A Novel Mobile Core Network Architecture for Satellite-Terrestrial Integrated Network

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***Abstract*—Loading the functions of base station on satellite can improve the flexibility of user access and expand the effective coverage of Satellite-Terrestrial Integrated Network (STIN). However, the functions of management and control that supports the satellite networking have not been well investigated. A large amount of signaling needs to be forwarded to the ground control center for processing, which increases the delay of network control and management. In this paper, we propose a novel mobile core network architecture that loads the mobility management function of core network on the satellite, which can improve the flexibility of management and control of STIN. Firstly, considering the on-board computing capacity and the dynamic characteristic of satellites, we design the lightweight Satellite Mobile Core Network (SMCN) to improve the flexibility of the Satellite next-generation NodeB (Sat-gNB) networking. Then, the interactive protocol for user access control, mobility control of Sat-gNBs and the coordinated control between terrestrial network and satellite network are designed to support the mobility management. Finally, in order to optimize the delay of Sat-gNBs networking, we construct the mathematical model for the multi-SMCN deployment. The simulation results show that compared to the architecture of Non-Terrestrial Networks (NTN), the proposed mobile core network architecture can improve the flexibility of mobility management and optimize the network delay.**

***Index Terms*—Satellite-terrestrial integrated network, Mobile core network architecture, Dynamic networking, Mobility management.**

I. INTRODUCTION

THE Low Earth Orbit (LEO) satellite constellation network has the characteristics of low delay, high bandwidth and global coverage, it can provide users with flexible access services and become a promising technology of the 6th Generation mobile networks (6G) [1]. In the future mobile network, as the network access layer, the satellite network can effectively alleviate the problem of limited network service capacity caused by the deployment location of base stations [2]. Due to the on-board computing capacity and the dynamic characteristics of satellites, the expansion of satellite functions of management and control becomes the key to the realization of the cooperative networking between satellite network and terrestrial network, which is also regarded as the bottleneck for improving the performance of STIN.

To utilize the advantages of satellite networks and improve the performance of terrestrial mobile communication networks, a lot of efforts were invested into the design of architecture and technology of STIN [3]- [5]. The TR38.811 issued by 3rd Generation Partnership Project (3GPP) demonstrated four options for the architecture of NTN [3]. Due to the satellite equipped with the function of next-generation NodeBs (gNB), the role of satellites was expanded from "bent-pipe" to "regenerative entity" that had the capability of computing and processing. Therefore, Sat-gNBs can effectively expand the coverage of terrestrial mobile communication networks by loading the functions of base station. Meanwhile, the flexibility of access services of satellite networks can be improved, which can increase the network capacity and reduce access delay for remote terminals.

Aiming at the integration of satellite networks and cellular networks, Di et.al [5] pointed out that the LEO satellites, which was taken as an access network for terrestrial networks, can effectively improve backhaul network capacity to support ubiquitous global wireless access. In order to improve the capabilities of management and control of STIN, some technologies of 5G were introduced into the satellite network. The computing capability was loaded to the Sat-gNB, which can reduce the response delay of terminal requests [6]- [10]. Liu et.al [8] paid attentions to introducing the cloud computing and edge computing into STIN, which can make network services closer to the terminal, to reduce network delay and balance the burden of the core network. Similarly, Software-Defined Networking (SDN) provided the opportunity for the deep integration of the satellite network and the terrestrial network [11]- [13]. Bi et.al [13] presented a composite architecture that integrated the components of space network and terrestrial network by utilizing SDN and mobile edge computing, which can facilitate the flexibility of network management.

Benefiting from the expansion of the capability of management and control in satellites, the satellite mobile communication network can quickly respond to the request of terminals and improve the flexibility of inter-satellite networking. Therefore, the coverage and delay of STIN can be effectively optimized. However, in the existing architecture, the functions of management and control that supports the networking of Sat-gNBs have not been well investigated, a large amount of signaling still needs to be forwarded to the Terrestrial Core Network (TCN) for further processing, which increases the delay of network control and management. In addition, the deployment location of TCNs is restricted by geographical factors, which brings more challenges to

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improving the flexibility of mobility management of STIN.

In this paper, we propose a novel mobile core network architecture of STIN, which can support the flexible networking of Sat-gNBs by expanding the capabilities of management and control at satellite networks. The simulation results show that compared to the network architecture of NTN, the proposed network architecture can improve the flexibility of core network deployment and provide terminals with more efficient mobility management services. Specifically, the main contributions of our work are presented as follows.

- Considering the limited resources of satellites, we design the lightweight SMCN on the satellite, which can optimize the function of network entities and process the interaction signaling of mobility management, to reduce the delay of network control and management.
- In order to improve the capability of cooperative control between terrestrial networks and satellite networks, we extend the network entity of satellite networking control on TCN and design the interactive protocols, which can improve the flexibility of Sat-gNBs networking.
- Based on the analysis of response delay for the networking of Sat-gNBs, we formulate the deployment problem of SMCNs as the optimization problem of network delay to improve the flexibility of multi-SMCN deployment and optimize the delay of Sat-gNBs networking.

II. Overview of Mobile Core Network

In the mobile network based on STIN, Sat-gNBs can effectively expand the network coverage and provide terminals with access services at anytime and anywhere. Since the functions of management and control that supports Sat-gNBs networking are incomplete in the satellite network, the signaling messages need to be frequently forwarded to TCN for processing, which can increase the control delay of network and affect the flexibility of mobility management.

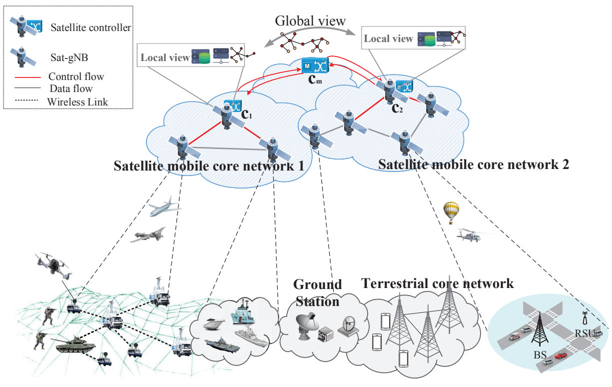


Fig. 1: Mobile communication network scenario of STIN

As shown in Fig. 1, this mobile network is composed of the satellite network and the terrestrial network. To improve the flexibility of mobility management of network, we propose a novel mobile core network architecture. In satellite network, the mobility management functions of core network are loaded on the satellite controller to achieve the flexible management and control of satellite network. Moreover, TCN can cooperate with the satellite network to support the dynamic deployment of SMCNs. Due to the dynamic characteristics of satellites, the following demands should be considered for designing the architecture of mobile core network.

- ***Lightweight SMCNs***: Affected by the dynamic characteristic of satellites, the network topology is updated frequently. In addition, since the processing capacity of the satellite is limited, the whole core network cannot be directly loaded on the satellite. Therefore, it is necessary to design a lightweight SMCN to support the Sat-gNBs networking while considering the on-board computing capacity and the dynamic characteristic of satellites.
- ***Mobility management of Sat-gNBs***: Due to the dynamic nature of satellites, the terminal needs to handoff among Sat-gNBs for the reliable communication service. In addition, the relative position between Sat-gNB and SMCN changes with the movement of satellites, Sat-gNBs need to handover between SMCNs, which is different from the fixed position of gNBs in the 5G network. Therefore, the mobility management of Sat-gNBs should be considered to improve the flexibility of the networking of satellites.

III. The Architecture of Mobile Core Network

3GPP designs the architecture of 5G Core network (5GC) as a decomposable network architecture with the micro-service, and the control plane can be decoupled from the user plane. In the control plane, the network function can be accessed through the service-based interface (SBI) without affecting other functions. The network function can be flexibly orchestrated to improve the flexibility of network deployment.

In order to improve the function of management and control of user equipment (UE) on the satellite side, we propose the mobile core network architecture based on 5GC. As shown in Fig. 2, the logical architecture of this mobile core network includes two parts: SMCN and TCN. Due to the limited processing capacity of satellites, SMCN is designed by simplifying the network entity functions and network entities of 5GC. Meanwhile, the new network entity is added to SMCN to support the mobility control of Sat-gNBs.

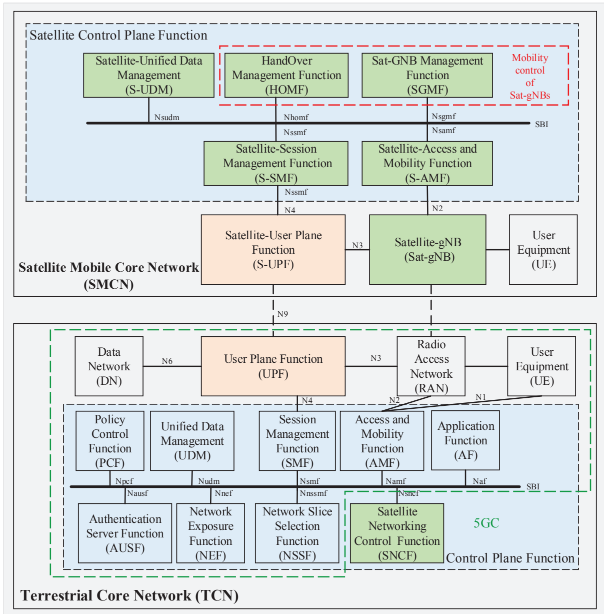


Fig. 2: Logical architecture of mobile core network

A. Satellite mobile core network

As a lightweight core network that supports the mobility management of Sat-gNBs networking, the functions of network entities of SMCN are as follows:

(1) **S-AMF:** Satellite-Access and Mobility Function (S-AMF) is mainly responsible for the interaction of control signaling between SMCN and users, the security of user data, authentication, the management of mobility and reachability and the transmission of session management messages.

(2) **S-SMF:** Satellite-Session Management Function (S-SMF) is mainly responsible for interacting with data plane, determining the continuity of sessions and session services and managing the notification of downlink data and the strategies of session and mobility.

(3) **S-UDM:** Satellite-Unified Data Management (S-UDM) is responsible for the maintenance and management of user contracts and authentication data.

(4) **S-UPF:** Satellite-User Plane Function (S-UPF) as the interconnection point between the satellite mobile infrastructure and the external network, it is responsible for the routing, forwarding, inspection and filtering of packets.

(5) **SGMF:** The function of Sat-GNB Management Function (SGMF) is the access management of Sat-gNBs, the maintenance of the connection of Sat-gNBs and the processing and forwarding of handover messages of control plane.

(6) **HOMF:** The function of HandOver Management Function (HOMF) includes the management of the handover process of Sat-gNBs, the maintenance of state transfer, the management of handover information, the interface communication with the SGMF and the communication interaction with S-UPF.

B. Terrestrial core network

In order to achieve the cooperative capacity of management and control between TCN and SMCN, TCN extends the network entity of Satellite Networking Control Function (SNCF) on the basis of inheriting 5GC. The network entity of SNCF is responsible for the following functions: (1) The synchronization of topology information of the satellite network. (2) The deployment of SMCNs.

C. Mobility management of mobile core network

In terms of the mobility management of the satellite network, we design the interaction protocol between network entities to support the network management and control of mobile core networks.

*1) **User equipment access**:* In order to improve the flexibility of mobility management of UEs, we design the lightweight access protocol of UEs. As shown in Fig. 3, an UE initiates a registration request to S-AMF through the Sat-gNB. When S-AMF receives the request message, S-AMF requests the authentication from S-UDM, and S-UDM performs this authentication. After this authentication is finished, S-AMF initiates a request of location update to S-UDM, and completes the policy update through S-SMF. Then, S-SMF initiates a request of session modification to S-UPF. When S-SMF receives the response from S-UPF, it notifies S-AMF that the session management context has been updated and replies to the user with a registration acceptance message through the Sat-gNB, the process of user access is completed.

*2) **The process of mobility control**:* In order to support the mobile management and control of Sat-gNBs, we design the handover protocol of Sat-gNBs. As shown in Fig. 4, in the phase of handover preparation, the Sat-gNB reports the measurement message to SGMF of original SMCN. When SGMF receives the measurement information, it forwards this information to HOMF for processing. Then, HOMF determines the trigger time of handover and target SMCN (T-SAT) through the received measurement information of Sat-gNBs and its own measurement results. In the phase of handover execution, the HOMF passes the request message of handover to T-SAT through SGMF. When T-SAT receives the handover request message, it replies with a response message. After SGMF passes the received response message to HOMF, HOMF determines whether there is uncompleted service data in the Sat-gNB that needs to be handed over. If it is, HOMF sends a notification to S-UPF (Option1) to create a data forwarding tunnel, and HOMF initiates a handover command. After the handover is completed, the data forwarding tunnel is deleted (Option2). Otherwise, HOMF initiates a handover command to complete the handover.

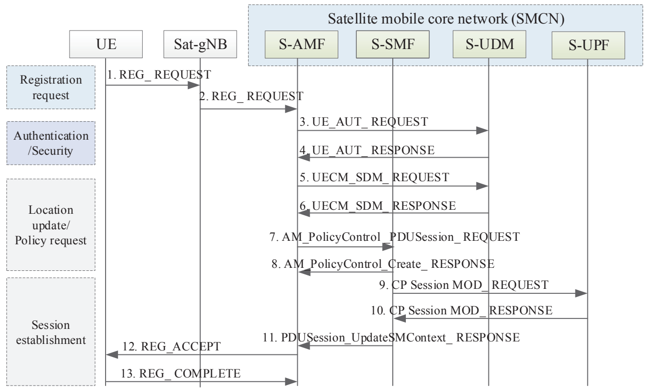


Fig. 3: The process of UE access

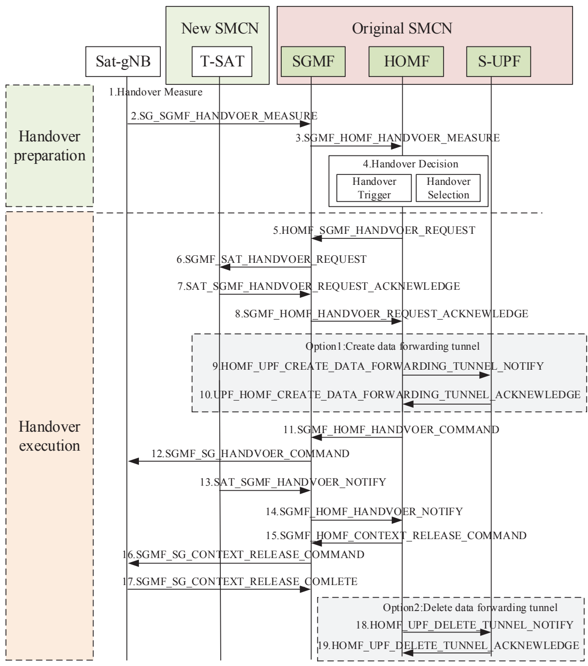


Fig. 4: Handover process of Sat-gNBs

*3) **Coordinated control of mobile core network**:* The mobile core network can achieve the dynamic deployment of SMCNs through the SNCF of TCN. According to the status information fed back by satellites and the deployment scheme of SMCNs, SNCF can calculate the number and location of SMCNs that need to be deployed, then TCN feeds back the results to satellites.

IV. Deployment of Satellite Mobile Core Network

With the increase of the number of satellites, one SMCN may not meet the demand of flexible Sat-gNBs networking, and the deployment of SMCNs has an impact on the network delay. In order to reduce the response delay of application requests in the process of Sat-gNBs networking, we analyze the network response delay between Sat-gNBs and SMCNs and establish an optimization model for the multi-SMCN deployment.

A. Delay analysis of Sat-gNBs networking

The distributed control process of Sat-gNBs networking in LEO constellation satellite network is shown in Fig. 5. The main parameters are listed in TABLE I.

TABLE I: Main parameters

Parameters	Definition
C	Set of controller satellites (SMCN)
V	Set of Sat-gNBs
p_{ij}	Matching relationship between satellite i and j
C'	Set of current controller satellites
p'	Sat-gNB association matrix in existing control domain
T_{re}	Interval of algorithm execution
T_s	Interval of network maintenance
d_{ij}	Distance from satellite i to j
F_{ij}	Request routing entries from satellite i to j
r	Link transmission rate

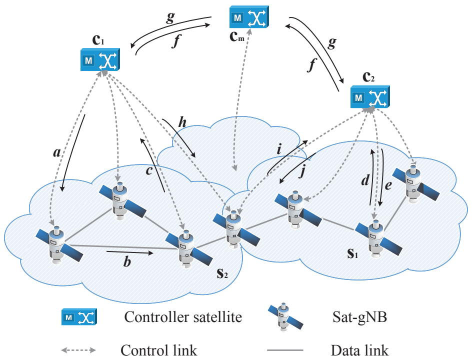


Fig. 5: Distributed control process of Sat-gNBs networking.

1) Network status maintenance time T_m: For the process from a to c, the controller satellite sends a link detection packet to Sat-gNB, and the Sat-gNB forwards packet to its neighbor Sat-gNBs. Then, the Sat-gNB uploads information to the control satellite connected with it through packet_in method ($T_{re} < T_s$).

$$T_m = \left\lceil \frac{T_{re}}{T_s} \right\rceil \left(\sum_{i \in C} \sum_{j \in V} \frac{2 d_{ij} p_{ij}}{r} + \sum_{i \in V} \sum_{j \in V} \frac{d_{ij}}{r} \right) . \quad (1)$$

2) Data flow setup time T_f: For the process from d to e, when a new flow arrives at S_1, S_1 sends packet_in information to the controller satellite C_2 since there is no matching data flow forwarding rule in the flow table of S_1, then C_2 sends packet_out message to S_1 and installs this forwarding rule.

$$T_f = \sum_{i \in C} \sum_{j \in V} \frac{2 d_{ij} p_{ij} F_{ij}}{r} . \quad (2)$$

3) Synchronization time of SMCNs T_{syn}: For the process from f to g, the controller satellite C_m sends network information of domain to TCN, then the global network information is synchronized through the interaction process between SMCNs.

$$T_{\text{syn}} = \left\lceil \frac{T_{re}}{T_s} \right\rceil \sum_{j \in C, C_m \neq j} \frac{2 d_{c_m j}}{r} . \quad (3)$$

4) Switching time of Sat-gNBs T_h: The process from h to j indicates Sat-gNB S_2 migration from C_1 to C_2. The original controller satellite sends switching information to migrate Sat-gNB, then the Sat-gNB sends a connection request to new associated controller, and the destination controller replies with a confirmation message after receiving the request.

$$T_h = \frac{1}{|V|} \left(\sum_{i \in C'} \sum_{j \in V} \frac{d_{ij}}{r} + \sum_{i \in C} \sum_{j \in V} \frac{2 d_{ij}}{r} \right) . \quad (4)$$

B. Problem formulation of multi-SMCN deployment

To meet the requirement of low-delay service, the optimization objective function can be obtained by minimizing $T = T_m + T_f + T_{\text{syn}} + T_h$. We formulate this deployment problem of SMCNs as the problem of delay minimization.

$$\min \ T_m + T_f + T_{\text{syn}} + T_h . \quad (5)$$

$$s.t. \ |C| = \sum_{i \in V} p_{ii} \leq |V| . \quad (6)$$

$$\sum_{i \in C} p_{ij} = 1, \forall i \in V . \quad (7)$$

$$\sum_{j \in V} F_{ij} p_{ij} \leq u_i, \forall i \in V, j \in V . \quad (8)$$

$$p_{ij} \in \{0, 1\}, \forall i \in V, j \in V . \quad (9)$$

Constraint (6) indicates that the number of SMCNs is not more than the number of satellites. Constraint (7) indicates that one Sat-gNB is only controlled by one SMCN. Constraint (8) ensures that the flow setup requests sent by Sat-gNBs can be processed by SMCN, u_i is a number of inter-satellite link. Constraint (9) shows that the association relationship of the control link p_{ij} is the binary number, if i=j, satellite i is selected as SMCN, when satellite i is connected to satellite j, $p_{ij} = 1$, otherwise, $p_{ij} = 0$.

Algorithm 1 Algorithm of multi-SMCN deployment

Input: Location of satellite s_{ij}, Number of SMCNs: N.
Output: Location set of SMCNs: C.

```
Divide the LEO constellation into N parts;
for n ← 1 to N do
    for m ← 1 to K do
        Get the topology of SMCN_n;
        Calculate the position of the satellite p_k for deploying SMCN that satisfies T_k=min {T};
    end for
    Calculate the placement of SMCNs C = {p_k};
end for
Return the deployment results of SMCNs.
```

As a discrete optimization problem, the deployment solution of SMCNs can be calculated offline by TCN, and the objective function (5) can be solved by the method of traversal search. Therefore, we design the deployment algorithm of SMCNs according to delay of the networking of Sat-gNBs. The specific process is shown in Algorithm 1. TCN can calculate the optimal solution through traversal search, and the algorithm complexity is $O(2^n n^3)$.

V. The Prototype Development and Evaluations

A. Prototype platform

In order to effectively evaluate the proposed mobile core network architecture, we develop a prototype platform of mobile core network based on Exata and STK. Firstly, STK generates the configuration file of LEO constellation satellite network, then Exata can obtain the mobility data, antenna model and the connection relationship of link from the configuration file. The main parameters are listed in TableII.

TABLE II: Simulation Parameter

Parameter	Value
Constellation	48/8/1
Satellite orbit height	1414 Km
Orbit inclination	52°
Step size	60s
Interval of algorithm execution T_{re}	1s
Interval of network maintenance T_s	0.9s
Simulation time	3600s

Based on the logical architecture of mobile core network and the interconnection protocols between network entities, we complete the development of SMCN and TCN. The established mobile core network scenario is shown in Fig. 6. UE can access SMCN through the Sat-gNB, or access TCN through the gateway on the ground. According to the proposed scheme of SMCNs deployment (5)-(9), 8 satellite mobile core networks are deployed, named $SMCN1$-$SMCN8$.

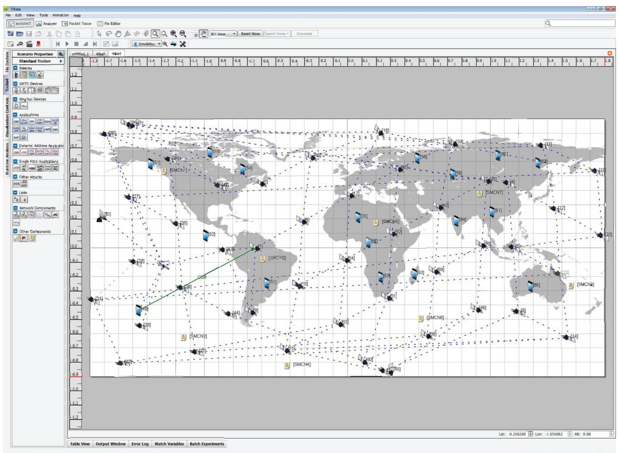


Fig. 6: Mobile core network scenario of STIN

B. Evaluations of mobile core network

In order to verify the capabilities of mobility management of mobile core network, we compare the proposed architecture to the architecture of NTN that the completed core network is deployed on the ground [3].

1) Resource occupancy ratio of SMCNs: As shown in Fig. 7, the average memory occupancy ratio of SMCN is about 50% of the completed core network in the process of UE access control. Taking into account the limitation of the computing and storage capabilities of satellites, SMCN can reduce the frequency of signaling interaction by simplifying the interaction process and functions of network entities, which makes the lightweight SMCN more suitable for satellite networks.

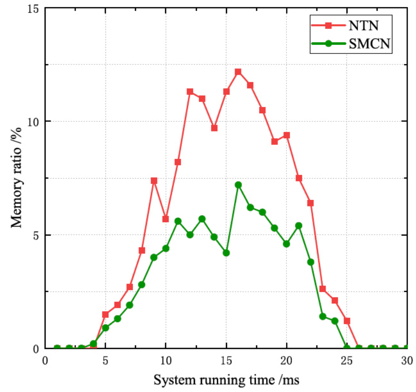
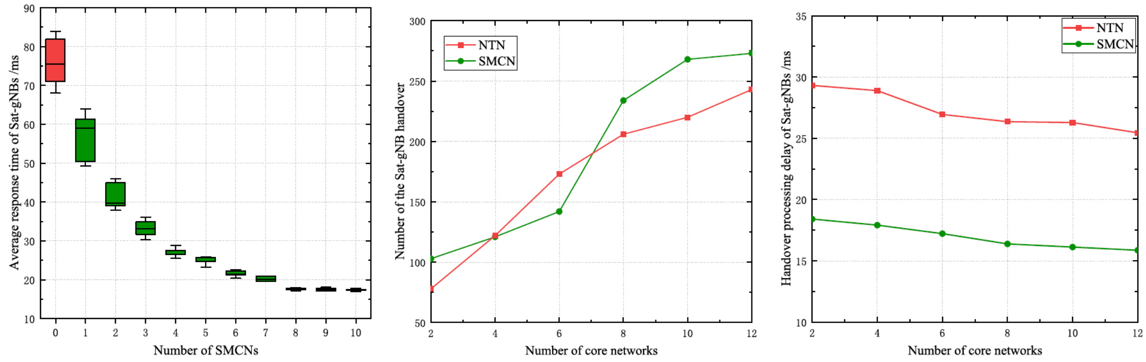


Fig. 7: Resource occupancy ratio of core network

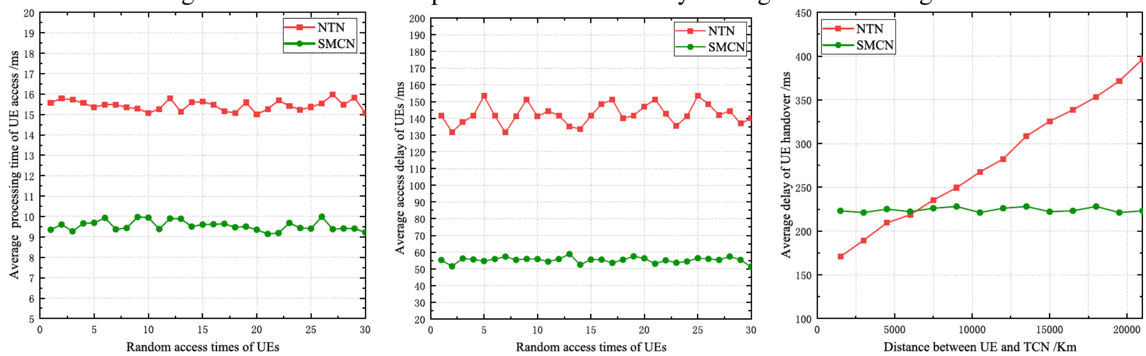
2) Mobility Management for Sat-gNBs: The comparison of the mobility management of Sat-gNBs is presented in Fig. 8. In Fig. 8(a), with the increase of the number of SMCNs, the response time of the Sat-gNB gradually decreases. When N=0, the network architecture is NTN, the Sat-gNB of NTN needs to forward the control requests of UEs to TCN for processing. The network response delay is limited by the position of ground station and TCN. When the ground station is within the coverage area of the Sat-gNB, the network delay is relatively small, which is about 75ms. Under the condition that the SMCN is deployed on the satellite, when N=8, the delay from Sat-gNB to SMCN is gradually stable, and the average interval is one hop of the inter-satellite link, it is about 20ms. In order to further verify the flexibility of the proposed architecture in the mobility management of Sat-gNBs, we have increased the number of TCNs that are only deployed on land. As shown in Fig. 8(b) and Fig. 8(c), with the increase of the number of core networks, the frequency of the Sat-gNB handovers is increasing to adapt to the dynamics of satellite networks. Benefiting from the flexibility of SMCN deployment, the proposed architecture can effectively optimize the distance between Sat-gNBs and core networks, SMCN can reduce the handover processing delay by an average of about 35% compared with NTN. Therefore, SMCN can alleviate the constraints on the mobility management of Sat-gNBs from the deployment of ground gateways.

3) Mobility Management for UEs: The comparison of the mobility management of UEs is elaborated in Fig. 9. From Fig. 9(a), it can be seen that the average processing time for user access of SMCN is about 9.5 ms, that of NTN is about 16ms. Compared with NTN, SMCN can reduce user access delay by about 38%. The reason is that the proposed mobile network architecture can simplify the interactions of signaling processing between network entities during the process of user access, which can reduce the management and control time of user access. In addition, SMCN can directly process user requests accessed by Sat-gNBs without forwarding them to the ground. As shown in Fig. 9(b), considering the link transmission delay, SMCN can reduce the access delay of UEs by about 60% compared to NTN. Therefore, SMCN can effectively improve the timeliness of user access control. Furthermore, the Fig. 9(c) shows that the average handover



(a) Average response time of Sat-gNBs. (b) Frequency of the Sat-gNB handover. (c) Average delay of the Sat-gNB handover.

Fig. 8: Performance comparison for the mobility management of Sat-gNBs



(a) Average access time of UEs. (b) Average processing time of UE access (c) Average delay of the UE handover.

Fig. 9: Performance comparison for the mobility management of UEs

delay of UE increases with the increase of the distance from user to TCN. For the SMCN, the handover delay of UE is relatively stable. The reason is that the requests of user handovers need to pass through multi-hop inter-satellite links before they are forwarded to TCN for processing, which increases the transmission delay of signaling. However, in the proposed architecture, these requests can be directly processed by SMCNs, which reduces the number of times that the signaling is forwarded, and then reduces the delay of the user handover. Therefore, the proposed architecture can alleviate the impact of the deployment location of TCN on the flexibility mobility control of UEs.

VI. Conclusion

Aiming at the improvement of the flexibility of mobility management in 6G network, we propose a novel mobile core network architecture to improve the capabilities of mobility management and control of Sat-gNBs networking. Firstly, the lightweight SMCN is designed to support the fast access of users and mobile control of Sat-gNBs. Then, the interactive protocols between network entities are designed to achieve the interconnection and intercommunication of STIN. Moreover, the deployment scheme of SMCNs is proposed to improve the flexibility of Sat-gNBs networking. The simulation results show that the proposed architecture can improve the flexibility of the mobility management and provide users with low-delay access services. In the future, the dynamic deployment scheme of SMCNs will be explored to provide UEs with more flexible access services.

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