Satellite-Terrestrial Integrated 6G: An Ultra-Dense LEO Networking Management Architecture

Ting Ma, Bo Qian, Xiaohan Qin, Xiaoyu Liu, Haibo Zhou, Lian Zhao

Abstract

With the rapid development of low earth orbit (LEO) satellites, the ultra-dense LEO satellite-terrestrial integrated networking has become a promising paradigm to provide wide coverage, high capacity and flexible services for the sixth generation (6G) mobile communication networks. However, the natural heterogeneity, high dynamics, and large scale of ultra-dense LEO satellite networks pose new challenges to network control and management. To this end, in this article, we propose a medium earth orbit (MEO), low earth orbit (LEO) and satellite Earth stations (SESs) integrated multi-layered management architecture for the ultra-dense LEO satellite network, where global controllers and local controllers are introduced to reduce the network management complexity. With the aid of this hybrid multi-layered management framework, we can efficiently implement the network status control, mobility management, resource management, and service management in the satellite-terrestrial integrated network. To obtain proper global and local controllers with high management efficiency in the hybrid multi-layered network management architecture, we further propose a novel and efficient grouping and clustering method for the ultra-dense LEO satellite network, where each group manager MEO satellite and cluster head (CH) LEO satellites are respectively considered as the global and local controllers of each LEO satellite group. Numerical simulations are carried out to evaluate the superiority and effectiveness of the proposed hybrid multi-layered ultra-dense LEO networking management architecture.

Introduction

It is widely acknowledged that traditional terrestrial communication network cannot provide all users with high quality services due to scarce network resources and limited coverage areas, especially for users in rural, disaster-stricken, or other difficult-to-serve areas (such as civil airplane). With the advance in satellite constellation network, it has been widely used as a supplement to the terrestrial communication system to provide high data rate, high reliability, and ubiquitous connectivity in future sixth-generation (6G) communication networks [1–3]. Compared with geostationary earth orbit (GEO) and medium earth orbit (MEO) satellite systems, the low earth orbit (LEO) satellite network admits lower propagation delay and smaller propagation loss [4–6]. However, the coverage of the LEO satellite is smaller due to its lower orbit. Nevertheless, owing to the lower cost and more flexible deployment of LEO satellites, the ultra-dense LEO satellite constellation can be utilized to achieve global coverage and high throughput. For instance, SpaceX began the Starlink satellite constellation project in 2015, which is comprised of over 1600 satellites in mid-2021 and is expected to reach almost 40,000 LEO satellites [7]. Hence, the ultra-dense LEO satellite-terrestrial integrated network is envisioned as a promising paradigm to provide full coverage of 3-dimensional spatial network, ubiquitous connection of users and real-time sharing of heterogeneous network resources [8].

For the ultra-dense LEO satellite-terrestrial integrated network, efficient network control and management are of great significance to achieve reliable and robust service performance. Currently, the LEO satellite network is mainly managed by the satellite Earth stations (SESs). However, since the SESs are not deployed enough to keep communication with each LEO satellite all the time, only relying on the SESs to manage the satellite network can not realize the full-time management of LEO satellites. Considering that satellites with higher altitude possess wider coverage, the satellite network with higher orbit is naturally considered to assist the SESs to manage the ultra-dense LEO satellite constellation. Literature [9] investigated the three-layered satellite network constructed by GEO, MEO, and LEO satellite constellations, where GEO satellites calculate and update the routing tables of each satellite. With the centralized control mechanism, it minimizes the routing delay as well as the signaling and computation costs. In [10], the GEO/LEO hybrid two-layer satellite network is utilized to deal with the load balancing issue with the provision of quality of service (QoS) by using the advantage of the interconnection between layers. For the MEO/LEO two-layer satellite networks, work [11] designed a novel LEO/MEO two-layer optical satellite network with zero phase factor, where MEO satellites are network managers linked to LEO

Ting Ma, Xiaohan Qin, Xiaoyu Liu, and Haibo Zhou (corresponding author) are with Nanjing University, China; Bo Qian is with Peng Cheng Laboratory, China; Lian Zhao is with Toronto Metropolitan University, Toronto, Canada.

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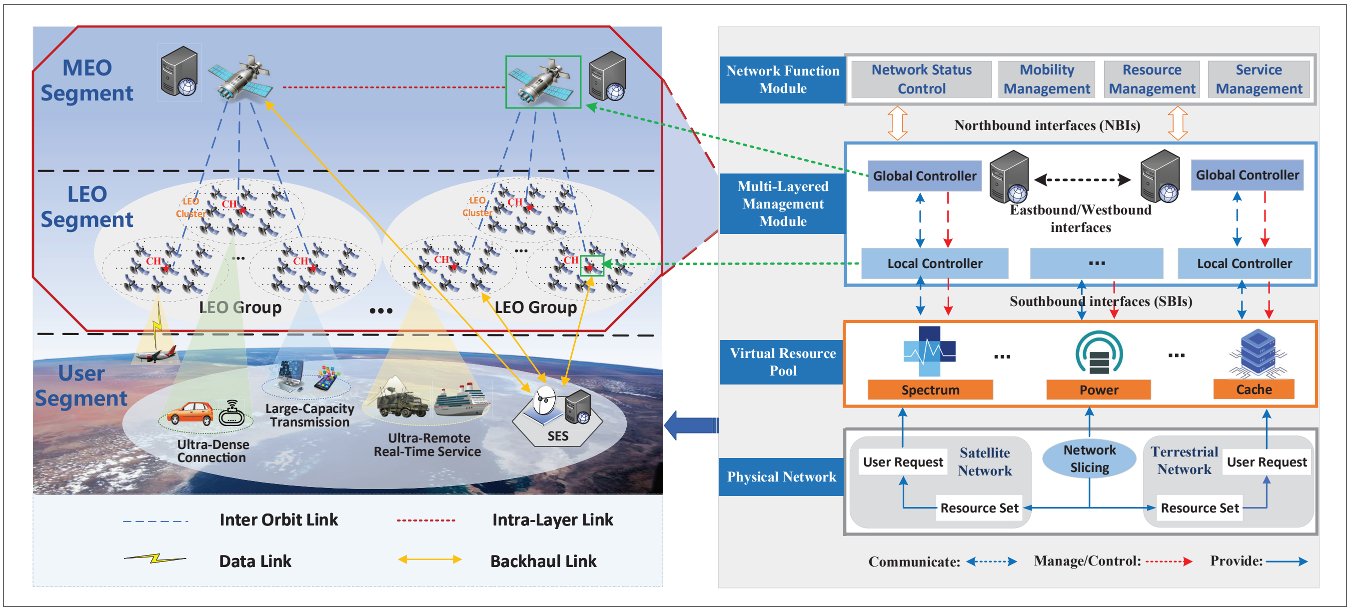

FIGURE 1. Hybrid multi-layered network control and management architecture for the ultra-dense LEO satellite network.

satellite groups, and LEO satellites are infrastructures of space information network accessed by mobile terminals. In [12] , the satellite grouping and routing protocol is proposed, where LEO satellites under the coverage of the same MEO are partitioned into a group and MEO satellites are responsible for computing and distributing the control information.

Until now, limited research efforts have been made on network control and management for the ultra-dense LEO satellite-terrestrial integrated network. There still exist many new challenges, for example, the high dynamics of LEO nodes will lead to frequent changes in network topology and network states such as channel condition, which aggravate the difficulty of network control and management. Meanwhile, the ultra-dense LEO satellite-terrestrial integrated network has characteristics of natural heterogeneity, high dynamics of nodes, large temporal and spatial scale, and time-varying status [13], which leads to a very complex and highly dynamic topology. Therefore, it is challenging but urgent to establish an efficient and lightweight network control and management system for the ultra-dense LEO satellite network.

In this article, considering the delay between GEO and LEO is larger than that between MEO and LEO, we introduce MEO satellites to implement network control and management for the ultra-dense LEO satellite network. Meanwhile, an SES is preferred to manage the LEO satellite if available due to the shorter delay. Inspired by the above, we establish an MEO, LEO and SES integrated multi-layered network management architecture, where an efficient grouping and clustering scheme is proposed for the ultra-dense LEO satellite network. The main contributions are summarized as follows.

Satellite-Terrestrial Integrated Multi-Layered Network Control and Management Architecture: We introduce an MEO, LEO and SES integrated multi-layered management architecture, where SESs are managers with the first priority if available. In this framework, global and local controllers are introduced to reduce the management complexity. Meanwhile, we elaborate challenges in the network status control, mobility management, resource management, and service management for the ultra-dense LEO satellite-terrestrial integrated network, and provide corresponding solutions on basis of the proposed hybrid multi-layered network management architecture.

Grouping and Clustering Methodology: We propose an efficient grouping and clustering method for the ultra-dense LEO network to obtain LEO groups and clusters with high management efficiency. Then, we consider group manager MEO satellites and cluster head (CH) LEO satellites as global and local controllers respectively in the hybrid multi-layered management architecture.

The rest of this article is organized as follows. In the next section, we introduce the hybrid multi-layered ultra-dense LEO networking management architecture, together with the network status control, mobility management, resource management and service management. Following that, an efficient grouping and clustering method is proposed for the ultra-dense LEO satellite network. After that, simulation results are carried out to verify the effectiveness of the proposed multi-layered management framework. Finally, we conclude the article.

Multi-Layered Ultra-Dense LEO Networking Management Architecture

In this section, we will detailedly introduce the satellite-terrestrial integrated multi-layered network control and management architecture. Meanwhile, based on the proposed multi-layered management architecture, we provide schemes of network status control, mobility management, resource management and service management.

As shown in Fig. 1, there are a few MEO satellites together with SESs as external managers of the ultra-dense LEO satellite network. Specifically, each MEO satellite as a global controller manages one set of LEO satellites. Due to the large number of LEO satellites in each set, if each LEO in one set establishes a link with the global controller MEO, referred to as inter orbital link (IOL), the network topology will be more complex. Meanwhile, since one MEO can only communicate with several LEO

The network status control is the building block of follow-up network management, and thereby the network status information update plays an important role.

satellites simultaneously, the queuing delay will be very large. Hence, we further select several LEO satellites as local controllers in each set, where each local controller manages LEO satellites in its management scope and only local controller LEO satellites communicate with the global controller MEO or available SES. In this way, the number of IOLs is greatly reduced, and the management efficiency is improved. For concise, we call an LEO that are not a local controller as the ordinary LEO. It is worth noting that, when there exists SES under the coverage of an LEO, it will first be managed by the SES because of shorter delay. For the ultra-dense LEO satellite-terrestrial integrated network, its network control and management are challenging due to the high dynamic, large scale and heterogeneity. Nevertheless, based on the proposed multi-layered management architecture, we can achieve efficient network status control, mobility management, resource management, and service management.

Network Status Control

The network status control is the building block of follow-up network management, and thereby the network status information update plays an important role. In the ultra-dense LEO satellite-terrestrial integrated multi-layered network management architecture in Fig. 1, we use the global controller MEO or SES as the data center. In the following, we introduce the periodic information collection mechanism and trigger information update mechanism to achieve real-time network status information update.

Periodical Information Collection Mechanism: At the beginning of each period, each global controller MEO distributes the status collection instructions to local controller LEO satellites in its set. After the local controller LEO receives the instruction, it sends the status collection instruction to all ordinary LEO satellites within its scope. The shortest transmit path is selected according to the optimal routing table stored in the local controllers. Once the ordinary LEO received the instruction, it sends the signaling message filled with its own status information, the adjacent node information and the corresponding link status information to its local controller LEO according to the best routing table stored in this node. Meanwhile, each local controller LEO also fills in its own status information and sends the received status information of its scope to the global controller MEO through IOLs. Note that, each LEO can simultaneously communicate with multiple LEO satellites accessible in one hop, and each MEO can communicate with multiple local controller LEO satellites simultaneously. In this way, the complexity of network status information collection by one MEO is shrunk down, and the queue delay is greatly cut down compared with the case that all LEO satellites directly upload messages to MEO. As a result, one MEO can periodically obtain all status information of LEO satellites in its set.

Trigger Information Update Mechanism: During the period of two periodic information collections, the trigger information update mechanism can be complementally used to timely discover the network status change. Since the distance from one LEO to the SES is much shorter than that from the LEO to the MEO, when the status information of an LEO node changes, it gives priority to spontaneously sending the new status information to the SES within its coverage, and the SES updates the status information of this LEO. If there is no SES in its coverage, it will transmit the updated status information to its local controller LEO. When there exists an SES in the coverage of the local controller, the local controller sends the updated status information to the SES, and the SES updates the status information of the LEO node. If there is no SES in the coverage of the local controller, then the local controller transmits the new status information to the global controller MEO, and the MEO will update the status information of the LEO satellite. For the case that the updated information must be transmitted to the SES, the MEO will further send the new status information to the SES.

Network Mobility Management

Mobility management can be partitioned into two categories: location information management and service continuity management. The first category focuses on tracking and recording the real-time location information of mobile terminals, which is the basis for providing various network services. The latter one is to implement the switch to ensure that the service is not interrupted.

Considering the mobility and large-scale of LEO satellites, mobility management faces the following new challenges.

Dual Mobility: The trigger of mobility handover is bidirectional. For the end user, it has the location movement and the change of service requirements. For the LEO satellite network, the high mobility of satellite nodes causes frequent changes in links between LEO satellites, referred to as inter-satellite links (ISLs), as well as in network states such as channel state and network congestion.

Highly Overlapping Coverage: In ultra-dense LEO satellite-terrestrial integrated networks, some users may have multiple visual LEO satellites and admit frequent handovers, which adds handover delay, signal overhead and decision-making burden.

Limited SES Deployment: Currently, mobility management is mainly based on the ground stations. However, SESs are usually unable to be deployed globally. Then, a large number of mobility management signals produced by LEOs can only be transmitted to a few SESs via ISLs, which may cause network congestion, unacceptable management delay and heavy signaling overhead.

Facing the highly dynamic topology and frequent handover in the ultra-dense LEO satellite-terrestrial integrated network, we design the multiple service delivery scheme based on the service function chaining (SFC) [14], where each service is delivered from a source LEO to a destination SES with a series of on-board processing. Each on-board processing can be envisioned as a virtualized network function (NF) and completed by one LEO. Thus, for one service delivery, it corresponds to one SFC consisting of several virtualized NFs [15]. One SFC is one path including on-board routing and offloading to SESs. To ensure service continuity, we need to approximately allocate the constituent NFs over LEO satellites and SESs to minimize the overall service delivery completion latency, which is referred to a SFC embedding problem. When sharing resources of both processing and communication, there exists competition among multiple SFCs. Therefore, the SFC embedding problem can be considered as a noncooperative game. Specifically, the player-set is the set of all SFCs. The strategy space is the integration of all possible paths for each SFC, including the source LEO, on-board routing path and the destination SES. The utility function of each player is its service delivery latency including propagation, processing and transmission delays. In a noncooperative game, the Nash equilibrium (NE) point, that is, the stable SFC orchestration scheme for all considered services, is a desirable strategy. For a NE solution, any player will not improve its utility by unilaterally changing its strategy. Therefore, we use a game based iterative algorithm to seek the NE solution.

Via leveraging the satellite-terrestrial integrated multi-layered network control and management architecture, we can realize location management and handover management to ensure service continuity. Specifically, for each local controller LEO, it stores the location information in its scope, provides access and routing services for mobile users, and implements the location and handover management for mobile users; For one global controller MEO, it can gather the location information of LEO satellites in its own set, and store the status information of the whole LEO satellite network via information interaction between adjacent MEO satellites.

Network Resource Management

For the satellite communication system, the link resource, energy resource, and cache resource are extremely scarce and valuable. Therefore, how effectively managing and allocating satellite network resources is an urgent problem. Meanwhile, considering the rapid change of network topology, the high mobility of LEO nodes, the change of terminal service load, etc, it is challenging to reasonably and effectively allocate satellite resources to the end users. The satellite resource management is mainly in terms of spectrum, power, and cache.

For the spectrum resources, it is more and more inadequate with the increasing maturity of satellite communication technology. Spectrum sharing technology is adopted to share spectrum between satellite networks and terrestrial networks to improve spectrum efficiency. Current spectrum sharing schemes are mainly partitioned into static one based on frequency planning and dynamic one based on cognitive radio. For power resources, it is provided alternately by solar panels or batteries, and the storage capacity is very limited. Satellite power allocation technology aims to match the traffic demand of each beam, improve the system throughput and reduce the overall power consumption. The allocation methods mainly include fixed allocation, on-demand allocation, and adaptive allocation. As for the cache resource, it is used as a shared resource in the satellite network, where the cached data can be shared to avoid bandwidth waste caused by repeated requests.

Through reasonably exchanging resource management information between global controller MEO and local controller LEO, it can form the optimal resource slicing structure, which effectively reduces the complexity of resource management. For the dynamic resource management of ultra-dense LEO satellite-terrestrial integrated network, each global controller MEO intelligently clusters resources, and then sends it to the local controller LEO satellites to obtain the resource scheduling scheme. That is, MEO performs resource slicing, while local controller LEO implements resource allocation.

Network Service Management

Nowadays, the ultra-dense LEO satellite-terrestrial integrated network is able to support more and more services. By analyzing the key performance index (KPI) characteristics of these services, they can mainly be partitioned into three categories: ultra-dense connection service, large-capacity transmission service, and ultra-remote real-time service.

For the ultra-dense connection service, such as Internet of things (IoT) and Internet of Vehicles (IoV), numerous nodes need to access the ultra-dense LEO satellite network for data transmission in a short time. Hence, its performance is mainly measured by the connection density, the capacity density of a single satellite, and the efficiency of a single satellite. The large-capacity transmission service usually needs to transmit numerous images or videos, such as video streaming and airborne monitoring. It requires large transmission capacity and wide coverage to realize real-time transmission. Therefore, the corresponding KPIs can be determined by service coverage, end-to-end throughput and load capacity, and so on. For springing-up ultra remote real-time services, such as ultra telemedicine collaboration and ultra-remote machine control, its KPI characteristics mainly focus on delay sensitivity and reliability. These three types of services admit their own different KPI characteristics. When improving the efficiency of managing these services, we can comprehensively enhance the network performance and service capability.

When implementing service management, ordinary LEO satellites first collect service requirements and other relevant information in real-time, and then upload the information to the local controller LEO. By analyzing the KPI characteristics of different services, local controller LEO satellites can forecast the service type in real-time. Meanwhile, local controller LEO satellites integrate the request and resource status information. Then, each local controller LEO can analyze the weight proportion of three service types, and uploads the results to the global controller MEO. On the other hand, each global controller MEO determines the utility function according to the service requirements and indicators, and optimizes the resource slicing ratio based on the weight proportion information of three different service types in its set, which aims at maximizing the utility within its set. After the resource slicing ratio for each service type is determined, each local controller LEO can further implement the dynamic resource slicing and decide how to allocate resources (channel and power, etc.) for current services. Facing the dynamic service, the dynamic resource slicing scheme can assist to ensure the quality of service.

Grouping and Clustering Scheme for the Ultra-Dense LEO Satellite Network

In order to obtain proper global and local controllers for the proposed hybrid multi-layered management architecture above, we propose an efficient grouping and clustering method for the ultra-dense LEO satellite network, where group manager MEO satellites and cluster head (CH) LEO satellites are respectively considered as global and local controllers.

Suppose that there are L LEO satellites, which are covered by M MEO satellites. Considering the high mobility of satellites, we implement grouping

Via leveraging the satellite-terrestrial integrated multi-layered network control and management architecture, we can realize location management and handover management to ensure service continuity

Input: Positions of L LEO satellites and M MEO satellites, adjacent matrix, the maximum number of LEO nodes in each cluster $N_{\max}$, thresholds N_1 and N_2 with $N_1 + N_2 = N_{\max}$.
Output: Grouping and clustering results.

```
for i = 1, 2, ..., M do
    Partition LEO satellites under the coverage of MEO satellite M_i into group G_i.
    Repeat
    Choose the set with one LEO satellite with the lowest connectivity degree as
        one initial cluster 𝒜.
    Find the set of LEO nodes reachable in one hop 𝒜_r.
    while |𝒜_r| > 0 and |𝒜| ⩽ N_1 do
      if |𝒜| + |𝒜r| ⩽ N_1 then
        Incorporate set 𝒜r into cluster 𝒜.
      else
        Incorporate LEO nodes in 𝒜r into 𝒜 one by one from small to large
            connectivity degrees until |𝒜| = N_1.
      end if
    end while
    Until all LEO nodes in group G_i are clustered.
    Merge clusters with the node number less than N_2.
    Elect the CH LEO satellite as the one with the minimum total hops to other
        nodes in the cluster.
end for
```

ALGORITHM 1. Grouping and clustering approach for the ultra-dense LEO network.

and clustering in each time slot, during which the topology of satellites is assumed to be unchanged. Obviously, the length of the time slot should be properly determined. A long time slot is unreasonable because the network topology is updated in real-time, while a short time slot will increase the frequency of clustering.

First, we partition LEO satellites under the coverage of the same MEO into a group, and the associated MEO is regarded as the group manager as well as the global controller of this LEO group. Then, each MEO only needs to supervise LEO satellites in its group, which reduces the management scale for each MEO and thereby improves the management efficiency. When an LEO satellite lies in two MEO satellites' coverage simultaneously, the LEO is designated to the group with nearer MEO. In this way, these L LEO satellites are divided into M disjoint groups. It is worth noting that, there still may be hundreds or thousands of LEO satellites in one group. Thus, we further adopt clustering in each group, and choose cluster head (CH) LEO satellites as local controllers. Then in each group, only CH LEO satellites communicate with its group manager MEO. Since the CH LEO should gather all status information in the cluster, the cluster should be fully connected, that is, the CH LEO is reachable to all cluster member (CM) LEO satellites in the cluster. Hence, the connectivity should be considered in clustering.

In one group, define the maximum number of LEO nodes in each cluster by $N_{\max}$. Then we give two thresholds N_1 and N_2 with $N_1 + N_2 = N_{\max}$. Moreover, we define the connectivity degree of an LEO as the number of LEO satellites reachable in one hop. We first choose the set with one LEO with the lowest connectivity degree as one initial cluster. Then we incorporate LEO nodes that are reachable with the cluster in one hop. Once an LEO is merged into the cluster, its corresponding row and column in the adjacent matrix are set to zero, which can guarantee that this LEO node will not lie in other clusters. If the number of LEO satellites in the cluster is smaller than N_1, we proceed to add LEO nodes that are reachable in one hop to the cluster. Note that, when the number of LEO nodes in the cluster exceeds the threshold N1 if adding all LEO nodes reachable in one hop, then we merge these LEO nodes to the cluster one by one from small to large connectivity degrees until the cluster just have N_1 LEO satellites. In this way, we give priority to these nodes with low connectivity degrees, which benefits the full connectivity of clusters. As a result, we can form a fully connected cluster with node number being N_1, or less than N_1 when there are no more adjacent nodes that are reachable in one hop. Similarly, we pick the set of one LEO among the remaining LEO satellites with the lowest connectivity degree as another initial cluster, and repeat the above process to form another cluster. After all LEO satellites in the group are clustered, we merge the clusters with node number less than N_2 with other clusters. In this way, the number of LEO satellites in each cluster will neither differ significantly nor exceed threshold Nmax. Furthermore, the CH LEO in each cluster is elected as the one with the minimum total hops to all other nodes in the cluster. The involved grouping and clustering approach for the ultra-dense LEO network is summarized as the following Algorithm 1.

It is noted that, Algorithm 1 is implemented at each MEO to obtain the grouping and clustering results. Specifically, in each time slot, positions of LEO and MEO satellites can be obtained in advance based on constellation design, and no extra information is needed, which leads to a low overhead of Algorithm 1. Then, each MEO can obtain the grouping results according to its coverage. Based on the adjacent matrix of LEO satellites in the group, each MEO can compute the clustering and CH selection results in a distributed way by Algorithm 1, which improves the efficiency of grouping and clustering for the ultra-dense LEO network. Meanwhile, each MEO also obtains the optimal routing table for each cluster by the Dijkstra algorithm. Subsequently, every MEO delivers the clustering results together with routing table to CH LEO satellites in its group, and then each CH LEO delivers corresponding clustering results and routing table to CM LEO satellites in its cluster. In this manner, the corresponding grouping and clustering results are delivered to each LEO satellite. In particular, each global controller MEO and local controller CH LEO only collect and exchange the information within their own management scope, which greatly improves the management efficiency and simplifies the network topology.

Simulation Results

We validate the efficiency of the proposed satellite-terrestrial integrated multi-layered network management mechanism by taking the SpaceX system as an example, which consists of two sub-constellations with a total of 11927 LEO satellites.

These LEO satellites are distributed in eight altitudes of {1325 km, 1275 km, 1130 km, 1110 km, 550 km, 345.6 km, 340.8 km, 335.9 km}, as shown in Fig. 2a. They are managed by 232 SESs and 12 MEO satellites, where the orbit configuration of MEO is designed by 4 × 3 with altitude 12000 km and inclination 60°. Figure 2b depicts the distributions of SESs. As can be seen, there are more SESs in middle and low latitudes, and SESs can hardly communicate with LEO satellites in high latitudes. Hence, only relying on SESs is not sufficient to implement the management of the ultra-dense LEO network.

In order to illustrate the efficiency of the proposed grouping and clustering management architecture, we will give time delays of the periodical information collection and the trigger information update.

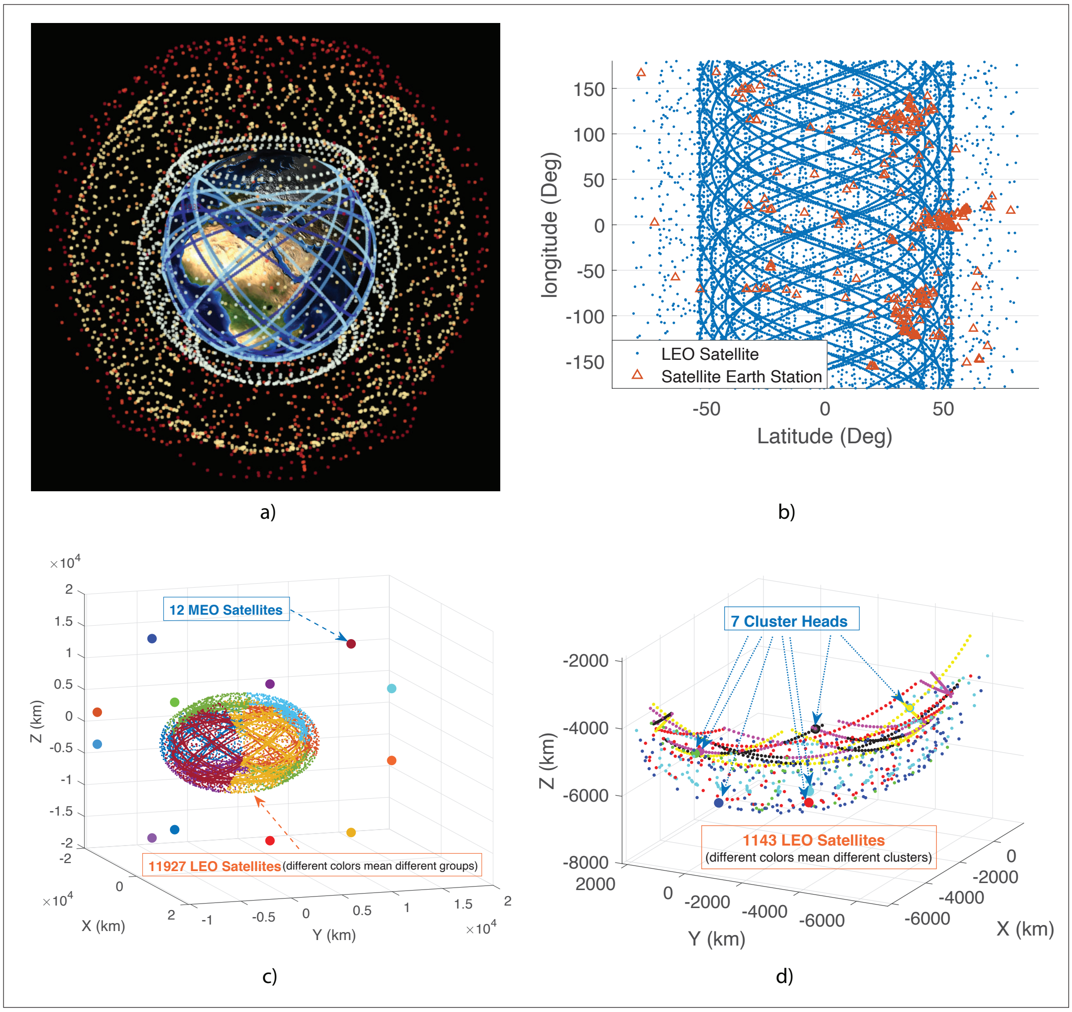

FIGURE 2. a) SpaceX; b) Distribution of SESs; c) Grouping of SpaceX; d) Clustering of Group 6 with N_{max} = 200.

Furthermore, the grouping result of 11927 LEO satellites is shown in Fig. 2c. Since there are 12 MEOs managing the LEO network, these LEO satellites are divided into 12 groups. Moreover, we show the clustering result of Group 6 as an example in Fig. 2d, where the maximum number of LEO nodes in each cluster is N_{max} = 200, and N_1 and N_2 in Algorithm 1 are set to N_1 = [0.75 Nmax] and $N_2 = N_{max} - N_1$ with [·] represents rounding a number. For Group 6, 1143 LEO satellites are divided into 7 clusters.

In order to illustrate the efficiency of the proposed grouping and clustering management architecture, we will give time delays of the periodical information collection and the trigger information update. When implementing the periodical information collection, we assume that one MEO in each group can collect the information of four CH LEO satellites simultaneously, and the information collection of each CH LEO in the same group is synchronous. For the trigger information update, the LEO will transmit its collected status information preferentially to the SES if there exists one SES under its coverage. Since the date packet is very small when LEO satellites only transmit status information, we ignore the transmission delay and only consider the propagation delay.

With 10 cases of N_{max} = {50, 80, 100, 120, 150, 200, 250, 300, 375, 450}, taking Group 6 as an example, Fig. 3a shows the results of the average cluster delay, delay of CHs to the group manager and group delay with respect to different N_{max}. It can be seen that, with the increase of N_{max}, the average delay of each cluster in the group increases and delay of CHs to the group manager will decrease. This is consistent with the intuition, because the average number of CM LEO satellites in each cluster will increase and the number of CH LEO satellites in the group will decrease with the increase of Nmax. Then, as shown in Fig. 3a, the group delay, which equals the sum of the average cluster delay and the delay of CH LEO satellites to the group manager, presents a trend of first decrease and then increase. We can conclude from Fig. 3a that the optimal selection of Nmax for Group 6 is N_{max} = 150. Furthermore, we compare the periodical information collection delay of the proposed grouping-clustering scheme with that of the only grouping scheme for each group, where we choose N_{max} = 150. For the only grouping scheme, the delay of each group includes the propagation delay from each LEO to MEO and the queuing delay from LEO to MEO. As can be seen from Fig. 3b, in each group, the time delay of the proposed grouping-clustering scheme is much less than that of the only grouping framework, which demonstrates the effectiveness of the proposed grouping-clustering architecture.

Meanwhile, we exhibit the time delays of the network status information update including the

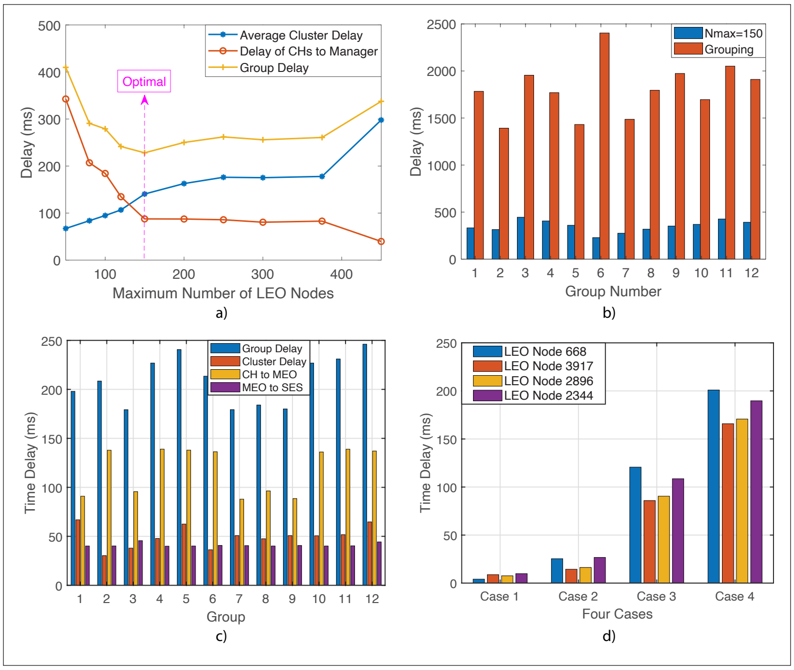

FIGURE 3. Delay results: a) group 6 for different N_{max}; b) delay comparison between only grouping scheme and the grouping-clustering scheme with N_{max} = 150; c) periodic Information Collection; d) trigger Information Update.

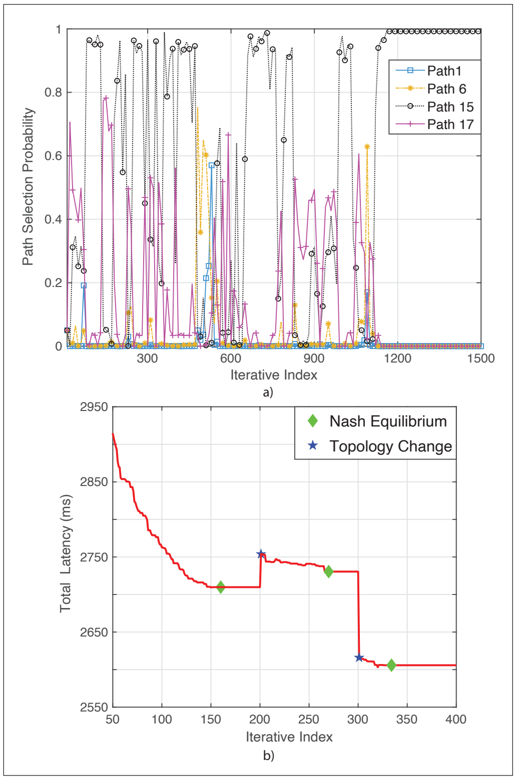

FIGURE 4. Delay results: a) path selection probability; b) results of the topology change.

periodic information collection mechanism and the trigger information update mechanism in Figs. 3c and d, respectively. In Fig. 3c, the group delays of 12 groups are shown, where the group delay equals the cluster delay plus delay of CH to MEO and MEO to SES. As can be seen, the periodical information collection of each group is very efficient, whose delay does not exceed 0.25 s. For the trigger information update in Fig. 3d, we consider Case 1: LEO to the SES; Case 2: LEO to CH LEO to the SES; Case 3: LEO to CH LEO to the MEO; Case 4: LEO to CH LEO to the MEO to the SES. It is easily seen that, for the trigger information update mechanism, when the SES is available to manage the LEO satellite network, the time delay of information update will be much shorter.

Moreover, we give the performance of the game based iterative algorithm for the service delivery in the mobility management. For a given SFC, each candidate path has a probability to be selected, called "path selection probability," among all possible paths. We depict the path selection probabilities of {Path 1, Path 6, Path 15, Path 17} as examples among all possible paths. As illustrated in Fig. 4a, the path selection probabilities of the four paths are first uniformly distributed, and finally reach the convergence status, where "iterative index" means the iteration steps of the game based iterative algorithm. In the stable status, this SFC will select Path 15 with probability 1, which implies that this SFC will choose Path 15 to delivery. In Fig. 4b, we show the topology change results, where "total latency" is the delivery latency sum of all services, and "topology change" means the change in the network topology or the network bandwidth resource. First, for a given topology network, the system achieves a stable state, that is, NE, after 150 iterations. Then, assuming the topology change occurs at the 200-th iteration, the total latency will change suddenly. Because the previous NE is no longer the local optimum of the current network, the system will re-iterate until reaching a new NE. Similarly, when the topology change at the 300-th iteration, the network also implements re-iterate to obtain a new NE. As a result, the proposed mobility mechanism can achieve efficient path selection and quickly adapt to the topology change.

Conclusion

In this article, we have proposed an MEO, SES and LEO integrated multi-layered network control and management architecture to realize efficient network status control, mobility management, resource management and service management for the ultra-dense LEO satellite network. Meanwhile, an efficient grouping and clustering method is proposed for the ultra-dense LEO satellite network, and each group manager MEO satellite and CH LEO satellites undertake as the global and local controllers of the LEO group, respectively. Extensive numerical results have demonstrated the efficiency and superiority of the hybrid management architecture for the ultra-dense LEO satellite-terrestrial integrated network. This study can promote the advance and development of future networking management for the ultra-dense LEO satellite-terrestrial integrated network, and shed light on more detailed network management methods and routing protocols based on the proposed hybrid multi-layered network control and management architecture.

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Biographies

Ting Ma [M] received the B.S., M.S. and Ph.D. degrees in statistics from Sichuan University, Chengdu, China, in 2013, 2016 and 2020, respectively. She is currently a Postdoctoral Fellow with the School of Electronic Science and Engineering, Nanjing University, Nanjing, China. Her current research interests mainly include robust hypothesis testing, space-air-ground integrated network, convex optimization theory and game theory.

Bo Qian [M] received the B.S. and M.S. degrees in statistics from Sichuan University, Chengdu, China, in 2015 and 2018, and the Ph.D. degree in information and communication engineering from Nanjing University, Nanjing, China, in 2022, respectively. He is currently a Postdoctoral Fellow with Peng Cheng Laboratory, Shenzhen, China. His research interests include resource management in B5G/6G networks, VANET, network economics, blockchain and game theory. He was a recipient of the Best Paper Award from IEEE VTC2020-Fall.

Xiaohan Qin [StM] received the B.S. degree in communication engineering from Central South University, Changsha, China, in 2020. She is currently working toward the Ph.D. degree in communications and information system with Nanjing University, Nanjing, China. Her research interests include space-air-ground integrated networks, network resource management and game theory.

Xiaoyu Liu [StM] received the B.S. degree in electronic and information engineering from Xidian University, Xi'an, China, in 2021. He is currently pursuing the M.S. degree with the School of Electronic Science and Engineering, Nanjing University, China. His research interests include space-air-ground integrated networks, network simulation and deep reinforcement learning.

Haibo Zhou [SM] is a Professor with the School of Electronic Science and Engineering, Nanjing University, Nanjing, China. He won the 2020 Norbert Wiener Review Award of IEEE/CAA J. Automatica Sinica. He was named the 2020 and 2022 highly cited researchers in cross-field. He was a recipient of the 2019 IEEE ComSoc Asia-Pacific Outstanding Young Researcher Award. He served as an Invited Track Co-Chair for ICCC'2019, VTC-Fall'2020 and a TPC member of many IEEE conferences, including GLOBECOM, ICC, and VTC. He served as an Associate Editor for the IEEE Comsoc Technically Co-Sponsored the J. Communications and Information Networks (JCIN) from April 2017 to March 2019, and a Guest Editor for the *IEEE Trans. Vehicular Technology* in 2021, the *IEEE Internet of Things Journal* in 2021, the *IEEE Commun. Mag.* in 2016, the Hindawi International J. Distributed Sensor Networks in 2017, and IET Communications in 2017. He is currently an Associate Editor of the *IEEE Internet of Things Journal*, the *IEEE Network*, the *IEEE Wireless Commun. Letters,* and the *JCIN*. His research interests include resource management and protocol design in vehicular ad hoc networks, 5G/B5G wireless networks and space-air-ground integrated networks.

Lian Zhao [F] received the Ph.D. degree from the Department of Electrical and Computer Engineering (ELCE), University of Waterloo, Canada, in 2002. She joined the Department of Electrical, Computer, & Biomedical Engineering, Toronto Metropolitan University (formerly Ryerson University), Toronto, Canada, in 2003. She was a Professor in 2014. Her research interests are in the areas of wireless communications, radio resource management, mobile edge computing, caching and communications, and the internet of vehicles networks. She has been an IEEE Communication Society (ComSoc) and IEEE Vehicular Technology Society (VTS) Distinguished Lecturer (DL). She received the Best Land Transportation Paper Award from IEEE VTS in 2016, Top 15 Editor in 2015 for IEEE Transaction on Vehicular Technology, Best Paper Award from the 2013 Int'l. Conf. Wireless Communications and Signal Processing (WCSP), Best Student Paper Award (with her student) from Chinacom in 2011, and the Canada Foundation for Innovation (CFI) New Opportunity Research Award in 2005. She has been serving as an Editor for *IEEE Trans. Vehicular Technology*, *IEEE Trans. Wireless Communications*, and *IEEE Internet of Things Journal*. She served as the Co-General Chair for IEEE GreeenCom 2018, the Co-Chair for IEEE Globecom 2020 and IEEE ICC 2018 Wireless Communication Symposium, the Workshop Co-Chair for IEEE/CIC ICCC 2015, the Local Arrangement Co-Chair for IEEE VTC Fall 2017 and IEEE Infocom 2014, and the Co-Chair for IEEE Global Communications Conference (GLOBECOM) 2013 Communication Theory Symposium.