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A Performance Evaluation Platform for Mega Satellite Constellation Network

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Abstract

With the rapid development of satellite technology, mega satellite constellations have become a research hotspot. A large number of related techniques have been developed on orbit topology, network routing, energy balance and resource control. However, it is difficult to accurately compare the performance of similar studies due to differences in the means of validation. Especially for invulnerability studies in many military applications, a unified evaluation system is essential. This paper proposes a network evaluation sys-tem for mega satellite constellations. Evaluation parameters include orbit topology, communication network, energy balance and invulnerability. Different application algorithms and traffic models were used to validate the specific system.

Keywords

Mega Constellation, Satellite Communication, Network Evaluation

1. Introduction

Recent decades witness the rapid development of sciences that had never been conquered during human being's history, one of which is aerospace technology. Especially thanks to the rocket technologies and satellite technologies which create the opportunities of small-size, light-weight, and low-cost satellites to operate as satellite constellations economically. Such mega satellite constellations characterize as low latency, high-reliability, and high broad-coverage. Along with these practical requirements, a large number of researches have been produced.

Among the many studies, network architecture, routing planning and beam strategy are particularly prominent. Y J *et al.* [1] proposed a cross-layer based constellation networking architecture. Lei Zhang *et al.* [2] introduced a new approach about two-dimensional lattice networks routing algorithm. A compass time-space model-based virtual IP routing scheme is introduced for mega constellations [3].

For many research techniques mentioned above, the common purpose is to optimize network performance [4] [5]. Therefore, accurate and comprehensive performance evaluation techniques are the basic technology for them. Peng *et al.* [6] proposed the performance evaluation of the three constellations Starlink, Oneweb and Telesat. Shaochi *et al.* [7] introduced a ground station deployment scheme based on satellite network throughput evaluation. However, these simulations apply only to specific designs and are not general.

Some studies on satellite communication performance evaluation have also attracted the attention of scholars. S Cheng *et al.* [8] proposed a neural network based performance evaluation for satellite communication system. S Liu *et al.* [9] proposed a throughput evaluation between ground station and satellite constellation. However, these contents only include part of the evaluation of communication performance. Neither orbital performance nor survivability assessments covered in them.

A satellite constellation network performance verification system must cover most performance parameters that need to be concerned. These parameters include not only communication capabilities, constellation orbit parameters, satellite energy balance capabilities, and satellite invulnerability. Specially for military satellite constellations such as Starshield, vulnerability is the most important design parameter. The performance evaluation platform needs to be compatible with different application algorithms.

In this paper, a network performance evaluation system suitable for mega satellite constellations is proposed. Orbit parameters, energy parameters, communication parameters and invulnerability parameters are analysed in the system. A variety of constellation designs with different algorithms are used to verify the specific system.

2. Constellation Analysis

For the stability of network performance, a symmetrical constellation configuration is necessary. Walker constellation is an excellent choice. For the walker constellation, there are two different topologies namely walker-delta and walker polar. The typical application of the former is Starlink and the latter is Oneweb.

For the actual track topology, it may be a mixture of sets of standard topologies with different structures, different heights and different characteristics. This will require performance verification platforms with the ability to decompose complex topologies.

In order to effectively verify network performance, a general network topology is necessary. For two walker constellations, a mesh like network topology is common. In this network topology, each satellite node only establishes connections with four neighbour satellite nodes around it.

The inter satellite link (ISL) not only transmits user data, but also periodically transmits Session initialization Protocol (SIP). All satellite nodes exchange status information through SIP, including link status, node status, energy status and business status.

A qualified satellite constellation network verification platform must take into account the orbital characteristics, network characteristics and ground coverage characteristics of the entire constellation. And take the network communication performance as the verification goal.

3. System Design

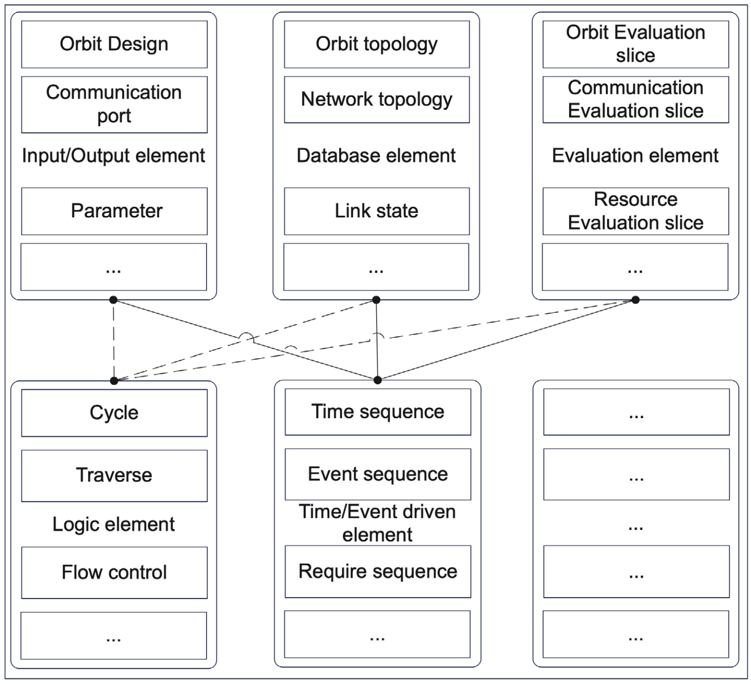
In order to guarantee the validity of the evaluation platform, we divide the verification parameters into four categories namely orbit type, communication type, power type and invulnerability type. In order to give a general design, only the most representative parameters are given for each category in this paper as shown in **Table 1**. The verification platform involved in this article is a system model, and verification objects can be added arbitrarily according to requirements.

The evaluation system is designed by network elements and slices. As shown in **Figure 1(a)**, each element contains a type of function, and can be increased or decreased as needed. For simplicity, five elements are designed namely Input/Output element, Database element, Evaluation element, Logic element and Time/event driven element. Each network element is composed of multiple network slices.

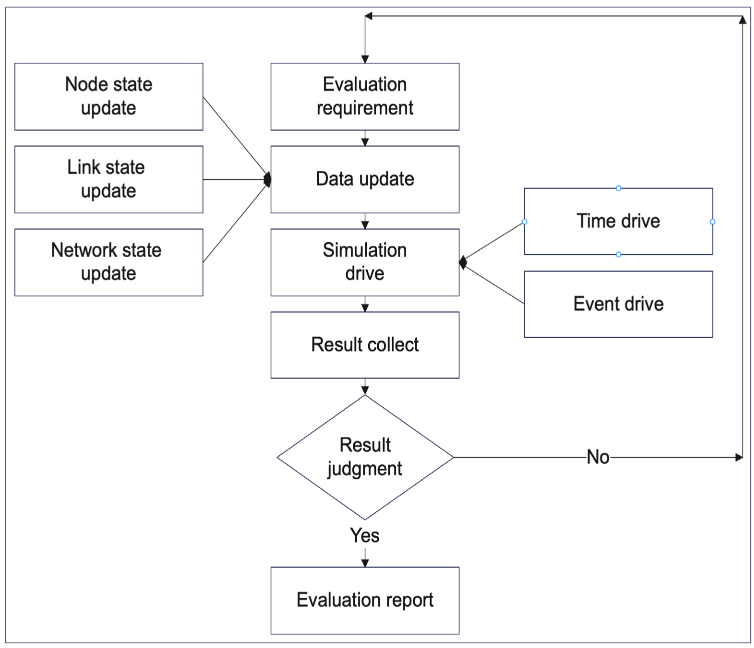
The Input/Output element is mainly responsible for the input of system design parameters and the output of simulation results. Database element is mainly responsible for data caching and system model storage during operation. Evaluation element is the core content of this system, including simulation slices of various performance parameters. This element can update evaluation parameters on demand via an external interface. Logic element is mainly responsible for the logic control part during the operation of the platform. The Time/event driven element is mainly responsible for business control in the communication function. According to different needs, it can be divided into time-triggered

Table 1. Network performance evaluation parameters.

Type	Performance
Orbit	Connection duration
Communication	Delivery loss ratio
	Throughput
Power	Residual energy
Invulnerability	Packet loss failure
	Delay failure



(a)



(b)

Figure 1. Evaluation platform design. (a) Evaluation platform structure (b) System flow.

services and event-triggered services. Different network elements implement different functions, and jointly realize the function of network performance evaluation.

Each element can work in parallel, and the data exchanged by the database element. The system operation process is shown in **Figure 1(b)**. The main loop controlled by the logic unit drives the operation of the entire platform.

During the operation, the orbital topology model is generated according to the input orbital parameters firstly. Link status is generated according to communication mode secondly. Mission is generated according to requirements thirdly. The main workflow is shown in **Table 2**.

The specific evaluation platform is composed of Python and C++, which calls a large number of data processing libraries. The system is compatible with various computing platforms.

In each function, different strategies can be embedded. Each strategy is responsible for a network element such as routing, beam resources, energy balance, etc. For example, the same constellation design can embed a variety of different routing algorithms, and finally select an optimal option.

For more realistic verification of evaluation platform, a realistic traffic model is essential [3]. According to a large number of traffic analysis, a traffic model including two business types is selected. The first service provides Internet access in remote areas, oceans, and mountains. The second service provides Device-to-Device (D2D) dedicated connection for financial, medical, and military applications. Traffics of both services are related to population distribution and time, and the traffics of the two services are independent. Traffic density can be adjusted on demand during the operation of the performance verification platform

4. Verification

For design efficiency, a unified traffic model is necessary. Different traffic densities are cyclically embedded in the platform operation process. The network evaluation system can be applied to different application layer algorithms, traffic models and optimization goals. In order to more effectively verify this system, a unified constellation with 1152/48/24 is introduced as an orbit topology. The constellation with T/P/F means that T is the total number of satellites, P is the number of orbital planes and F is the phase factor.

Table 2. Operation workflow.

Num	Function	Result
1	Orbit analysis	Orbit topology model
2	Communication analysis	Link topology model
3	Coverage analysis	Coverage duration model
4	Link analysis	Link state information
5	Resource analysis	Energy, bandwidth, power and time information
6	Mission analysis	Operation requirements
7	Traffic analysis	Communication traffic
8	State analysis	State information

In this section we show the different parameters of the evaluation platform, including orbit, communication, energy and survivability, etc.

Figure 2 shows the coverage parameter evaluation results. The results show the duration of the connection of the satellites in this constellation to ground fixed targets per orbital period. This parameter expresses the ground coverage capability of the constellation, which is related to orbit design and ground communication resources.

Figure 3 shows the evaluation results of node energy performance of the system for energy sensitive and congestion balance (ESCB) and virtual-topology-based shortest path (VT-SP) routing algorithm [10]. The results evaluate the energy-balancing capabilities of network algorithms.

Figure 4 shows the performance evaluation results of packet loss rate for Compass time-space Model-based Virtual IP (CMVIP) and Virtual-Topology-based Shortest Path (VT-SP) routing algorithms [3]. And evaluated the packet loss rate under different traffic densities. This parameter represents the communication capability of the satellite constellation system.

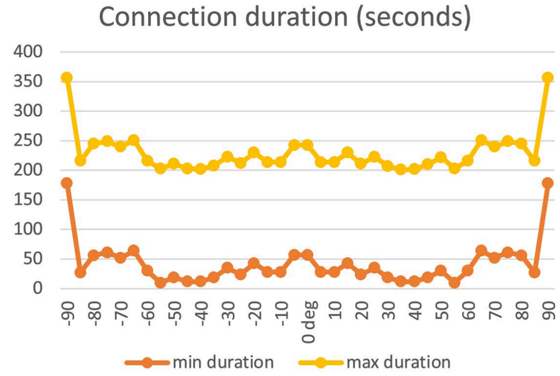


Figure 2. Coverage parameter.

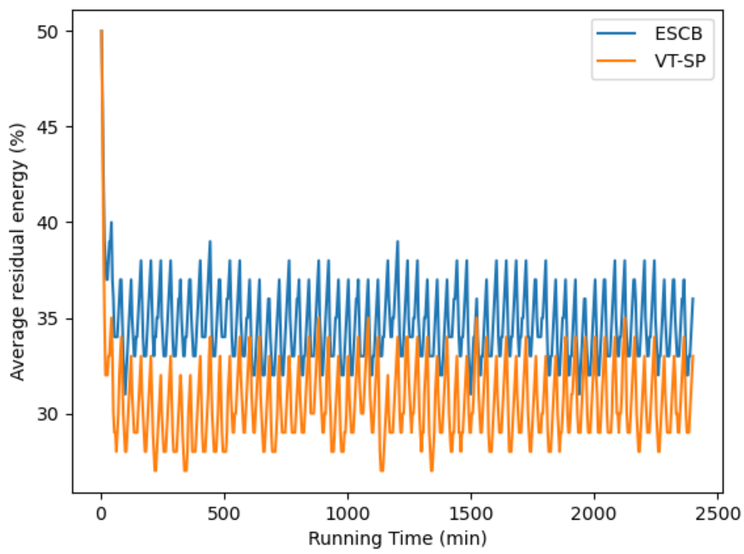


Figure 3. Energy parameter.

Figure 5 shows the throughput performance evaluation results for CMVIP and VT-SP. These two evaluation parameters determine the communication capabilities of the satellite constellation network.

In order to evaluate the invulnerability of the constellation network, it is assumed that some satellite nodes are in a failure state to evaluate the network performance. The selection of failed nodes will involve related constellation attack algorithms [10]. This article uniformly uses the random selection method. The specific attack method is beyond the scope of this article.

As shown in **Figure 6**, the performance evaluation of the packet loss rate in the state where the number of failed nodes is 0, 100, 200, 300, 500. According to the performance attenuation threshold, the relationship between the number of failed nodes and performance can be known from the evaluation results.

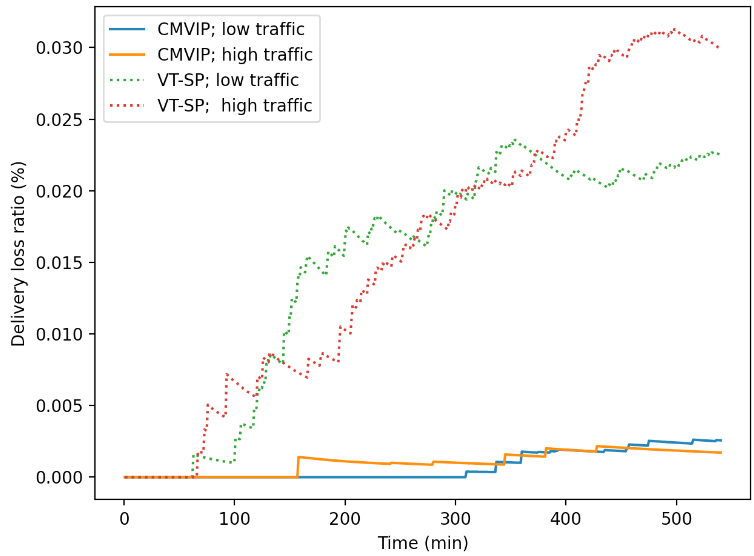


Figure 4. Delivery parameter.

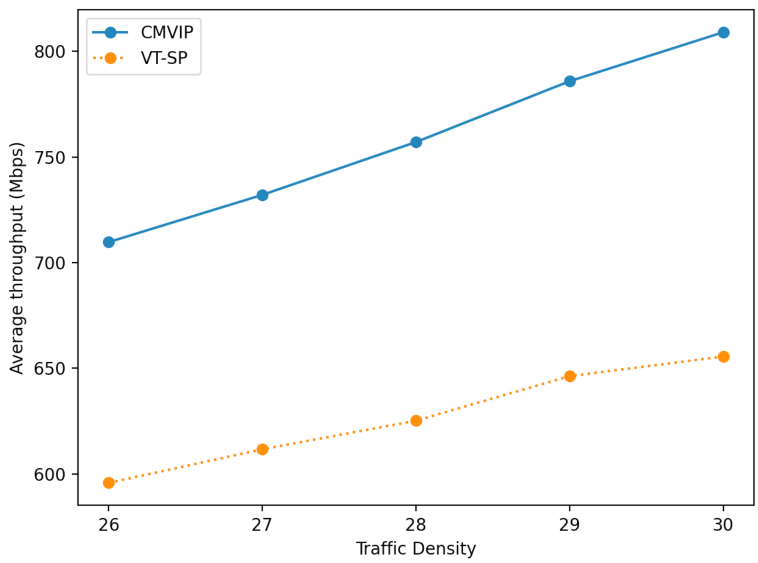


Figure 5. Throughput parameter.

Similarly, **Figure 7** shows the relationship between the number of failed nodes and the delay. Traffic density represents the data traffic density of ground traffic services. Average throughput indicates the amount of data transmitted during satellite operation. Average delay represents satellite forwarding delay, including transmission delay, processing delay, etc.

The above evaluation results include orbital design, energy balance, communication capability and survivability. Clear guidance could be given during the satellite constellation network design and implementation phase.

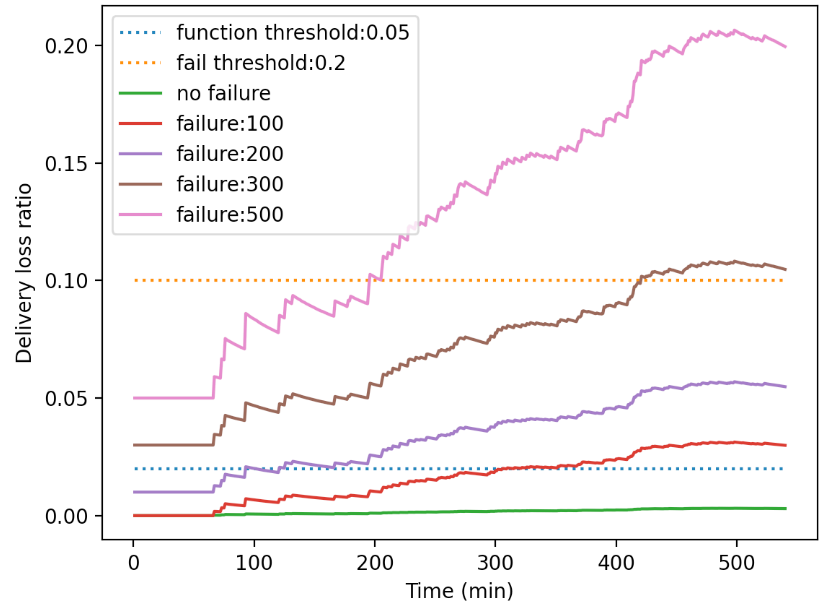


Figure 6. Delivery failure parameter.

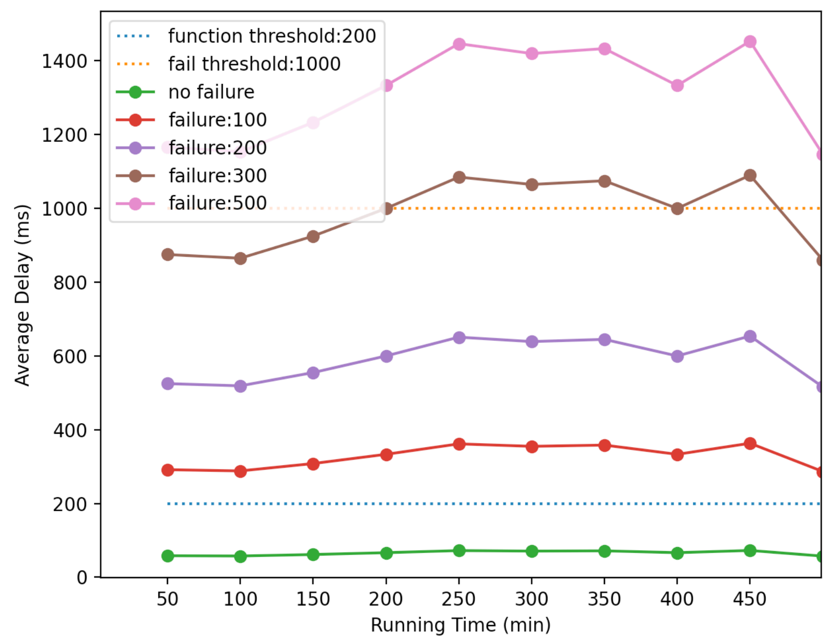


Figure 7. Delay parameter.

5. Conclusion

This paper proposes a network evaluation system for large-scale satellite constellations. Evaluation parameters include track coverage, capacity, energy balance and network invulnerability. Different application algorithms, traffic models and control strategies are used to verify the system. The evaluation results demonstrate the effectiveness of the system.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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