Design and modeling of satellite network structure for business scenarios

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Abstract. In view of the actual decentralized development of the satellite service constellation and the trend of space-ground integrated information network, based on the idea of clustering, methodology of complex network community structure, a business scenario-oriented satellite network structure is designed. On the one hand, it reflects the different separation and integration of satellite constellations in business scenarios. On the other hand, the "head node" mechanism is introduced to be responsible for the interaction between constellation in different business scenarios. The satellite network structure is modeled using the growth and priority connection mechanism, and through computational derivation and simulation validation, the scale-free characteristics of the satellite network are revealed. Finally, through the simulation experiments on different satellite network parameters, the effect of different parameters on the static geometry, network efficiency, etc., are obtained. The influence of the law of the network will provide theoretical and methodological reference for the design of satellite network structure.

1. Introduction

With the increasing maturity of distributed satellite system[1]technologies such as satellite inter-satellite networking and constellation overall cooperative control, a constellation of multiple satellites can achieve wide area coverage through networking, forming a flexible network topology, greatly expanding the business scale and enhancing the information transmission capacity. However, due to various reasons, the satellite constellations of different business functions are separated from each other, and the status of independent development has been formed. The pattern of integrated development of interconnection and interconnection of different business constellations has not yet formed. The problems of satellite networks, such as single service function, mutual isolation, and operational dependence on the ground, are gradually becoming prominent[2]. At the same time, the major project on the space-ground integrated information network adopts the "Space-based network and Land-based network " structure[3], which is only a general development framework, there is not yet a shaped satellite network structure that solves the satellite interoperability problems of different business scenarios. The literature[4-6] has carried out the overall and systematic design of satellite network structure from the perspectives of spatial information network structure, logical function structure and business logic structure, but no specific modeling implementation method has been proposed; in the literature[7-8], LEO/GEO and LEO/MEO two-layer communication satellite network structures are proposed using virtual node strategy and satellite packet idea to address issues such as satellite coverage, satellite operation topology and number of inter-layer links. However, none of them take into account the phenomenon of operational separation of satellite constellations and overall connectivity. In fact, the satellite constellations are tightly connected internally, and there is basically no connection between the constellations, which is
very similar to the characteristics of the close connection of the community structure in a complex network and the sparse structure of the connection between communities. This paper proposes a new type of satellite network structure for business scenarios, and regards satellite constellations in different business scenarios as networks of different community structures[9]. Using a community-based design of the satellite network structure not only ensures the independence of the business logic of the satellite constellation, but also considers the comprehensiveness of the integration of all satellites. At the same time, the growth and priority connection mechanisms are used to model the designed network structure, and the regular characteristics of the network are revealed through simulation experiments.

2. Satellite network structure design for business scenarios

2.1. General requirements for network structure design
Satellite network structure design should focus on satellite network development trends and practical application of business scenarios, especially in combination with satellite network construction and application. At present, the main satellite operational networks or constellations in various countries are: satellite communication networks[10], navigation and positioning satellite constellations[11], remote sensing satellite constellations[12], meteorological and hydrological satellite constellations[13] and so on. Due to development history and other reasons, various types of business satellite networks or constellations have been independently designed and operated independently. Focusing on the integrated development of satellite networks, it is impossible to overhaul and redesign, forward compatibility and inheritance are necessary. In particular, there is still much room for the overall allocation and intensive utilization of resources such as orbital slots and frequencies, which can be achieved by "merging similar items". Specifically, satellite network structure design is to clarify the composition and structure of the satellite network according to the needs of satellite network construction, depict the basic constituent elements of the network, and define the relationship between the constituent elements, so as to build an integrated network structure that can independently operate and maintain, seamlessly interconnect with the ground-based network, and dynamically reconfigure the platform, protocol system and functions.

2.2. Specific design of network structure
The overall structure of the integrated heaven and earth network for business scenarios is shown in figure 1; in terms of space segment, it includes space-based backbone networks, space-based service access networks and low-orbit satellite internet. These networks and the air data link and platform, mobile communication network, Internet, submarine optical cable network, underwater wireless communication network form a multidimensional integrated network of sky, ground and sea.

This paper focuses on space-based satellite networks, which are generally classified in the space dimension as high orbit (including geostationary orbit, inclined geosynchronous orbit), medium orbit and low orbit. According to the functional logic, the space-based satellite network can be divided into three layers: space-based backbone network, space-based service access network and low-orbit Internet satellite[14]. It should be noted that there is a crossover between the two divisions, such as the Beidou operational satellite constellation spans both high and medium orbit levels. The information transmission and communication subnetworks involve three levels: high, medium and low orbit. The high-orbit space-based backbone network is responsible for information on-planet processing, relay communication, mission scheduling, security protection, gateway access, measurement and control, etc. Supported by the backbone network composed of interstellar links, the nodes in the space-based backbone network play different roles and are independent in terms of their tasks and business logic. Space-based service access networks, mainly composed of satellite constellations deployed in different service scenarios in high or low or medium orbit, can provide services directly to users, providing on-demand access and support for networking among users. The space-based service access network takes full account of clusters or key users such as incoming connected spacecraft platforms, security protection and anti-strength platforms, achieving connection to the space-based backbone network at the top and connecting satellite Internet users at the bottom. The low-orbit satellite Internet mainly focuses on the
development trend of civil and commercial low-orbit satellite Internet, provides broadband services for
ground end users, and accepts the measurement, control and management of space-based backbone
network nodes.

2.3. Characteristics of network structure design
The network structure design for business scenarios, on the one hand, it reflects the separation and
integration of satellite constellations in different service scenarios, and divides the space-based service
access network into mapping community network, remote sensing community network, communication
community network, hydrological and meteorological community network and so on. At the same time,
the operational independence of different functional networks, such as space-based backbones and low-
orbit satellite Internet, can also be seen as different communities network structure. The eventual
convergence of the networks of these societies with different business scenarios via interstellar links; on
the other hand, it is reflected in the introduction of the “head node” mechanism, setting up multiple head
nodes in different business communities, responsible for the interaction between the upper (backbone
node) and the lower (user). As the head node of the community, it has the function of managing the
internal nodes of the community network to realize the fusion transmission and information exchange
of data within the community. The establishment of head nodes greatly reduces the complexity of space-
based networking, especially the interaction between networks at different levels, and has a positive
significance for reducing resource consumption on the planet and balancing communication loads.
In order to generate a model that fits the structure of the above-mentioned satellite network, not only considering the actual satellite network, but also to facilitate problem research, network modeling is mainly based on the following assumption:

1. Regardless of the hierarchy and level of each node in the satellite network, all nodes are powerless nodes and a directionless network.

2. To facilitate modeling and calculation, set up a limited number of business community subnets. The number of communities in the network generated by modeling in this paper is six: the space-based backbone community network, communication community network, navigation community network, remote sensing community network, hydrological and meteorological community network and low-orbit interconnection community network.

3. Fix a community $z$ (community 1) as a space-based backbone community network. The satellites in the community network serve as a hub for controlling scheduling. The number of nodes should not be too many, so the probability of new nodes joining the community is much smaller than that of new nodes joining other communities. Fix a community $j$ (community 2), as a low-orbit interconnected community network, the number of nodes in this community is far more than the number of nodes in other communities, so the probability of new nodes joining is much greater than the probability of joining other communities.

4. In order to highlight the role of the space-based backbone community network to control the dispatching hub while taking into account the interconnection requirements of each community, the probability of the new interconnection between other communities is smaller than the probability of connecting the space-based backbone community network (community $z$).

5. The total number of nodes remains unchanged after the modeling is completed, but because of the space-time relationship of the satellites rotating around the earth, the connection relationship between satellite nodes and satellites in the actual satellite network changes dynamically. This article simulates the dynamic connection relationship of the entire satellite network by dynamically deleting and restoring the connection relationship between some nodes (to ensure that no isolated nodes are generated when deleting nodes and connecting edges).

6. This article defines the head node as: the number of nodes in the community that are connected to other communities.

3.2. Network modeling algorithm

This paper proposes a community structure network generation algorithm. The core idea of the algorithm is the principle of priority for nodes with large degrees when newly added nodes are connected to other nodes. The main algorithm process is as follows:

1. Initialization: There are initially $M$ communities, each of which is composed of $m_0$ nodes. The connection between nodes is a fully coupled network structure, ensuring that each community has an edge connected to other communities at the initial time. The number of coexisting edges is $M(M-1)/2$.

2. Growth of community nodes: Join a node in each time step, enter community $z$ with probability $p_1$, enter community $j$ with probability $p_2$, and enter one of the remaining $M-2$ communities with probability $p_3$. ($p_1 + p_2 + (M-2)p_3 = 1, p_1 \ll p_2, p_1, p_2, p_3 \neq 0$)

3. Priority connection within the community: The newly added node enters the community $z$ and connects $m(1 \leq m \leq m_0)$ nodes. Assuming that the probability of each node in community $z$ being selected follows the mechanism of degree preference. $s_{iz}$ is defined as the degree of the i-th node in community $z$, the probability that the new node is connected to the i-th node in community $z$ is:

$$
\prod(s_{iz}) = \frac{s_{iz}}{\sum_k s_{kz}}
$$

(1)

$\sum_k s_{kz}$ represents the sum of the total number of edges between all the nodes in the community, the
newly added node enters the community \( j \) and enters any one of the remaining \( M - 2 \) communities (such as the community \( h \)), which also connects \( m(1 \leq m \leq m_0) \) nodes in the community. The probability of their connection are:

\[
\prod(s_{ij}) = \frac{s_{ij}}{\sum_k s_{kj}} \tag{2}
\]

\[
\prod(s_{ih}) = \frac{s_{ih}}{\sum_k s_{kh}} \tag{3}
\]

(4) Priority connection between communities:

1) If the newly added node is in community \( z \), connect with other \( M - 1 \) non-\( z \) communities with probability \( q_2 \) to connect \( n(1 \leq n \leq m) \) nodes. Before connecting between communities, first select the connected community (such as community \( h(h \neq j \neq z) \)), and the probability of selecting other \( M - 1 \) communities is \( q_1 \) (\( q_1 < q_2 \), \( q_1, q_2 \neq 0 \), \( (M - 1)q_1 + q_2 = 1 \)). \( l_{iz} \) is defined as the degree of connection between the newly added node in community \( z \) and the i-th node in community \( h(h \neq z) \), the connection probability is:

\[
\prod(l_{iz}) = \frac{l_{iz}}{\sum_{m,n,n \neq z} l_{mn}} \tag{4}
\]

2) If the newly added node is in a non-\( z \) community (such as community \( j \)), connect with other \( M - 2 \) communities with probability \( q_1 \) (excluding community \( z \) and community \( j \)), and connect \( n(1 \leq n \leq m) \) nodes. It is also necessary to select the connected community (such as community \( h(h \neq j \neq z) \)), the selection probability is all \( q_1 \). Establish a connection with community \( z \) with probability \( q_2 \) to connect. \( l_{ij} \) is defined as the degree of connection between the community \( j \) and the i-th node of other communities, where \( l'_{iz} \) and \( l'_{ih} \) represent the connection degree of the i-th node of the community \( j \) and any of the other \( M - 1 \) communities (such as the community \( h(h \neq j \neq z) \) or the community \( z \)). The connection probability is:

\[
\prod(l_{ij}) = \prod(l'_{iz}) + \prod(l'_{ih}) = \frac{l'_{iz}}{\sum_{m,n,n \neq j \neq z} l_{mn}} + \frac{l'_{ih}}{\sum_{m,n,n \neq h \neq j} l_{mn}} \tag{5}
\]

3.3. The network generated by modeling

According to the above modeling process, it is assumed that the main modeling parameters are: \( M = 6 \), \( m = 2 \), \( m_0 = 5 \), \( n = 1 \), \( q_1 = 0.04 \), \( q_2 = 0.8 \), \( p_1 = 0.05 \), \( p_2 = 0.5 \), \( p_3 = 9 / 80 \), \( N = 500 \). Through Matlab simulation, the network generated by modeling is shown in Figure 2.
As can be seen from Figure 2, each community has at least one head node, which establishes connections with other communities, and each community also has several relatively large nodes, which serve as control nodes within the community. It has the function of managing and controlling the internal nodes of the community.

In order to simulate the dynamic change of the connection between the nodes caused by the rotation of the satellite around the earth, it is assumed that the community $z$ (community 1) averages 30% of the inter-node connection interruption at any time, and the community $j$ (community 2) average 50% of the inter-node connection interruption at any time, 40% of the other four communities' connections between nodes are interrupted. It must be ensured that each node cannot become an isolated node, each node establishes a connection with at least one other node. Figure 3 shows the actual network graph at any time based on the network graph generated in Figure 2.

4. Simulation experiment

Adjust the generation parameters of the network. Through 100 simulation experiments, verify the influence of each parameter on the static geometric characteristics of the entire network, the network efficiency, the number of head nodes and the number of connected edges between communities.

4.1. The relationship between static geometric characteristics, network efficiency and the number of head nodes

4.1.1. Adjust connection parameters $q_1$ and $q_2$ between communities. Assume that the network parameters are: $M = 6, m = 2, m_0 = 5, n = 1, p_1 = 0.05, p_2 = 0.5, p_3 = 90/80, N = 500$, the simulation results are shown in Table 1.

Table 1. The influence of parameters $q_1$ and $q_2$ on the static geometric characteristics of the network, network efficiency and the number of head nodes.

| $q_1, q_2$ | $A$ | $<k>$ | $L$ | $D$ | $C$ | $E$ | $T1$ | $T2$ |
|-----------|-----|-------|-----|-----|-----|-----|------|------|
| 0.04, 0.8 | 1022 | 4.0869 | 4.1796 | 7.84 | 0.3462 | 0.2636 | 4.67 | 13.26 |
| 0.1, 0.5  | 1039 | 4.1540 | 4.1112 | 7.80 | 0.3318 | 0.2672 | 6.61 | 40.07 |
| 0.16, 0.2 | 1064 | 4.2601 | 4.0163 | 7.64 | 0.3152 | 0.2722 | 4.77 | 81.13 |

Note: $T1$ represents the number of nodes connected to other communities in the community $z$, that is, the number of head nodes. $T2$ represents the sum of the number of head nodes of non-$z$ communities.

It can be seen from Table 1 that only the connection probability between communities is adjusted, and other parameters remain unchanged. As the connection probability $q_2$ between community $z$...
and other communities decreases, the connection probability $q_1$ with other communities increases. The number of connections across the entire network $A$, average degree $<k>$ and network efficiency $E$ have improved, the average distance $L$, the network diameter $D$ and the clustering coefficient $C$ have decreased, indicating that flexibility and efficiency of the entire network are slightly improved, but due to the increase in the number of connected edges between communities, the entire network aggregation is slightly reduced and tend to homogenize. It can also be seen from Table 1 that the sum of the head nodes $T1$ and $T2$ grows rapidly, but the static geometric characteristics of the entire network change is not obvious, which shows that the number of head nodes is not a key factor affecting the network geometric characteristics and network performance.

4.1.2. Adjust the number of new nodes connected to the community after joining the community. Assume that the network parameters are: $M = 6$, $m_0 = 5$, $n = 1$, $q_1 = 0.04$, $q_2 = 0.8$, $p_1 = 0.05$, $p_2 = 0.5$, $p_3 = 9/80$, $N = 500$, the simulation results are shown in Table 2.

Table 2. The influence of the parameter $m$ on the static geometric characteristics of the network, network efficiency and the number of head nodes.

| $m$ | $A$  | $<k>$ | $L$  | $D$  | $C$  | $E$  | $T1$ | $T2$ |
|-----|------|-------|------|------|------|------|------|------|
| 1   | 552  | 2.063 | 5.1084 | 12.49 | 0.0417 | 0.2196 | 4.58 | 12.58 |
| 2   | 1022 | 4.0869 | 4.1796 | 7.84 | 0.3462 | 0.2636 | 4.67 | 13.26 |
| 3   | 1491 | 5.9678 | 3.8767 | 7.02 | 0.3539 | 0.2858 | 4.56 | 13.15 |

It can be seen from Table 2 that adjusting the parameter $m$ has a great influence on the static geometric characteristics of the entire network. The larger the value of $m$, the shorter average distance $L$ and network diameter $D$, the network structure tends to be flat and more flexible. The clustering coefficient $C$ and the network efficiency $E$ have increased significantly, the network is more robust and efficient. This shows that strengthening the connection of the nodes within each community makes each community generate more "control" nodes, this can significantly improve the geometric characteristics and network performance of the entire network. At the same time, Table 2 also reflects the adjustment parameter $m$, which has basically no effect on the generation of the head node.

4.1.3. Adjust the number of new nodes connected to other community nodes. Assume that the network parameters are: $M = 6$, $m_0 = 5$, $m = 2$, $q_1 = 0.04$, $q_2 = 0.8$, $p_1 = 0.05$, $p_2 = 0.5$, $p_3 = 9/80$, $N = 500$, the simulation results are shown in Table 3.

Table 3. The influence of the parameter $n$ on the static geometric characteristics of the network, network efficiency and the number of head nodes.

| $n$ | $A$  | $<k>$ | $L$  | $D$  | $C$  | $E$  | $T1$ | $T2$ |
|-----|------|-------|------|------|------|------|------|------|
| 1   | 1022 | 4.0869 | 4.1796 | 7.84 | 0.3462 | 0.2636 | 4.67 | 13.26 |
| 2   | 1063 | 4.2532 | 4.0524 | 7.77 | 0.3182 | 0.2706 | 4.56 | 18.34 |
| 3   | 1087 | 4.3470 | 4.0077 | 7.65 | 0.3142 | 0.2733 | 4.49 | 21.69 |

It can be seen from Table 3 that adjusting the number of new nodes connected to other community nodes has little effect on the static geometric characteristics and network efficiency of the entire network. At the same time, the number of head nodes $T2$ of non-z communities has a small increase, but the increase is much smaller than the increase caused by adjusting $q_1$ and $q_2$.

4.2. Number of connected edges between communities
Study the number of interconnected edges between communities, and derive the control of community $z$ over the entire network.
Assume that the network parameters are: \( M = 6 \), \( m = 2 \), \( m_0 = 5 \), \( p_1 = 0.05 \), \( p_2 = 0.5 \), \( p_3 = 0.05 \), \( p_4 = 0.05 \), \( N = 500 \), the simulation results are shown in Table 4, 5, 6.

Table 4. The effect of parameters \( q_1 = 0.04 \), \( q_2 = 0.8 \), \( n = 2 \) on the number of consecutive edges between communities (The community 1 is abbreviated as C1).

|     | C1  | C2  | C3  | C4  | C5  | C6  |
|-----|-----|-----|-----|-----|-----|-----|
| C1  | 0   | 3.38| 3.52| 3.60| 3.44| 3.54|
| C2  | 3.38| 0   | 6.38| 6.62| 6.78| 6.42|
| C3  | 3.52| 6.38| 0   | 3.18| 3.14| 3.02|
| C4  | 3.60| 6.62| 3.18| 0   | 3.00| 3.16|
| C5  | 3.44| 6.78| 3.14| 3.00| 0   | 3.38|
| C6  | 3.54| 6.42| 3.02| 3.16| 3.38| 0   |

It can be seen from Tables 4 and 5 that Table 5 reduces the probability \( q_2 \) and increases the probability \( q_1 \). The number of edges connected by community \( z \) to other communities increased, but the proportion of the total number of connected edges between communities decreased from 40.6% in Table 4 to 27.4% in Table 5, that reduced the control of the community \( z \). This is the probability that a new node joins other communities is much greater than the probability of joining community \( z \). The result of a very large node cardinality multiplied by a smaller connection probability is greater than the result of a very few node cardinality times a larger connection probability.

Table 5. The effect of parameters \( q_1 = 0.1 \), \( q_2 = 0.5 \), \( n = 2 \) on the number of consecutive edges between communities

|     | C1  | C2  | C3  | C4  | C5  | C6  |
|-----|-----|-----|-----|-----|-----|-----|
| C1  | 0   | 1.72| 1.80| 1.66| 1.73| 1.81|
| C2  | 1.72| 0   | 1.49| 1.43| 1.44| 1.43|
| C3  | 1.80| 1.49| 0   | 1.14| 1.14| 1.17|
| C4  | 1.66| 1.43| 1.14| 0   | 1.23| 1.18|
| C5  | 1.73| 1.44| 1.14| 1.23| 0   | 1.11|
| C6  | 1.81| 1.43| 1.17| 1.18| 1.11| 0   |

Table 6. The effect of parameters \( q_1 = 0.1 \), \( q_2 = 0.5 \), \( n = 3 \) on the number of consecutive edges between communities

|     | C1  | C2  | C3  | C4  | C5  | C6  |
|-----|-----|-----|-----|-----|-----|-----|
| C1  | 0   | 2.20| 2.35| 2.15| 2.22| 2.15|
| C2  | 2.20| 0   | 4.23| 4.05| 4.28| 4.06|
| C3  | 2.35| 4.23| 0   | 1.99| 2.13| 2.25|
| C4  | 2.15| 4.05| 1.99| 0   | 2.23| 2.04|
| C5  | 2.22| 4.28| 2.13| 2.23| 0   | 2.01|
| C6  | 2.15| 4.06| 2.25| 2.04| 2.01| 0   |

It can be seen from Tables 5 and 6 that as the number of \( n \) nodes connecting new nodes to other communities increases, the number of connected edges between community \( z \) and other communities also increases accordingly. In Table 6, the proportion of the total number of inter-community connections
by community $z$ is 27.9%, which is almost equal to the result in Table 5. The reason for this result is that the inter-community borders increase proportionally, so there is basically no change in the control of community $z$.

5. Conclusion
This paper presents a new type of satellite network structure oriented to business scenarios, which provides an academic reference for the design of the structure of satellite networks. The proposed network structure is also analyzed and verified through mathematical modeling, derivation proofs and simulation experiments, which solves the problem that the previous structure is difficult to analyze and verify.

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