEO SATNETS

SIGMA is a mobility management scheme where an MN can keep using its old IP address while obtaining a new IP address [4]. Every time the MN obtains a new address, it updates the location manager (LM) database and sets this new address as its primary address. To start a communication, the CN queries the LM with the MN's identity, and the LM replies with the primary IP address of the MN. Then, the CN can initiate communication with the MN in its new location. When dealing with satellites, the scheme uses satellite predicted mobility to predict the time of setting the primary address to the new IP address and deleting the old IP address. However, this scheme does not consider the extensive signaling that will result from frequent satellite handovers in future mega-constellations.

To decrease the location management cost, fixed Location Areas (LAs) can be chosen for location management in IP-based LEO SatNets. Fixed geographical location areas fulfill this requirement as they reduce the bending update frequency. However, when delivering data to an MN, complex operations must be done by the network to determine which satellites the MN is connected to at that moment and to hide the effect of frequent satellite movement from the MN [7]. A location management scheme based on dual LAs in an IP-based LEO SatNet was proposed in [50]. The scheme used two types of LAs, the fixed Earth station (FES) LA and satellite LA. Every FES LA was connected to three LEO satellites. Initially, the MNs reported both the satellite LA and FES LA information to its HA. A binding update will not be triggered unless the MN moves out of the two LAs that were reported to the HA through the last binding update procedure. Although this scheme suppresses the binding update frequency, its loose location management necessitates the use of paging to locate MNs (to which one of the three satellites the MN is connected). To send a packet to an ideal MN, the packet is first routed to the MN's HA and then routed to the FES. The FES sends a paging request to the satellite to which the MN has been registered (the last stored SAT ID). If the MN is still in the coverage area of that satellite, the packet will be delivered successfully. Otherwise, the FES predicts the satellite that covers the MN and sends the paging request to it. Clearly, this scheme reduces the cost of binding updates but at the expense of paging and suboptimal data packet routing.

To overcome the scalability issue of the centralized IP-based location management solutions, some studies proposed distributed solutions that have the advantages of optimal or near-optimal routing paths, workload distribution, and improved handover performance with shorter packet delivery latency. There are two types of distributed location management: anchor-based and anchorless [51]. In anchor-based location management, the responsibilities of location management are permanently assigned to certain network entities. In contrast, in anchorless approach the role of location management is continuously shifted from one network entity to another based on network topology changes. Figure 9 presents a comparison of anchor-based and anchorless approaches.

In [52], the author presented an IP-based distributed location management scheme. The scheme was anchor-based as it depended on the availability of distributed ground station (GS), which can communicate and collaborate to manage the locations of satellites and attached MNs. GSs register the binding (location) information of MNs and satellites, and they also forward the data from and to the MN. When a CN needs to communicate with an MN, it will forward the data through a satellite to the GS, and then the GS will forward the data through satellites to the MN's corresponding GS. Thus, forwarded data packets must go through GSLs, which is considered a non-optimal route that consumes GSL bandwidth and increases the packet delivery delay. Although distributing location management tasks over GSs improves the system scalability, it introduces a large amount of signaling overhead in the terrestrial network when binding updates are globally exchanged among GSs.

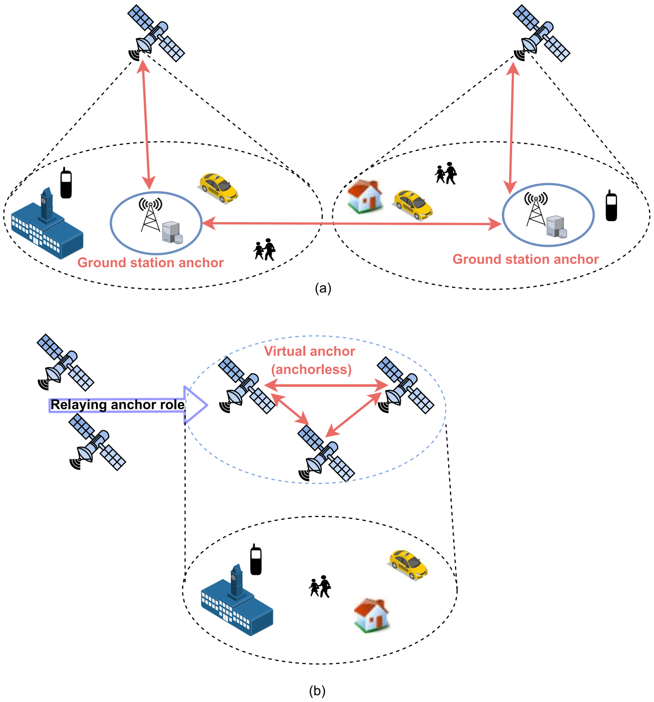


FIGURE 9. **(a) Anchor-based approach (using ground station anchor). (b) Anchorless approach (using a set of satellites as a virtual anchor for a certain LA).**

A virtual mobility management scheme, called VMIPv6, which is an enhancement to MIPv6, was proposed in [7]. VMIPv6 adopts the anchorless concept of location management and the distributed architecture introduced in the IETF's DMM requirements document (RFC 7333) [53]. To reduce the location management overhead and delay, the author created a virtual agent cluster (VAC) to co-manage the mobility of users in the corresponding virtual agent domain (VAD). A set of LEO satellites on top of one specific LA is called a VAC. The whole coverage area of all satellites in a VAC is defined as a VAD. With changes in topology, a VAC is reconstructed by adding the new satellites sliding into the LA and deleting the ones sliding out of the LA. The departing satellite relays the LA's binding information to the new satellite. Every VAC has multiple local Mobile Agent Anchors (MAAs) and one home mobile agent anchor (HMAA). The MAA and HMAA are on-board routers in an LEO satellite to provide location management and routing services for the registered MNs. The MAAs of a VAC share the mobility information of the MNs and cooperatively manage their binding. The HMAA maintains the connection between the VAC and HA, and the MN registers its HMAA's subnet IP address at its HA. The local MAA is responsible for controlling the connection links between the MN and the VAC, and the MN binds its local MAA's IP address to each MAA

TABLE 3. Comparison of IP-based location management enhancements for LEO SatNets.

Algorithm	Location management placement	Anchor based/ Anchorless	Distributed/ centralized	Location update frequency	Data forwarding route	Main limitation in LEO satellites mega-constellation
SIGMA [4]	Ground	Anchor-based	Centralized	Every time the MN moves from one AR (satellite) coverage to another	It has to pass through terrestrial gateways	Did not consider the high frequency of satellite handovers in future LEO SatNets. Non-optimized routing through terrestrial networks.
Dual LAs [50]	Ground	Anchor-based	Centralized	When the MN leaves both FES LA and satellite LA	It has to pass through HA and FES	Requires paging to locate MN. Did not consider satellite's location management.
Distributed location management using GSs [52]	Ground	Anchor-based	Distributed	Every time a MN/satellite changes its GS	It has to pass through GSs	Assumes the availability of many GSs. Did not consider the direct communication between satellites and MN.
VMIPv6 [7]	Satellites (location management), Ground (home agent)	Anchorless	Distributed	When the MN switches its connection to a new satellite within the same VAD, the MN only updates the local care-of address with the new MAA. If the HMAA of a MN slid out of the VAD or the MN moved to another VAD, then the global care-of address will change at HA.	It has to pass through HA then satellites	When a VAD is serving thousands of MNs, relaying MNs' binding records from the departing satellite to the new satellite consumes ISLs resources. Having a fixed HA on the ground causes non-optimal routing.
Flexible agent [8]	Satellite	Anchorless	Every time a MN changes its access satellite	Distributed	It has to pass through the HA which is the current access satellite	In future LEO SatNets it is not easy to determine the next access satellite since there will be multiple candidate satellites in the mega-constellations and LEO satellites have limited processing resources.

of its related VAC. Within a VAD, each MN has a global care-of-address and a local one. When a satellite's mobility forces the MN to switch its connection to a new satellite within the same VAD, then the MN only updates the binding information with the new MAA. Thus, only the local care-of address will change. If the HMAA of an MN slid out of the VAD or the MN moved to another VAD, then the global care-of-address would change. In this case, the MN should choose another MAA in the VAC as its new HMAA and send the binding update information to the HA/CN to inform its new global care-of-address.

The author of [8] identified two main drawbacks of placing the home agent entity in a ground station: 1) ground stations are fixed and do not move with satellites, which makes it hard to communicate with the home agent when the satellite is not in line-of-sight; and 2) ground station deployment is bounded by Earth's geography. In addition, fixed home agents on satellites will require several hops to complete binding updates when the satellite is not in line-of-sight, which increases the update delay and consumes ISL bandwidth. To overcome such problems, [8] proposed using a flexible agent placed on LEO satellites, where the home agent functionality is relayed from one satellite to another (i.e., the satellite that is closer to the MN) in a flexible manner. Once the binding update procedure at the correspondent node is finished, the functionality of the home agent will relay from the previous flexible agent to the current access satellite. Although this solution reduces the delay in communicating with the home agent, frequently transferring the home agent records from one satellite to another will consume resources of ISLs. Nevertheless, having the HA on a satellite may result in data packets being forwarded through satellites even though the CN and the MN are connected through terrestrial networks. Table 3 shows a comparison of the IP-based location management enhancements for LEO SatNets, and highlights their limitations with respect to future LEO SatNets. In [54], the authors designed the IP address allocation method of a space-based network using geographic partitioning. Basically, the Earth's surface is divided into multiple regions and location areas based on network structure and geographic information. Satellite IP addresses are allocated on the basis of geographical areas. In this strategy, the terminal information remains unchanged, thereby ensuring that the terminal address within the area remains unchanged. When a satellite enters a new geographical area, it will switch to a new IP address allocated for that area.

B. ISSUES TO CONSIDER

IP-based location management has been investigated in GEO satellite mesh networks [47]. Nevertheless, future LEO SatNets require new research on location management solutions that consider the special characteristics of future mega-constellations. The following points summarize some important issues that should be considered in IP-based location management for future LEO SatNets.

- In IP-based location management, the anchor entity has two roles: managing terminals locations and routing data packets to terminals. When anchor nodes are placed on Earth, location management in future LEO SatNets faces the problem of limited link resources and long propagation delays while communicating with anchor nodes for binding updates or data delivery. On the other hand, placing anchor nodes on LEO satellites can be a problem due to limited on-board processing and storage and the fast movement of satellites.
- Studying the placement of anchor nodes (in both anchor-based and anchorless solutions) is vital for route optimization. Though previous studies suggest that neither space placement nor terrestrial placement of anchor nodes can give favourable routing performance in all forwarding scenarios.
- IP-based location management solutions require complex signaling, such as the dynamic construction and release of tunnels, which increases the load on satellites' OBP units. The limited computational power of satellites should be considered.
- The proposed enhancements of IP-based location management in LEO SatNets face the problem of high location management overhead due to the unprecedented network architecture, where satellite-mounted BSs move at high speeds causing frequent handovers of users or MNs in large groups.
- Unlike location management in terrestrial networks, IP-based location management in future LEO SatNets has two levels. The first level is the location management of MNs. The second level is the location management of satellites that act as BSs, routers, or terminals. Separating the two levels of location management might reduce the complexity of the location management system. However, there is still a need for some kind of mapping and coordination between the two levels.

VI. APPROACH #2: LOCATOR/IDENTIFIER SPLIT IN LEO SATNETS

Current satellite network architecture uses IP addresses as both identifiers (i.e., to identify who the endpoint is) and locators (i.e., to identify where the endpoint is). However, the dual role of IP addresses diminishes their ability to support mobility, especially in future SatNets where, mobility, scalability, and tight time constraints are pressing requirements [3]. Mobility support in IP networks depends heavily on the network topology that has static anchor nodes, which makes IP mobility solutions impractical when applied to satellite networks. In a satellite network, location management should be intrinsically designed with the consideration of the network topology in order to avoid scalability issues. Some emerging mobile network architectures (e.g., MobilityFirst [55], [56]), considered the separation of identifier and location as a way of enhancing mobility management. In particular, the scalability of routing with the implementation of the locator/identifier split has been well investigated [3]. With locator/identifier splitting, a remote node can be identified even if it is using multiple addresses during the communication (e.g., multi-homing concept). Thus, with locator/identifier separation, it is possible to keep an ongoing communication continuous, since moving MNs can keep their identifiers [57].

Conventional mobility management consists of two main procedures: location management and handover management. However, in the location/identity split approach, mobility management is achieved through two correlated steps, namely location (binding) updates and location resolution [58].

Based on the location/identity split approach, HIP [59], [60] was proposed as a draft at IETF in 1999 followed by various subsequent improvements. The HIP architecture adds a new layer, called the host identity layer, between the IP layer and the transport layer, thereby decoupling the layers from each other, and splitting the dual roles of IP addresses. When HIP is used, IP addresses function as pure locators. Instead of IP addresses, the applications use host identifiers to name peer hosts. To establish an HIP association, the two communicating parties involved issue a four-way handshake. HIP has a number of implementations, such as OpenHIP [61] and HIPL [62]. However, the implementation of HIP for satellite networks has not been investigated.

Locator/Identity Separation Protocol (LISP) [63] was initiated at the Internet Research Task Force (IRTF) in 2007, and has been developed by the IETF working group since 2009. LISP has been promoted by Cisco and several research organizations, such as LISP4.net [64] and LISP-Lab [65] with worldwide testbeds. LISP has multiple implementations, such as Open-LISP [66] and Cisco IOS [67], which significantly accelerated its development. LISP divides a network into a core and edge, and it divides the IP addressing space into an end identifier (EID) and a routing locator (RLOC). An EID is topology-independent and used as a local address by hosts within edge networks, while an RLOC is used as a global locator to transmit packets within the core network. In LISP, the border router that forwards packets from the edge to the core is called an ingress tunnel router (ITR), whereas the one that forwards packets in the opposite direction is called an egress tunnel router (ETR). The ITR maintains a cache of RLOC-EID mapping locally. If the ITR does not have the location of the destined EID, it will send a map-request to the mapping system. Afterward, the ITR will send the data packet to the proper ETR. There are a number of proposals for LISP mapping systems, such as LISP-Tree [68] and LISP-DDT [69]. However, the application of LISP has not yet been investigated in satellite networks.

In [3], GRIMM was proposed as a gateway-based regional mobility management architecture for a locator/identifier split approach in satellite networks. GRIMM divides the coverage of the satellite system into regions based on the distribution of terrestrial gateways. Each gateway is equipped with a terrestrial gateway mapping server (TGMS) and is responsible for the localized location management of the MN within its region. The global location management operates through the synchronization of all gateways. When a foreign TGMS receives global updates, it generates the mapping entry between the MN's ID and its corresponding TGMS. To avoid the non-optimal routing, GRIMM's location resolution is conducted before forwarding data packets. In GRIMM, an MN accesses a satellite with a fixed identifier (ID) and the local TGMS records the MN's ID and its corresponding accessed satellite. When the MN ID is registered locally for the first time, the TGMS will trigger a global update among all TGMSs. To start a session between an MN and a CN, the accessed satellite will first send a request of location resolution to the local TGMS upon receiving the first data packet. If the local TGMS does not have the specific locator of the enquired CN's ID, the request will be redirected to the corresponding TGMS. After receiving the requested CN location, the source satellite begins to encapsulate the data packet with location information and then forwards it through inter-satellite links to that area. The destined satellite can decapsulate the packet and then sends it to the CN. When an MN moves from one satellite area to another, subsequent messages will notify the accessed satellite of the CN to update the MN's location in the cached mapping entry. This is to update the routing path between satellites. Although regional location management greatly reduces the management cost and facilitates the scalability of the network, global updates may create high signaling overhead among the gateways. In addition, keeping records of every MN's ID and corresponding TGMS in all foreign TGMSs requires massive storage resources.

SAT-GRD is a proposed locator/identifier split network architecture for integrating satellite and terrestrial networks [9]. It separates the identity of both the network and the host from their locations. It introduces a hierarchical mapping and resolution system that enables the separation of the control and data plane in SAT-GRD as well as the decoupling of the intra-domain routing policy from the inter-domain routing. Each edge network has its own edge mapping system, and there are two core mapping systems: one in space (using GEO and MEO satellites); and the other on the ground (for terrestrial network). Between satellite and terrestrial networks, there are a number of border routers that handle the mapping of the host's ID and location between the two networks. An identity mapping systems was presented in [70], where mapping between IP addresses and the identifiers of network node (i.e., routers and terminals) is done at distributed identifier switch routers located at GEOs, LEOs, and ground gateways.

A heterogeneous satellite-terrestrial network architecture, HetNet, is presented in [71]. HetNet merges locator/identifier split and information-centric networking. The author assumed the availability of a network manager node at each edge network that handles the location registration and the location-to-ID resolution. In addition, there were network management nodes in the core network that formed a hierarchical structure with the edge network management nodes. For satellite networks, their network management nodes were placed in the ground gateways. When an MN moves within the same network, its location is updated in the local network management node, whereas an upper network management node needs to update the MN location only when it moves from one network to another. However, the author did not clarify whether a satellite moving from one gateway to another would cause a local or a higher level location update. Moreover, the proposed architecture did not consider direct communication between satellites and MNs; it assumed that MNs could communicate with satellites through ground gateways only.

A locator/identifier split approach can enhance mobility in satellite networks. However, due to the high mobility of LEO satellites, conventional binding (location) update schemes will create a large number of binding updates for both MNs and satellites, each with a high binding update rate. To mitigate the effect of frequent satellite handover on the binding update rate, the authors of [58] and [72] proposed the concept of a virtual attachment point (VAP) to make binding updates independent of a satellite's motion, where the VAP stays in a fixed position relative to the ground. The VAP scheme decouples the binding of endpoints and satellites into two types of independent bindings: the binding between the endpoint and the VAP, and the binding between the VAP and the physical satellite. The two independent bindings provide the binding information required for endpoint mobility based on the locator/identifier split approach. Thus, a virtual spherical network consisting of fixed VAPs is superimposed over the physical satellite topology in order to hide the mobility of satellites from the terrestrial endpoints. A VAP is created and maintained by the satellites that pass over the fixed network location of the VAP. Then a binding between the MN identity and the fixed virtual attachment point (rather than the physical satellite passing over the MN) is carefully maintained by an identity-to-location resolution system. For the binding of the physical satellites to a certain VAP, the proposed scheme takes advantage of the periodic and predictable LEO satellite movement as well as the predefined satellite constellation topology. Thus, periodically, a group of satellites leaves a VAP and rebinds to the next VAP.

To enable a locator/identifier split in satellite networks, there is a real need for a rapid mapping system that can resolve identifiers to network locations in a real-time manner. Conventional ground station–based satellite system control is restricted to the land distribution. The distributed mapping

TABLE 4. Comparison of locator/identifier split algorithms.

Algorithm	Location resolver placement	Location update frequency	Location query trigger	Main limitation in LEO satellites mega-constellation
HIP [59], [60]	Ground-based	Every location change	Establishing a connection with CN or when CN change its location	Not investigated for satellite networks
LISP [63]	Ground-based	When MN moves from one edge network to another	When the location is not available in ITR cache	Not investigated for satellite networks
GRIMM [3]	Ground-based	Global update: when a MN moves from one region to another. Local update: when accessed satellite change	When new data session starts and its done through SGLs	Global updates will create high network overhead, requires large storage to keep global records, Ground-based location resolution delays session initiation
SAT-GRD [9]	Ground and satellite-based	When MN moves from one AR to another within the same edge, the location update is in the edge mapping system. Whereas, moving from one edge network to another results in location updates at the core mapping system level	When moving from one AR to another or from one edge network to another	Did not consider the direct communication between satellites and users. The border routers might encounter high loads and bottlenecks when direct communication between satellites and users is considered.
HetNet [71]	Ground-based	Upper hierarchical level update: when MN moves from one edge network to another. Local update: when MN moves within the same edge network	When new data session starts and its done through SGLs	Did not consider the direct communication between satellites and users
VAP [58]	Satellite-based	When a MN or satellite changes its VAP region	When new data session starts and it is done through ISLs	Creates overhead on ISLs when location-ID records are transferred from one satellite to another.
RMRS [73]	Satellite-based	Updates are done in the original and replica satellites when a MN or satellite changes its virtual region	When new data session starts and its done through ISLs	Creates overhead on ISLs when location-ID records are transferred from one satellite to another. Creating replicas increases the location update cost and consumes the satellite limited processing power.

system formed only by ground stations may be too far to access for global scattered mobile users. Consequently, the location resolution latency becomes another challenge. To address this issue, [73] presented a space-based distributed rapid mapping resolution system (RMRS) along with a dynamic replica placement algorithm. The goal of RMRS is to achieve low location resolution latency, low update cost, and high system availability (resilience to failures). The two main components of RMRS are the virtual resolvers and replica placement controllers. The space-based fixed virtual resolvers are responsible for maintaining the mapping replicas and responding to user requests, while the replica placement controllers on the ground are responsible for determining the number and locations of the mapping replicas. The virtual resolvers have the same concept as the VAPs [58]. The virtual resolvers are fixed with respect to Earth and create a virtual overlay network upon underlying moving physical satellites. Each virtual resolver is maintained at a certain time by specific satellites. When a satellite leaves a virtual resolver region, then the mapping records handled by this virtual resolver are then transmitted to the subsequent satellites passing by. The replica placement controllers usually reside in the ground stations and communicate with the virtual resolvers (LEO satellites) through GSLs. Replicating every mapping at every possible location would create a high cost, especially with the rapid movement of satellites and their large-scale network. Therefore, the replica placement controllers use the dynamic replica placement algorithm to determine the number and locations of replicas for each mapping entry so as to provide a tradeoff between location resolution latency and update cost. However, an accurate calculation of the region size is required with consideration of the number of satellites in the constellation. This is to avoid the situation of there being no satellite in the virtual resolver region for some time.

The locator/identifier split approach also has natural advantages in mobility support. The identifier uniquely represents the node in the network and the varying locator is used for routing. Through dynamic mapping from identifier to locator before sending packets, the independent location management is achieved, and non-optimal routing is mitigated. Independent implementation of mapping service provides more flexibility and its advantages can become more significant with the increase of network scale, especially in scenarios with continuous mobility. Existing locator/identifier split architectures mainly focus on the terrestrial network. And related work on its application feasibility in satellite networks has not been conducted [3]. Table 4 compares the reviewed studies on locator/identifier split algorithms and highlights their limitations for future LEO SatNets.

A. ISSUES TO CONSIDER

This section highlights the issues that should be considered in implementing the location/identifier approach for future LEO SatNets.

- To implement a location/identifier split approach in future SatNets, it is important to have optimal location update and resolution schemes that are scalable and can work rapidly with reduced signaling costs. Due

to the limited computational power of satellites, the designed schemes should be lightweight and have low complexity.
- Placing location resolvers on the ground may create delays for location updates and resolution, and they might not be uniformly distributed due to the geographical structure of Earth. On the other hand, placing the location resolvers of a certain region on satellites requires periodic transmission of location-ID mapping records from one satellite to another, which may congest the ISLs. In this regard, placing location resolvers on a high altitude platform system (HAPS) may be a good solution, as HAPSs are positioned between satellites and ground users, and HAPSs are considered quasi-stationary with respect to Earth [74] and [75].
- Although many studies have proposed location/identifier splitting methods for location management in LEO SatNets, such methods have not received much consideration for real applications due to their incompatibility with IP-based networks. One of the main purposes of future LEO SatNets is to provide global broadband and Internet services. In the future, satellite networks will be integrated with vertical heterogeneous network (VHetNet) [76]. Therefore, any locator/identifier split system should consider retaining backward compatibility with legacy IP locator and identifier systems.
- Global updates performed by some of the existing solutions seem impractical, especially when there are thousands of satellites and millions of user devices communicating with the satellite networks.
- Most existing studies have not considered that future satellite networks will consist of several mega-constellations, which will provide connectivity and Internet services not only in rural or remote areas but also in urban areas.

VII. APPROACH #3: SDN-BASED LOCATION MANAGEMENT IN LEO SATNETS

An SDN separates the control plane from the data plane. In SDNs, controllers are considered the brain that performs intelligent functionalities. Through the northbound interfaces, the controllers interact with applications to decide on how to create or update flow tables saved in the SDN switches. Communication among SDN controllers can be done through westbound and eastbound interfaces. Through secure channels, an SDN controller can communicate with one or more SDN switches. Actions on how to treat the received packets are predefined in the switch flow tables. Whenever a new packet is received at the SDN switch, a flow table lookup is done. In the lookup process, if the packet header matches a record in the lookup table, then the predefined actions are performed. If the match is not found in the flow table entries then the packet will be forwarded to the controller through the southbound interface [35]. For more details on SDNs, the interested reader may refer to [77].

Based on the received network topology information, the SDN controller makes the routing and forwarding decisions. Unlike traditional networks, topology management is a fundamental task in SDNs. Topology discovery (TD) is a key component to support the logically centralized control and network management principle of SDN. TD enables a controller to have global visibility of the complete network. Discovering the network topology includes the discovery of switches, hosts, and interconnected switches. In the TD process, each entity in the network can collect information about the network topology. The information collection can be done at different levels and in many ways. In addition, the TD process must be efficient in terms of sending topology information only when changes happen and not flooding the controllers with unnecessary information [78].

TD also provides a major part of the functionality of location management in SDNs. Basically, location management and TD both provide information about the location of network entities (logical location) within the network and the interconnections between different entities. For this reason, several studies have proposed SDN-based mobility management schemes where TD is used for location management. For example, [79] proposed a location management scheme for a 5G mobile core network that relied purely on SDN. The scheme was used to manage the MN status and the paging procedure.

In [78], the author discussed the challenges of TD protocol for SDN-based wireless sensor networks. In so doing, attention was drawn to the issue of limited resources of sensor networks that require a lightweight TD protocol, which is a similar requirement in satellite networks. Although satellite networks will have more resources than wireless sensor networks in terms of power and processing capabilities, applying existing TD protocols to satellite networks will result in high network overhead. In particular, due to the high speed of satellites and frequent topology changes in densely deployed mega-constellations, more packets will be sent to the controller to update the topology and flow table. Such overhead traffic could negatively affect the efficiency of network resource utilization.

The authors in [80] and [81] used an SDN to construct and manage the topology of an information centric network (ICN) overlaid on a legacy IP network using the controller's management capabilities. A centralized controller would construct the ICN topology dynamically when new customer networks would join the overlay, and the controller was capable of modifying the topology of the ICN overlay in order to reduce the load on the congested links. This dynamic topology control performed by the centralized controller is a useful feature for future LEO SatNets. However, the centralized nature of SDNs present a problem with respect to satellite network scalability.

In an SDN, the controller is responsible for updating the forwarding rules of the network elements in the data plane. The time required for a rule to be installed is referred to as the flow setup time. In a large-scale network, such as an LEO

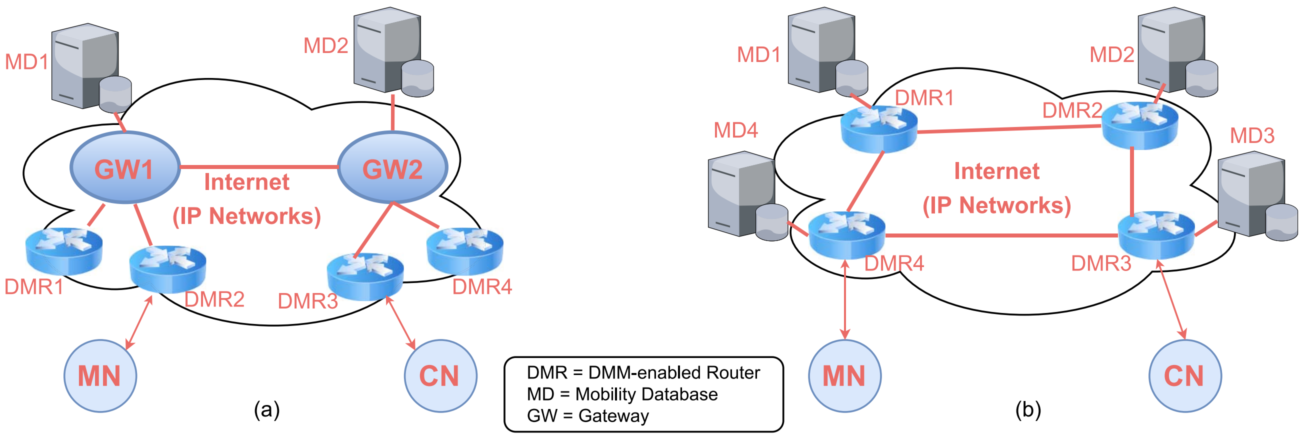


FIGURE 10. DMM architecture. (a) Partially distributed. (b) Fully distributed.

mega-constellation, a single controller with limited resources will not be able to handle all the update requests originating from the data plane, and the controller might encounter bottlenecks. Furthermore, due to the large distances between the satellites and the controller, there is no guarantee of meeting the acceptable control plane latency. Therefore, having a distributed control plane becomes mandatory. However, it is very important to choose the optimum number of controllers and their locations based on the traffic load distribution and topology changes [30].

A. MERGING OF SDN AND DISTRIBUTED MOBILITY MANAGEMENT (DMM)

The DMM concept was introduced by IETF to overcome the limitations of centralized management, such as the one point of failure, bottlenecks, and high delays. DMM-based solutions can be categorized into two types (Figure 10), depending on the distribution level of the control plane [6].

- Partially distributed: The control plane is centralized in certain control points in the network, whereas the data plane is completely distributed among the network entities.
- Fully distributed: Both control plane and data plane are completely distributed among the network entities, and there exists no central entity of control.

Some researchers consider SDN to be an enabler for DMM [82]. They hold that DMM approaches will push mobility anchor points to be distributed at the network edge and support the SDN separation of data and control planes. This allows for a quicker configuration and provision of network connections, which is an enabler for managing mobility in a distributed way at the edge. On the other hand, some studies have suggested that DMM can help in mitigating the drawbacks of SDN centralization. The merging of SDN and DDM concepts has been investigated in several types of networks. For example, in [6], the authors proposed an architecture that used the SDN paradigm with the DMM concept in an environment of heterogeneous IP networks. This architecture was shown to avoid the centralization problem of SDN and to present a hierarchical cluster-based implementation of the SDN-DMM controllers that improved the scalability of the control plane and reduced the availability problem related to the single point of failure. By merging SDN and DMM, a large portion of data traffic can be handled locally at the network edge, which reduces the probability of bottlenecks at the network core. When an MN moves to another network, it does not need to change its IP address in an ongoing session. Instead, the controller will update the IP flow related to the moving MN to ensure that the forwarded packets will reach the MN in the new network. In addition, several studies have investigated merging DMM and SDN in 5G [83], [84].

B. SDN-BASED LOCATION MANAGEMENT IN LEO SATNETS

A simple software defined satellite network (SDSN) architecture was proposed in [85]. It consisted of three planes: the data plane (satellite infrastructure, terminal router), the control plane (a group of GEO satellites), and the management plane (network operation and control centre (NOCC)). Similarly, the author of [86] proposed an SDSN where the controllers were located on GEO satellites and the switches were deployed on MEO and LEO satellites. In [87], the authors proposed placing controllers in ground gateways, and flow tables in LEO satellites were updated through GEO satellite communication. However, every time the group of terminals attached to an LEO satellite changes due to the satellite movement, the new logical location of the terminals had to be reported to the global location server. Afterwards, the controllers would receive the updates from the location server and update the flow tables accordingly, and then send the updates to the LEO satellites.

Since frequent handovers will rapidly increase flow table sizes in SDSNs, many flows will be dropped during topology changes (handovers) due to the limited size of the flow table. In particular, a commodity switch can store about 1,500 entries only because of the high cost and energy consumption of the ternary content addressable memory (TCAM), which is usually used by SDN switches [88]. After a handover, the flow table will have unexpired entries occupying the flow table space, but these will not be used any more. The subsequent flows may be dropped if the TCAM space is limited. To address this problem, the author of [86] proposed a heuristic timeout strategy-based mobility management (TSMM) algorithm, which aimed to reduce the drop-flow during handover. The TSMM algorithm adjusts the timeout of entries dynamically while considering two key points, the limited flow table space and the satellite link handover. This is to discard the flow entries that belong to the former connection when the handover occurs. This work has been extended in SAT-FLOW [89], which is a multi-strategy flow table management method for SDSN. SAT-FLOW is composed of two heuristic algorithms, the dynamic classified timeout (DCT) algorithm and the TSMM algorithm. DCT calculates a dynamic idle timeout value for the flow entries taking limited TCAM space and classified traffic into consideration. TSMM utilizes the result of DCT and considers link handover in satellite networks. Thus, DCT aims to reduce the flow table size, and TSMM aims to reduce the drop-flows during the handover. A time estimation model was proposed by [90] to estimate the mean time required to complete the SDN control (i.e., finding or creating the necessary traffic flow) and to deliver the first packet to the destination. The author considered an architecture where three GEO satellites played the role of SDN controllers and the data plane was distributed among several LEO satellites.

However, the fixed controller placement at GEO satellites might not be able to react to traffic fluctuations caused by variable user activities and different time zones. In addition, with densely populated and highly dynamic LEO mega-constellations, having few controllers placed at a GEO satellite may result in bottlenecks and high delays while updating routing flows.

To overcome the fixed placement problem, a dynamic SDN controller placement solution was considered in [30]. The author developed a mathematical model and formulated it as an integer linear programming (ILP) problem to find the optimal controller placement and the number of satellites that would work as controllers. The goal of the model was to minimize the average flow setup time with respect to the traffic dynamics. The model was derived from an SDN architecture, where the control plane layer consisted of several LEO satellites whose number varied on the basis of traffic demands in addition to seven satellite gateways placed on the ground and served as entry points to the backbone network. The gateways position was fixed and was obtained from the existing IRIDIUM system. The satellites that were part of the control plane served as both controllers and network switches. They managed, controlled, and updated the forwarding rules of the flow tables of the satellites of the data plane. On the other hand, the satellites of the data plane were only responsible for forwarding packets based on rules defined by the corresponding controllers. However, this study considered a constellation with hundreds of LEO satellites, which is less than what is expected for future mega-constellations characteristics of future networks. Densely deployed satellite networks in the future may have huge flow tables with a very short lifetime. This is due to the fast changes in LEO SatNet topology. Once a controller leaves its current service area, its flow table entries could become inapplicable and useless to the new service area where the controller has moved.

A framework of SDSN was proposed by the author in [12]. In so doing, he defined a dynamic controller placement problem (DCPP), a static controller placement problem (SCPP), and used an accelerated particle swarm optimization (APSO) algorithm to solve these problems. The author considered the parameters of propagation delay, reliability, controller load, signaling cost, and the dynamic characteristics of satellite networks. In the DCPP, the number and location of active controllers can be adjusted on the basis of the changes in network conditions. The author assumed an architecture of multiple controllers that could be placed in LEO, MEO, or GEO, whereas the switches were all placed in the same LEO constellation. In the same work, the data plane switches sent periodic "hello" messages to their controller, and these messages were used to collect information about changes in network topology (i.e., topology discovery). In addition, the periodic "hello" messages were used to connect with a new controller when the switch lost the connection with the current controller. Controllers exchange the obtained topology discovery information to build up a global view of the network.

A three-layer hierarchical controller architecture for a software-defined GEO/LEO satellite networks was proposed in [11]. The solution exploited the wide coverage ability of GEO satellites, the easy upgrading and maintenance of NOCCs, and the stability of inter-satellite links in the same low-Earth orbit. The control plane consisted of domain controllers, slave controllers, and a super controller. The GEO satellites were set as domain controllers because of their broadcast capabilities over a wide-coverage area and stable connection with the ground station. The domain controller monitored and managed the LEO satellites in its coverage. The LEO satellites forwarded and collected the network status information, and were divided into different domains according to the GEO coverage. Several slave controllers were selected from LEO satellites. The GEO domain controllers communicated with just the slave controllers under their own authority instead of with all LEO satellites in their domain. By using inter-satellite links, the slave controllers collected the status information of the LEO satellites under their own authority, which was then sent to the corresponding domain controllers. The NOCC was deployed as a super controller that could obtain the knowledge of the overall network through the primary GEO satellites. Based on the aforementioned description, a logically centralized control plane with global knowledge was created through physically distributed LEO controllers. To select the slave

TABLE 5. **Comparison of SDN based location management in LEO SatNets.**

Algorithm	**Study objective**	**Controller placement**	**Dynamic/Fixed**	**Location update frequency**	**Main limitation in LEO satellites mega-constellation**
OpenSAN [85]	Proposed a SDN-based satellite network architecture	In GEO satellites	Fixed	Based on satellite movement prediction, flow tables are updated	This architecture is designed to provide services for terrestrial users through ground gateways only and not through direct communication.
TSMM [86], DCT [89]	To manage flow tables and reduce the drop-flows due to frequent handover	In GEO satellites	Fixed	With every handover	The authors presented a good idea to manage flows tables, however, the focus was on satellites only without considering terrestrial terminals or users.
Time estimation model[90]	To estimate the mean time required to complete the SDN control and to deliver the first packet to destination	In GEO satellites	Fixed	Periodically based on satellite movement	Communicate with terrestrial networks using ground gateways. No consideration for the case when thousands of users are directly connected to LEO satellites.
Dynamic controller placement-ILP [30]	To present a mathematical model that finds the optimal controller placement and the number of satellites that will work as controllers	In LEO satellites (with variable number and placement)	Dynamic	Based on the satellite movement prediction	Due to LEO satellite fast movement, SDN controllers will change frequently. It is very complicated to manage the changes in controllers seamlessly in a network consisting of thousands of satellites while serving millions of users.
Dynamic controllers placement-Swarm optimization [12]	To present an architecture of multiple controllers placed dynamically using swarm optimization	In GEO, MEO, LEO satellites	Dynamic	Using periodic hello messages	Using periodic hello messages will consume the ISLs resources especially in large scale networks.
Hierarchical dynamic controller placement [11]	To present a hierarchical dynamic controller architecture	In GEO and LEO satellites	Dynamic	Periodically collected and sent by LEO controllers	Maintaining the hierarchical architecture in a very dense satellite network consumes ISLs resources due to the very frequent topology changes.

controller, each LEO orbit plane was regarded as a separate management area. The LEO satellites in each orbit plane were divided into two groups such that one group moved from north to south and the other from south to north. In each group, the LEO satellite whose latitude was nearest to 0° was selected as the slave controller to collect the status information of other LEO satellites in its group. However, if more than one LEO satellite had the same lowest latitude, then the slave controller was chosen as the one which could maintain a longer communication time window. Table 5 presents a comparison of the aforementioned studies and highlights their limitations in the context of future LEO SatNets.

C. ISSUES TO CONSIDER

This section discusses several important issues that should be considered in order to utilize SDN-based location management for future LEO SatNets.

- In software-defined future LEO SatNets, there will be millions or billions of user devices connected to LEO satellites. This will create a huge number of flow records at each switch (LEO satellite), and such records will expire once the satellite moves to serve a different group of people. Setting up new flow records with every satellite handover consumes resources and creates delays. However, the idea of relaying flow tables from a departing satellite to an arriving one is worth investigating..
- When terrestrial and satellite networks are integrated, there will be millions or billions of flows. Storing, maintaining, and searching through these flow table records will be a complicated and critical issue. Thus, placing controllers in satellites with limited computational powers might create bottlenecks.
- Some SDN-based solutions, such as [85] and [90], assume that all users communicate with a satellite through a ground gateway. However, in future LEO SatNet, it is expected that users will be able to connect directly to satellites. It is recommended to consider the challenges of direct connectivity between users and satellites in future SDN-based location management solutions.

- Although distributed SDN architectures are preferred in SatNets environment, the limited satellite resources needed to implement all distributed SDN functions should be taken into consideration.
- To take advantage of dynamic SDN controller placement in future LEO SatNets, a number of factors should be considered, such as traffic demands, user distribution, user mobility, signaling cost, and the dynamic characteristics of satellite networks.
- Future network management automation will merge the concept of SDN with artificial intelligence and machine learning [91]. Thus, the utilization of artificial intelligence in SDN-based LEO SatNet location management should be considered. In particular, artificial intelligence and machine learning algorithms can be useful in selecting the SDN controllers and their placements in order to adapt to the dynamic nature of LEO SatNets. For example, reinforcement learning or deep reinforcement learning algorithms (e.g., deep deterministic policy gradient) can be useful as they can learn the optimum positions of controllers and adapt to changes in SatNet topology and user demand patterns. Although there are no existing studies on SatNets that use intelligent learning algorithms for controller placement, there is some inspiring work that has been done on software-defined vehicular networks [92]. However, to utilize machine learning in SatNets, the limited computational power of the satellite needs to be considered. This highlights the pressing need for lightweight machine learning algorithms that are suitable for SatNets.
- In terrestrial networks, SDN controllers update the flow tables using the information obtained through topology discovery protocols. In satellite networks, a large portion of the topology update overhead can be saved by predicting satellite movement. However, with mega-constellations of thousands of satellites, user devices will have multiple candidate satellites to handover. In this situation, updating user related flows based on mobility predictions will be complicated.

VIII. CURRENT VIEW AND FUTURE DIRECTIONS

The previous three sections focused on what has thus far been done to address the problem of location management in LEO SatNets. Some researchers tackled the problem by extending or enhancing IETF IP-based location management techniques, which come as part of IPv6 mobility management protocols. In contrast, a considerable number of studies highlighted the dual role played by IP addresses as both identifiers and locators as the main cause of poor performance in IETF IP-based location management techniques in LEO SatNets. Consequently, several researchers investigated the employment of a location/identifier split concept in LEO SatNets. A third approach utilized the network softwarization and the advantages offered by SND of decoupling control and data planes to support location management in LEO SatNets in a flexible way.

Clearly, the IETF IP-based location management techniques and location/identifier split algorithms are based on two totally different concepts, as the former considers the dual role of an IPv6 address while the latter separates the two roles. The main disadvantages of location/identifier split algorithms are their incompatibility with IP-based networks and the high overhead of keeping the resolution systems updated. IPv6 and SDN are interrelated technologies, where IPv6 operates on the network layer and SDN handles the management of the networking operations. From a location management perspective, SDN focuses more on providing routing services by using the flow concept rather than IP addresses to deliver packets to their destinations. Thus, in an SDN, IP addresses are still used but their main role is as identifiers. In SDN, the locator role of IP addresses is minimized, and it is the controllers instead that handle the routing and forwarding of data packets. This adds more flexibility to SatNet location management. Also, adopting a distributed SDN control plane supports the network scalability.

Using one or another of the aforementioned approaches, several solutions have been proposed to deal with location management in LEO SatNets. Although such solutions have some potential when applied to future LEO SatNets, many challenges will be encountered as well. This is due to the complicated mobility and topology characteristics of future LEO SatNets, as discussed in Section II.

For IP-based solutions, the main challenge is to minimize and manage the consequences of frequent IP address changes (e.g., signaling costs, delays, and packet loss), non-optimized routing, and inefficient placement of physical or logical anchors (i.e., a home agent). With respect to the second approach involving a locator/identifier split, the main challenges are backward compatibility with existing IP-based networks, the scalability of location update and resolution systems, and the placement of the location resolution system. Although the SDN-based location management approach is promising for future LEO SatNets, it also presents challenges. Managing a distributed SDN control plane over a large-scale network is complex due to the controller selection and placement and the critical processes related to managing the rapidly changing flow tables in the highly dynamic environment of future LEO SatNets. Table 6 summarizes the advantages and challenges of each of the three location management approaches from the perspective of future LEO SatNets.

Intensive research is needed to overcome these challenges and unlock the potential of future LEO SatNets and their capacity to provide continuous and ubiquitous connectivity with the required QoS. In the following, we draw attention to some critical issues that require further investigation for efficient topology management in future SatNets.

- In future LEO SatNets, there will be several mega-constellations with different orbital parameters. Such parameters will have an effect on a number of variables, including propagation delays, handover frequency and duration, footprints, and density of satellites. Such

TABLE 6. Summary of three approaches' advantages and challenges when applied to future LEO SatNets.

Approach	Advantages	Challenges
Approach #1: Extensions of IETF location management techniques	• Easy to deploy as they are extensions of the IETF IPv6 standardized mobility management protocols. • Easy to ensure compatibility with other IP-based networks (even with IPv4-based networks).	• Since the IP address is used as a locator as well, frequent IP address changes will occur in the highly dynamic environment of future SatNets where thousands of users, mobile BS (satellite), routers are changing their access point every moment. This will result in high signaling cost, delays, and packet loss. • Depending on IP addresses for data packets forwarding will result in non-optimized routing, which will extremely degrade the network performance especially when ground to space communication links resources are used for dispensable routes. • The performance of the proposed extensions will be severely affected by the placement of the nodes that will play the anchor role in the location management of future LEO SatNets.
Approach #2: Locator/identifier split	• Terminals and network entities can keep their identifiers and they need to update their location as they change their point of access. • As data packets are forwarded to the destination logical location rather than its IP address, more optimized routing can be achieved.	• This approach might face some incompatibility issues with IP-based networks. • It requires an efficient location update/resolution system that can handle a rapidly changing topology where millions of users and network devices are involved. The system should be scalable and provide fast responses with low complexity and signaling costs. • The placement and the architecture of the location resolution system is a very challenging issue in future LEO SatNets, where distance and restrictions on link budget affect communication.
Approach #3: SDN-based location management	• SDN concept adds the programmability feature to network management which supports agility and flexibility. • SDN supports policy-driven network management and network automation.	• It is foreseen that the merging of SDN and DMM concepts will support the scalability of future LEO SatNets. However, this will come with the price of increasing the complexity of the control and management planes due to following the distributed architecture instead of centralized. • In software defined future LEO SatNets, controllers placement is a critical issue. • With the large number of user devices and network entities, flow tables storage and maintenance require new techniques that can handle the frequent topology changes that happen in large volumes.

variables affect the performance of location management algorithms. Thus, for different orbits or constellations, location management might be different. In addition, the diversity in required QoS for user devices or applications should be taken into consideration while designing location management solutions for future LEO SatNets.

- Advances in communication technologies will enable direct communication between satellites and small devices with limited power (e.g., mobile phones and sensors). We envision that future LEO SatNet communication services will be used frequently in highly populated areas. Providing services to rural and remote areas may not be economically viable by itself, and satellite network operators will likely elect to also provide services in urban areas with high user density to improve market penetration and create their business case. However, most of the existing research on location management in LEO SatNets focuses on cases with a low density of users (e.g., users in rural or remote areas) or indirect communication with satellites through ground gateways. But to support future LEO SatNets, location management schemes should be designed to handle thousands or millions of devices connected directly to satellites. In such a scenario, issues of address resolution and mapping, flow table management, and handovers of a large group of users should be considered and investigated.

- Future networks are expected to be self-evolving networks (SENs) that utilize artificial intelligence to make future integrated networks fully automated, which will allow them to evolve intelligently with respect to the provision, adaptation, optimization, and management aspects of networking, communications, computation, and infrastructure node mobility [91]. To work in the self-evolving environment of future LEO SatNets, location management systems should be able to self-restructure the network logical topology to improve network performance. In this regard, the technologies of SDN and network slicing have promising potential. However, this topic requires further research.
- The authors in [93] considered that the main causes of the current Internet's problems are the so-called triple bindings, namely user and network binding, control and data binding, and resource and location binding. The author proposed a collaborative Internet architecture that completely cancels the restrictions imposed by the triple bindings. Although the applicability of this approach for future LEO SatNets was not discussed, it is worth investigating as it may add flexibility to network topology management.
- As part of the secure mobility management work presented in [94], the author proposed using blockchain technology for group location management in vehicular ad hoc networks. Blockchain technology is well known for managing ledgers in a secure and distributed way. This feature of blockchain might be advantageous in managing the flow tables in SDN-based LEO SatNets.
- Recently, several authors have discussed the proposal of a "New IP Address" for 2030 networks [95], [96], [97], which aims to connect heterogeneous networks, provide deterministic forwarding, and support intrinsic security. Theoretically, New IP offers more efficient addressing and network management than the existing TCP/IP standard. However, there are some concerns that New IP would require authorization and authentication of sent data packets, user identity, and Internet addresses.
- Named data networking (NDN) in LEO satellite constellation is considered a potential solution for flexible mobility management in future mega-constellations. Some recent studies, such as [98], [99], and [100], investigated the architectural benefits of NDN. It was shown that NDN can provide adaptive forwarding, in-network caching, off-the-grid communication, data-mule-service, in-network and edge computing, mobility support, and data-centric security, which make it a promising solution. However, research on adopting NDN in future LEO mega-constellation is still in its early stages, and further investigations are required.
- A very important point that should be considered in future SatNet topology management is the limited computational power of satellites. This creates constraints in maintaining and searching huge routing tables, and it restricts the functionality of controllers in software-defined SatNets. Therefore, there is a need to design lightweight location management strategies that provide efficient location management functionality with low computational costs.

IX. CONCLUSION

Efficient location management is essential to unlocking the potential of future LEO SatNets. This article has aimed to explore the current development in location management and to identify the research gaps and challenges that face the realization of effective location management for future LEO SatNets. From the perspective of future LEO SatNets, this article has critically reviewed the existing three location management approaches, including extensions of the IETF location management techniques approach, the locator/identifier split approach, and the SDN-based location management approach. It was shown that the deterministic aspects of the LEO mega-constellations and the fixed terminals can be exploited to support location management. It is expected that the concept of a software-defined satellite network will play a major role in supporting location management in future LEO SatNets. To this end, recommendations for future research were given in the penultimate section. This article can be used as a road map to guide research efforts in developing effective location management for future SatNets.

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