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Survivability Analysis of LEO Satellite Networks Based on Network Utility

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ABSTRACT The LEO satellite network is threatened by accidental faults, malicious attacks and other factors during its operation. This paper proposed a model of survivability evaluation based on network utility. First, calculate the communication performance indicators of delay, congestion rate and throughput of LEO satellite networks by different types of queue theory birth and death model; then, combined these performance indicators with reliability and cost planning to construct network utility function which is used for evaluating the survivability of LEO satellite networks under natural failure, random attack, deliberate attack and saturation attack modes. The case study shows that: the greater the arrival rate of natural faults, the shorter the time required to descend to the network utility threshold, the network is more vulnerable to intentional attacks; the survivability can't be enhanced by adding buffers; the importance of nodes and links is related to the proportion of real-time and non-real-time services and the traffic of different satellite coverage areas.

INDEX TERMS LEO satellite network, queue birth and death, network utility, survivability.

I. INTRODUCTION

Due to short roundtri delays and wide-area coverage characteristics including urban, rural, remote and inaccessible areas, Low Earth Orbit (LEO) satellite networks are becoming increasingly important [1]. An LEO satellite network system is made up of a constellation consisting of a number of satellites in circular orbits at altitudes ranging from 500 km to 1500 km [2]. With the development of space resources by satellites, satellites have gradually become the targets of cyber warfare, it also means that satellite communication network must have a high survivability in order to provide satisfying services to its users. The survivability of satellite communication network means that the system can provide the ability to complete the transmission of data in time under the condition that the satellite or communication link fails after an accident, failure or attack [3], [4]. Further analysis shows that static survivability and cascading failure [5], [6] are the two main directions of network survivability research. However, in terms of invulnerability measures, there is no suitable measurement to estimate the survivability of LEO satellite network. At present, graph theory, complex network theory and super network theory are the main basic theories used to study network survivability. Graph-based survivability is analyzed purely from the perspective of network structure, initially measured by cohesion and connectivity [7] which developed into k-connected [8]. Connectivity-based survivability assessment method is simple, but the discrimination is not high. Subsequently, Chvatalz et al. [9] studied the toughness of graph which can reflect the number of connected branches after the graph is segmented. The less connected branches, the better the invulnerability. The integrity proposed by Barefoot et al. [10] takes into account the vertex cut and the maximum branch size. Unlike graph theory, some survivability measures taken into account the impact of actual network transmission performance in complex networks. Gao et al. [11] established a model of structure entropy combine with information transfer efficiency. Bond and Peyrat [12] extended the study of network reliability to network performance, examined the effect of removing a node or edge on packet transmission delay, the diameter of graph is used to reflect the network speed. As a single network performance index, time delay refers to the time required for data to be transmitted from one end of

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a satellite network (or link) to the other end, are likely to result in degraded performance, poor robustness, and even instability [13], [14], previous methods equating it with path hops or distances is simple but imprecise and ignores the limitation of network resources. The efficiency in the communication between two generic points *i* and *j* can be defined to be inversely proportional to the shortest distance, the efficiency between *i* and *j* is 0 when there is no path in the graph between *i* and *j* [15], the network survivability can be measured by average efficiency. But this binary networks which only considered link is either present or absent is not accounted for intensity (weight) of the links. So, Bellingeri and Cassi [16] used weighted efficiency to measure the network efficiency during the node removal process which is based on the weighted shortest paths notion. Wang et al. [17] proposed an invulnerability assessment method based on the entropy theory and subsystem failure distance. This is mainly from several aspects of research, such as the network connectivity, network efficiency, node criticality and network dynamic evolution [18]. For complex networks, Albert et al. [19] proposed an invulnerability measure index for complex networks based on the maximum connected subgraph and average path length, studied the invulnerability of complex networks and scale-free networks under random attack and intentional attack, respectively. Holme et al. [20] attacks the network by four strategies: the size of node degree, the size of node betweenness, the current size of node degree and the current size of node betweenness, and ER(Random Networks), WS(Small World Networks), BA(Scale-free Networks) show distinction when faced different attack strategies. In the study of super-large-scale network systems, the emergence interweaving problem of logistics network, information network and capital network, or network problems in the network, the general network graph can not fully describe the characteristics of this real world network. Nagurney and Dong [21] calls this kind of interlaced network which is higher than and higher than the existing network as ''super network'', which has the characteristics of multi-level, multi-dimensional, multi-attribute and network congestion. Wang et al. [22] analyzed the structure relationship of the hypernetwork model of the equipment system, and obtained the network survivability under different attack strategies. The nodes in military communication network are classified according to information interaction types, information function chain is proposed and the invulnerability of QFD-style military communication network association model is analyzed in [23] based on hypernetwork. These research method is primarily devoted to their influence on the topology. The above part of the research method is not applicable to the field of non-linearity such as satellite work, which the research core is the data delivery capability under the attack environment include time delay, congestion, throughput and so on [24]. Some studies fail to reflect the impact of comprehensive survivability performance which the research core is the data delivery capability under the resource-constrained and service diversity environment.

This paper uses network communication efficiency to construct network utility function to measure the survivability of LEO satellite network, illustrate the ability of completing communication tasks before and after failure or attack. Because of the unusual difficulty of satellite repair, this paper does not consider the impact of satellite repair rate on network survivability.

A. RELATED WORK

Satellite networks are often subject to failures caused by energy depletion, software or hardware fault of nodes, environment events, hostile attacks, and other reasons. At the same time, storage resources and communication resources of satellites are generally limited, node and link failures will lead to network congestion, data loss and long delay, decrease the service performance and network utility. Therefore, routing technology, congestion control and survivability technology are all key technologies to improve satellite network. For network survivability, some scholars research survivability from the perspective of network utility [25]. A novel early warning method based on attack gains and cost principle (AGCP) which can be summarized as ''during an attack, attackers expect to get the minimum ratio of cost to gains'' is proposed in [26], provided the optimal attack route, but the attack gains refer to what the attackers obtain from the attacked target. It means the maximum attack gains are expected by paying as little attack cost as possible. However, the formula of attack gains is not given in detail. Similarly, system architecture, the cost to the enemy to destroy the network, the cost to the communicator to implement the network, and the rate of throughput is proposed in [27] to measure the electronic and physical survivability of satellite communications. During network recovery, Huang et al. [28] propose a new formulation used for defense against deliberately attacks based on cost and load. Liu [29] considered the expected queuing delay and propagation delay of ISL for the link weight to provide self-adaptive load balancing without elaborate on the method of calculating the delay concretely. A fault-tolerant interruption network routing algorithm based on GEO relay network is proposed in [30]. The optimal transmission path is obtained according to the expected delivery time and estimated delivery cost. A connectivity restoration strategy constructed with connection cost function, load balance function and reliability function are proposed in [31], in order to improve the network survivability. The connection cost function is depend on path distance, which can not reflect the transmission delay strictly and energy consumption of the link.

B. CONTRIBUTIONS

Existing research on survivability mainly considers load balancing, routing strategy and constellation structure, but doesn't specify take reliability, network efficiency, service utility and cost into account, there is no detailed assessment of the impact of communication mechanisms and complex environments on network utility. In this paper, we first construct a utility function of satellite network based on queuing birth and death model which can quantitatively describe the network delay combining with the characteristics of satellite networks. The contributions of this paper are:

1) The communication process of satellite network is theoretically analyzed by queuing birth and death model, considering the characteristics of information flow in different services, using reliability, throughput, delay and service to restructure residual network utility function can more comprehensively reflect the ability of the network to complete tasks after being attacked.
2) A component importance analysis method based on network utility is proposed, which can reflect the impact of topology, node function in application environment, information flow generation speed, and service type on component importance. On this basis, the attack strategy set in the case of limited cost is also discussed.
3) Deals with the multiple link or node failures, a more precise method for evaluating network survivability by utilizing utility changes after network encounters node or link failure is presented. This method is oriented to four kinds of faults, and can synthesize the delay, energy consumption, reliability and other factors affecting the invulnerability of satellite networks.

In the remainder of this paper, Section II presents the queuing birth and death model for satellite communication and key concepts. Section III introduced the proposed utility survivability assessment model. Simulations and results are presented in Section IV. Finally, section V concludes our study.

The frequently used notations are presented in Table 1.

II. PERFORMANCE EVALUATION MODEL OF LEO SATELLITE NETWORK

Assuming that the path between source A and destination B consists of n intermediate satellite nodes and inter-satellite links, and that satellite nodes can be regarded as routers based on storage and forwarding and FIFO (First In First Out) queuing strategy, each inter-satellite link has its own capacity and bandwidth. At the same time, the data in real-time task needs have validity limit. Once the data waiting for processing exceeds its validity or the capacity of satellite buffer, it will be deleted directly by the system and will not be processed. The workflow of LEO satellite is basically shown in Figure 1.

A. QUEUING LOSS M/M/m/m Model FOR ACCESS TO LOW EARTH ORBIT SATELLITE NETWORK

There are N satellites in the satellite network, and each satellite has the same performance parameters. The satellite s_i spot beam covers the users in the cell sharing m_1 channels.

When the new call packet arrives, the new call will be rejected if there is no idle channel in the user link. Therefore, user access can be regarded as an M/M/m/m queue model. Assuming that the service arrival rate of the user link is λ_{ui},

TABLE 1. List of notation of frequently used terms.

Notation	Description
v_i	Satellite node i
N	Number of nodes
$e_{i,j}$	Link traversing v_i and v_j
λ_{ui}, λ_{si}, λ_{sisj}, λ_{gpi}	Packet arrival rate of satellite s_i's user link i,satellite s_i's receiver, intersatellite link $e_{i,j}$ and ground station i
m_1,m_2,m_3	Channel number of user links, intersatellite links and feed links channel
B_r,B_s	Receive buffer, Send buffer size of satellite i
μ_{up}, μ_{sp}, μ_{ss}, μ_{gp}	Service rate of user link, satellite processor, intersatellite link and ground station processor
P_{ci}^{block}, P_{bri}^{block}, P_{bsi}^{block}	Blocking rate of user link access, receive buffer and send buffer
$w_{q\,spi}$, $w_{q\,ssi}$	Wait time in node i processing phase and sending phase
δ	Saturated attack intensity
α_v,α_e	Failure arrival rate of nodes and links
n_v,n_e	Number of attacked nodes and links

and the service rate of the channel is λ_{upi}, the state transition diagram of the user link in the access phase is shown in Fig 2.

Access blocking rate is the probability that there is no idle channel in user link during call request access stage.

$$P_{ci}^{block} = P_{m_1} = \frac{(\frac{\lambda_{ui}}{\mu_{upi}})^{m_1}}{m_1!} \Bigg/ \sum_{n=0}^{m_1} \frac{(\frac{\lambda_{ui}}{\mu_{upi}})^{n}}{n!} \tag{1}$$

Effective arrival rate of user terminals transmitted to satellite processing front-end via m_1 channel is

$$\lambda_{usi} = n_s \left[(1 - P_{ci}^{block}) \right] \lambda_{ui} \tag{2}$$

After the user packet is accessed through the user link channel of the current visual satellite, it is transmitted to the satellite receiving buffer for processing. In addition to the new call service, the satellite s_i also forwards the services of other satellite nodes. For real-time services, visual satellites are processed by physical layer, link layer and network layer 3, and transmitted directly from the satellite network without landing at the gateway station, which saves the upper and lower satellite-to-ground delay. For non-real-time services, satellites are transparently forwarded by layer 1, while all the upper layers of layer 1, layer 2 and layer 3 are processed at a nearby gateway station, and the processing results are returned to the access satellite. In the equilibrium state, the total packet arrival rate received before satellite s_i processing is consist of the new calls λ_{us_i} of users in coverage area, the forwarding packets $\lambda_{s_j s_\omega}(i)$ of other satellite s_j, the non-real-time service

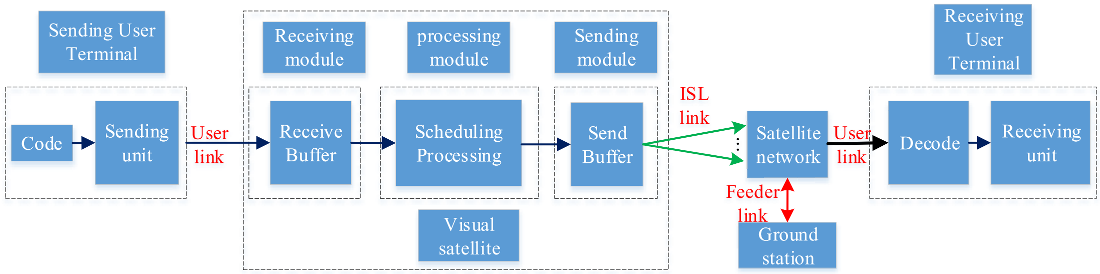

FIGURE 1. Basic flow chart of LEO satellite communication network communication.

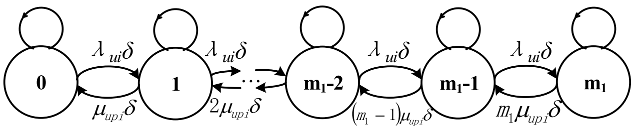

FIGURE 2. Queuing state transition diagram of user links.

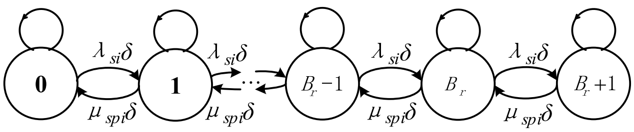

FIGURE 3. Satellite processing queuing state transition diagram.

packets $\lambda_{g_k s_i}$returned to s_i after the processing of gateway station, the non-real-time service packets $\lambda_{s_j g_k}(i)$ of satellite s_j forwarded to g_k of gateway station via satellite s_i, and the grouping composition of the non-real-time service processing results forwarded by the station g_k to the satellite s_j via the satellite si $\lambda_{g_k s_j}(i)$, i.e. Satisfaction formula

$$\lambda_{s_i} = \lambda_{us_i} + \lambda_{s_j s_\omega}(i) + \lambda_{g_k s_i} + \lambda_{s_j g_k}(i) + \lambda_{g_k s_j}(i) \quad (3)$$

B. M/M/1/m QUEUING MODEL FOR LEO SATELLITE SIGNAL PROCESSING

The received data packet needs to be processed by frequency conversion and amplification before satellite transponder forwarding. Unprocessed data packets are temporarily queued by buffer. When the number of data packets exceeds the capacity of network devices (buffer capacity and processing capacity), congestion will occur. If the buffer size is Br, the satellite processing process can be regarded as an M/M/1/m model queuing system of single server with Br capacity. If the satellite processing rate is set to represent real-time and non-real-time services respectively, then the expected processing rate of satellite services is set to be

$$\mu_{spi} = \frac{(1-p_{nr})\lambda_{usi}}{\lambda_{si}}\mu_{spi}(1) + \left[1 - \frac{(1-p_{nr})\lambda_{usi}}{\lambda_{si}}\right]\mu_{spi}(2) \quad (4)$$

Satellite receiving buffer blocking rate is

$$P_{bri}^{block} = P_{B_r+1} = \frac{1-\rho_{spi}}{1-\rho_{spi}{}^{B_r+2}}\rho_{spi}{}^{B_r+1} \quad (5)$$

Generally, the processing speed of satellite can satisfy the channel grouping rate through the matching of channel design. When the receiving buffer state is in Br, the packet can not enter the satellite for processing. Therefore, the effective arrival rate of the user terminal processed by the processor and transmitted to the satellite transmission buffer is

$$\lambda_{spi} = \lambda_{si}(1 - P_{B_r+1}) = (1 - P_{bri}^{loss})\lambda_{si} \quad (6)$$

The average queue length of the receiving buffer is

$$L_{qspi} = \sum_{n=0}^{B_r+1}(n-1)P_n = \begin{cases} \dfrac{\rho_{spi}}{1-\rho_{spi}} - \dfrac{(B_r+1)\rho_{spi}{}^{B_r+1}}{1-\rho_{spi}{}^{B_r+2}}, & \rho_{spi} \neq 1 \\ \dfrac{B_r \cdot (B_r+1)}{2(B_r+2)}, & \rho_{spi} = 1 \end{cases} \quad (7)$$

Average waiting time in processing phase is

$$w_{q^{sp}} = \frac{L_{q^{sp}}}{\lambda_{sp}} \quad (8)$$

Satellite processing time for different services is

$$T_{sp}(y) = \frac{1}{\mu_{sp}(y)}, \quad y = 1, 2 \quad (9)$$

Average sojourn time is

$$W_{sp} = w_{q^{sp}} + \frac{1}{\mu_{sp}} \quad (10)$$

C. M/M/s/k QUEUING MODEL FOR LEO SATELLITE SIGNAL TRANSMISSION

There are three types of antennas on the satellite, which are aimed at user terminals, neighbor satellites and ground stations. Among them, "Ka" inter-satellite link phased array antenna on the satellite achieves real-time communication between satellites and neighbor satellites with different phases. The satellite transmitter contains m_1 user links, m_2 intersatellite links and m_3 feeder links. When the packet arriving at multiple input terminals of the satellite requests to output from the same link of the satellite, if the total arrival rate of the service exceeds the transmission rate of the output link, the processed packet will be queued at the output terminal, i.e. it enters the sending buffer and waits

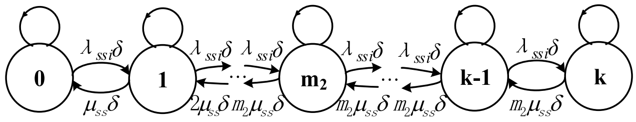

FIGURE 4. Queuing state transition diagram of intersatellite links at satellite transmitter equilibrium state.

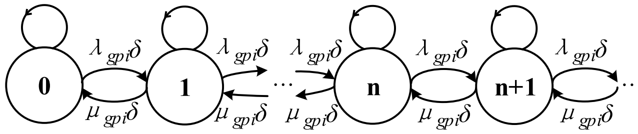

FIGURE 5. Queuing state transition diagram of ground station.

for transmission. If the set of neighbor nodes of s_i is set and the satellite is within the visual range of the gateway station, the output grouping satisfies the following formula

$$\lambda_{s_i} = \lambda_{s_i u_i} + \sum_{j \in \Lambda_i} \lambda_{s_i s_j} + \lambda_{s_i g k} \tag{11}$$

The process of grouping satellite transmission buffer into three different channels can be regarded as M/M/s/k queuing model [32], sharing a dynamic waiting space with capacity of Bs, the cache depth of each ISL virtual channel requires on-demand allocation. Taking the inter-satellite link as an example, the packet transmission process from the satellite si to its neighbor satellite is a M/M/m_2/k queue model with arrival rate $\sum_{j\in\Lambda_i} \lambda_{s_i s_j}$, waiting capacity Bss, number of servers m_2, system space $k = m_2 + Bss$, and channel transmission service rate of the inter-satellite link of μ_{ss}. When the total queue length of the transmit buffer is longer than the transmit buffer capacity Bs, the channel will be congested.

$$\rho_{ss_i} = \frac{\sum_{j\in\Lambda_i} \lambda_{s_i s_j}}{\mu_{ss}} \tag{12}$$

$$\rho'_{ss_i} = \frac{\sum_{j\in\Lambda_i} \lambda_{s_i s_j}}{m_2 \mu_{ss}} \tag{13}$$

Channel idle probability is

$$P_0 = \begin{cases} \left[\sum_{n=0}^{m_2-1} \frac{\rho_{ss_i}{}^n}{n!} + \frac{\rho_{ss_i}{}^{m_2}(1-\rho'_{ss_i}{}^{B_{ss}+1})}{m_2!(1-\rho'_{ss_i})} \right]^{-1}, & \rho'_{ss_i} \neq 1 \\ \left[\sum_{n=0}^{m_2-1} \frac{\rho_{ss_i}{}^n}{n!} + \frac{\rho_{ss_i}{}^{m_2}(B_{ss}+1)}{m_2!} \right]^{-1}, & \rho'_{ss_i} = 1 \end{cases} \tag{14}$$

Satellite s_i sending buffer blocking rate is

$$P_{bsi}^{block} = P_k = \frac{\rho_{ss_i}{}^n}{m_2! m_2{}^{B_{ss}}} \tag{15}$$

The average queue length is

$$L_q^{ss} = \sum_{n=m_2}^{m_2+B_{ss}} (n - m_2) P_n \tag{16}$$

The queue length is

$$L^{ss} = L_q^{ss} + m_2 + P_0 \sum_{n=0}^{m_2-1} \frac{(n-m_2)\rho_{ss_i}{}^n}{n!} \tag{17}$$

Using dynamic buffer allocation algorithm[33], Acquire the send buffer allocated for each channel, such as Bss. Queuing delay of send buffer is

$$w_{q^{ss_i}} = \frac{L_q^{ss_i}}{\lambda_{ess_i}} \tag{18}$$

ISI transmission delay

$$T_{ISL} = \frac{1}{\mu_{ISL}} \tag{19}$$

Similarly, the queuing delay and congestion rate of satellite-to-ground user links are consistent with the above methods. Effective achievement rate of group is

$$\lambda_{ess_i} = \lambda_{ssi}\left(1 - \frac{\rho_{ss_i}^k}{m_2! m_2^{B_{ssi}}} P_0\right) \tag{20}$$

D. GROUND STATION M/M/1 QUEUING MODEL FOR ORIENTED NON-REAL-TIME SERVICE

The processing rate of ground station is μ_{gp} bps, and its capacity is very large. There is no congestion and only delay. It is regarded as an M/M/1 queuing system, as shown in Figure 5.

The average waiting delay of each user group at the ground station is

$$w_{q^{gp}} = \frac{\rho_{gpi}}{\mu_{gpi}(1-\rho_{gpi})} \tag{21}$$

Processing delay is

$$T_{gp} = \frac{1}{\mu_{gp}} \tag{22}$$

E. PERFORMANCE EVALUATION OF LEONSATELLITE NETWORK COMMUNICATION

The access delay is the access transmission delay of the user group upstream link. Suppose L, h_{sg}, h_{ss}, C, R_{up}, R_{sg} and R_{ISL} represent the packet size, distance from ground to satellite, distance between satellites, propagation speed, user link bandwidth, feed link bandwidth and intersatellite link bandwidth respectively. The receiving time of the satellite user link channel is

$$T_{up} = T_{us} = T_{su} = \frac{L}{R_{up}} + \frac{h_{sg}}{C} \tag{23}$$

The transmission delay of up-down feeder link between satellite and ground station is

$$T_{uplink} = T_{downlink} = \frac{L}{R_{sg}} + \frac{h_{sg}}{C} \tag{24}$$

Inter-satellite link transmission delay is

$$T_{cross} = \frac{L}{R_{ISL}} + \frac{h_{ss}}{C} \tag{25}$$

1) COMMUNICATION PERFORMANCE EVALUATION OF REAL-TIME SERVICE

If the user terminal u_i in the satellite s_i coverage area sends voice packets to the user terminal u_j in the satellite s_j coverage area, the set of nodes constituted by the transmission path is $L_{ij} = \{s_i, s_2, \cdots, s_j\}$, and the length of the transmission path is $numL_{ij}$, the total data transmission delay in the path consists of four parts: the downlink and downlink delay between satellite and user T_{usi}, T_{suj}, queuing delay $w_{q^{spm}}$, $w_{q^{ssm}}$, satellite processing delay $T_{spm}(y)$ and transmission delay of each ISL on the path T_{cross}. Then the total delay of real-time tasks is

$$D_{rij} = T_{usi} + T_{suj} + \sum_{m\in L_{ij}} W_{spm} + \sum_{m\in L_{ij}} w_{q^{ssm}} + (numL_{ij} - 1)T_{cross} \tag{26}$$

Real-time service blocking rate of u_i and u_j through path L_{ij} transmission is

$$B^r_{ij} = (1-P^{block}_{ci})\left[1 - \prod_{m\in l_{ij}, m\neq i} (1-P^{block}_{brm})(1-P^{block}_{bsm})\right] \tag{27}$$

where, P^{block}_{brm} and P^{block}_{bsm} represent the receiving buffer blocking rate and the sender buffer blocking rate of node m are represented respectively.

2) COMMUNICATION PERFORMANCE EVALUATION OF NON-REAL-TIME SERVICE

Ignoring the distance difference between satellites and different ground user terminals and customs stations, and ignoring the distance difference between in-orbit inter-satellite links and Inter-orbit inter-satellite links, the total delay of non-real-time tasks is as follows:

$$\begin{aligned} D_{nrij} &= 2T_{up} + T_{uplink} + T_{downlink} + T_{gp} + \sum_{m\in L_{ig}} w_{q^{spm}} \\ &\quad + \sum_{m\in L_{ig}} w_{q^{ssm}} + \sum_{m\in L_{gi}, m\neq g} w_{q^{spm}} + \sum_{m\in L_{gi}, m\neq g} w_{q^{ssm}} \\ &\quad + \sum_{m\in L_{ij}, m\neq i} w_{q^{spm}} + \sum_{m\in L_{ij}} w_{q^{ssm}} \\ &\quad + (num_{L_{ig}} + num_{L_{gi}} + numL_{ij} - 5)T_{cross} \\ &\quad + (num_{L_{ig}} + num_{L_{gi}} + numL_{ij} - 3)T_{sp}(2) \end{aligned} \tag{28}$$

Non-real-time service blocking rate of u_i and u_j through path L_{ij} is

$$\begin{aligned} B^{nr}_{ij} &= (1 - P^{block}_{ci}) \prod_{m\in L_{ij}, m\neq i} (1 - P^{block}_{brm})(1 - P^{block}_{bsm}) \\ &\quad \times \prod_{m\in L_{ig}, m\neq g} (1 - P^{block}_{brm})(1 - P^{block}_{bsm}) \\ &\quad \times \prod_{m\in L_{gi}, m\neq g} (1 - P^{block}_{brm})(1 - P^{block}_{bsm}) \end{aligned} \tag{29}$$

III. ASSESSMENT OF THE SURVIVABILITY OF LEO SATELLITE NETWORKS

A. CONSTRUCTION OF SERVICE UTILITY FUNCTION

Assuming that I can be paid for whe unit packet are successfully transmitted, C_D is the is the penalty cost of delay, the delay threshold is $D^{h.}$ when the packet delay $D = D^{h.}$ the profit of the packet is 0, that is, the utility function satisfies the following relationship.

$$I - C_D D^h = 0 \tag{30}$$

Similar to research [34], [35], Task overhead is proportional to the delay D_{ij} of the packet, since the longer the transmission delay, the lower the user satisfaction; second, it is proportional to the service time T_{ij} of the packet, since the longer the service delay, the more energy consumed. The utility function of task grouping W_{ij} can be expressed as

$$U_{ij} = (1 - B_{ij})(I - C_D D_{ij} - C_T T_{ij}) \tag{31}$$

Assuming that I_r and I_{nr} (usually $I_r > I_{nr}$) are payments for real-time and non-real-time grouping respectively, D^{rh} and D^{nrh} ($D^{rh} < D^{nrh}$) are delays for real-time and non-real-time grouping respectively. The utility of the network in unit time_is

$$\begin{aligned} U = \sum_{i=1}^{N}\sum_{j=1}^{N} \Big[&\lambda^n_{ij}(1 - B^r_{ij})(I^r - C^r_D D^r_{ij} - C_T T^r_{ij}) \\ &+ \lambda^{nr}_{ij} R^{nr}_{ij}(1 - B^{nr}_{ij})(I^{nr} - C^{nr}_D D^{nr}_{ij} - C_T T^{nr}_{ij})\Big] \end{aligned} \tag{32}$$

B. IMPORTANCE ANALYSIS OF NETWORK COMPONENTS

The utility of network from satellite node v_i or link *e(i,j)* are considered as the importance of nodes and links.

1) IMPORTANCE OF SATELLITE NODES

$$I_{vi} = \begin{cases} U(g) - U(g - v_i), & v_i \in g \\ U(g + v_i) - U(g), & v_i \notin g \end{cases} \tag{33}$$

$$I_{vi} = \frac{I_{vi}}{\max(I_{vi})} \tag{34}$$

$U(g)$ is the initial utility of satellite networks, $U(g - v_i)$ is the utility of satellite network after removing node v_i, $max(I_{vi})$ is the maximum node importance of the network.

2) IMPORTANCE OF SATELLITE LINK

$$I_{e(i,j)} = \begin{cases} U(g) - U(g - e(i,j)), & e(i,j) \in g \\ U(g + e(i,j)) - U(g), & e(i,j) \notin g \end{cases} \tag{35}$$

$$I_{e(i,j)} = \frac{I_{e(i,j)}}{\max(I_{e(i,j)})} \tag{36}$$

U(g-e(i,j)) is the utility of satellite network after removing link *e(i,j)*, *max(Ie(i,j))* is the maximum link importance of the network.

C. CONSTRUCTION OF SURVIVABILITY FUNCTION BASED ON SERVICE UTILITY

For a network whose initial utility is U, strikes it nodes or links in the order of decreasing network efficiency. When the failure ratio of nodes or links reaches the collapse threshold $U \cdot T_h$, which is called node or link survivability, the greater the survivability of satellite networks, the better the survivability of satellite networks.

1) NATURAL FAILURE

Definition 1: When network utility decreases over time to an acceptable utility threshold, then time t_0 is survivability f_F^*.

$$f_F^* = t_0 = f^{-1}(T_h U) \tag{37}$$

The failure time of satellite nodes and three kinds links is exponential distribution [36] of parameters α_v and α_e, the reliability of satellite and link is

$$R_v(\tau) = e^{-\alpha_v \tau} \tag{38}$$
$$R_e(\tau) = e^{-\alpha_e \tau} \tag{39}$$

After network operation t_0, if the set of disjoint paths passed by task group W_{ij} is L_{ij}, then the reliability of successful transmission of the task is as follows

$$\begin{aligned} R_{ij} &= \prod_{v,e \in L_{ij}} R_v(t_0+\tau) R_e(t_0+\tau) \\ &= \prod_{v,e \in L_{ij}} e^{-\alpha_v(t_0+\tau)} e^{-\alpha_e(t_0+\tau)} \\ &= e^{-\alpha_v \sum\limits_{v \in L_{ij}} (t_0+\tau)} e^{-\alpha_e \sum\limits_{e \in L_{ij}} (t_0+\tau)} \\ &= e^{-\alpha_v(t_0+\tau) numL_{ij}} e^{-\alpha_e(t_0+\tau)(numL_{ij}+1)} \end{aligned} \tag{40}$$

Face fault-oriented network utility is

$$\begin{aligned} U_F &= \sum_{i=1}^{N}\sum_{j=1}^{N} [R_{ij}^r \lambda_{ij}^n (1-B_{ij}^r)(I^r - C_D^r D_{ij}^r - C_T T_{ij}^r) \\ &\quad + R_{ij}^{nr} \lambda_{ij}^{nr} (1-B_{ij}^{nr})(I^{nr} - C_D^{nr} D_{ij}^{nr} - C_T T_{ij}^{nr})] \\ &= \sum_{i=1}^{N}\sum_{j=1}^{N} [e^{-\alpha_v(t_0+\tau) numL_{ij}^r} e^{-\alpha_e(t_0+\tau)(numL_{ij}^r+1)} \\ &\quad \times \lambda_{ij}^n (1-B_{ij}^r)(I^r - C_D^r D_{ij}^r - C_T T_{ij}^r) \\ &\quad + e^{-\alpha_v(t_0+\tau) numL_{ij}^{nr}} e^{-\alpha_e(t_0+\tau)(numL_{ij}^{nr}+1)} \\ &\quad \times \lambda_{ij}^{nr} (1-B_{ij}^{nr})(I^{nr} - C_D^{nr} D_{ij}^{nr} - C_T T_{ij}^{nr})] \\ &= f(t_0) \end{aligned} \tag{41}$$

2) HUMAN ATTACKS

Definition 2: Satellite network human attack survivability is the normalized attack cost that reduces network utility to the threshold $T_h \cdot U$.

a: RANDOM ATTACK

The cost of attacking a satellite or link is c_v, c_e(generally $c_v > c_e$), when $c_v \to \infty$ or $c_e \to \infty$ denotes that only links or nodes can be attacked. d is node degree, refers to the number of one-hop neighbors a node has [7], [37], mean the total number of satellites that can be directly connected by a single hop of inter-satellite links. If attacking n_v satellite node and n_e links, the average node degree of the network is $\overline{d}$, then the probability of attacking each node and each side is $\frac{n_v}{N}$ and $\frac{n_e}{M-n_v\overline{d}}$ respectively, then the reliability of the satellite in random attack mode is $R_v = (1-\frac{n_v}{N})$, and the reliability of the side is $R_e = (1-\frac{n_e}{M-n_v\overline{d}})$, $n_e < M-n_v\overline{d}$, the utility in random attack mode is formula (42) which satisfy constraint (43). the normalized minimum attack payment cost minf_{ra}^* when network utility reaches the collapse threshold $T_h \cdot U$ is the network survivability under strategic attack.

$$\begin{aligned} U_{ra} &= \sum_{i=1}^{N}\sum_{j=1}^{N} \Big[R_{ij}^r \lambda_{ij}^n (1-B_{ij}^r)(I^r - C_D^r D_{ij}^r - C_T T_{ij}^r) \\ &\quad + R_{ij}^{nr} \lambda_{ij}^{nr} (1-B_{ij}^{nr})(I^{nr} - C_D^{nr} D_{ij}^{nr} - C_T T_{ij}^{nr}) \Big] \\ &= \sum_{i=1}^{N}\sum_{j=1}^{N} \Big[R_v^{numL_{ij}^r} R_e^{(numL_{ij}^r+1)} \lambda_{ij}^n (1-B_{ij}^r) \\ &\quad \times (I^r - C_D^r D_{ij}^r - C_T T_{ij}^r) \\ &\quad + R_v^{numL_{ij}^{nr}} R_e^{(numL_{ij}^{nr}+1)} \lambda_{ij}^{nr} (1-B_{ij}^{nr}) \\ &\quad \times (I^{nr} - C_D^{nr} D_{ij}^{nr} - C_T T_{ij}^{nr}) \Big] \\ &= \sum_{i=1}^{N}\sum_{j=1}^{N} \Big[(1-\frac{n_v}{N})^{numL_{ij}^r} (1-\frac{n_e}{M-n_v\overline{d}})^{(numL_{ij}^r+1)} \\ &\quad \times \lambda_{ij}^n (1-B_{ij}^r)(I^r - C_D^r D_{ij}^r - C_T T_{ij}^r) \\ &\quad + (1-\frac{n_v}{N})^{numL_{ij}^{nr}} (1-\frac{n_e}{M-n_v\overline{d}})^{(numL_{ij}^{nr}+1)} \\ &\quad \times \lambda_{ij}^{nr} (1-B_{ij}^{nr})(I^{nr} - C_D^{nr} D_{ij}^{nr} - C_T T_{ij}^{nr}) \Big] \end{aligned} \tag{42}$$

$$\begin{aligned} &\min f_{ra}^* = \frac{n_v c_v + n_v c_e}{N c_v} \\ &st.\ U_{ra} \le T_h U(g) \end{aligned} \tag{43}$$

b: CALCULATED ATTACK

Attacking nodes or links in a network in descending order according to network utility, the attacked node set and link set are V_s and V_e respectively, the normalized minimum attack payment cost minf_{ca}^* when network utility reaches the collapse threshold $T_h \cdot U$ is the network survivability under strategic attack.

$$\begin{aligned} &\min f_{ca}^* = \frac{n_v c_v + n_e c_e}{N c_v} \\ &st. \begin{cases} V_s \cap E_s = \emptyset \\ U(g) - U(g - V_s - E_s) \le T_h U(g) \end{cases} \end{aligned} \tag{44}$$

TABLE 2. List of satellite-related parameters.

Symbol	Parameter	Value
h_{sg}	Orbital height	780km
ψ	Phase difference between adjacent satellites	32.73°
h_{ss}	Inter-satellite distance	4000 km
m_1	User link full-duplex channel number	100
m_2	Inter-satellite link full-duplex channel number	20
m_3	Feed link full-duplex channel number	40
Br & Bs	Satellite buffer	50 packets
L	Packet length	100 bit
R_{up}	User link bandwidth	4.8Kbps
R_{ISL}	Inter-satellite link bandwidth	10 Mbps
R_{sg}	Feed link bandwidth	10 Mbps
R_{gp}	Processing speed of ground station	10 Mbps
$Rsp1$	Satellite processing speed for real-time service	1 Mbps
C	Link propagation speed	3×10^5km/s

Saturation attack [38] refers to invalid replication of data packets to be sent, which occupies the resources of satellite nodes and increases the throughput of satellite nodes until the satellite network reaches the threshold or cannot work. Setting the saturation attack intensity δ, the data packets created by satellite nodes are duplicated δ and sent to the corresponding nodes. Saturation attack intensity δ, which reaches the potential utility threshold $T_h \cdot U_P$, is regarded as the survivability of satellite network. The greater the saturation intensity, the stronger the survivability.

$$f_{ca}^{*} = \delta \quad \text{st.} \begin{cases} U_\delta(g) \le T_h U_P(g) \\ U_P(g) = \sum_{i=1}^{N} \delta\lambda_{i0} p_{nr} I_{nr} + \delta\lambda_{i0}(1 - p_{nr}) I_r \end{cases} \tag{45}$$

IV. CASE ANALYSIS

Establish a reference scenario to test the impact of different factors on network performance and network survivability. In this scenario, there are six satellites and a ground station located in Beijing (40°N, 116°E). The parameters are as follows: packet length $L = 100$ bit, link propagation speed C is 3×10^8m/s, user link channel number, inter-satellite link channel number, feed link channel number are 100, 20, 40, voice service transmission rate is R = 4.8 kbps, feed link up and down. Link transmission rate is 10 Mbps, ISL transmission rate is 10 Mbps, satellite buffer $Br = Bs = 50$ packets, and the bandwidth of the regional gateway station is 10 Mbps. Referring to Iridium satellite system, the length of user link and feeder link is 780 km, and the length of inter-satellite link, that is, the average distance between satellites, is about 4000 km. Payments for real-time and non-real-time services are 2 and 0.5 respectively, the upper limit of delay is 1 s and 10 s respectively, and the unit service time cost is 1.

A. NETWORK PERFORMANCE AND UTILITY ANALYSIS

In Figure 7, p_{nr} represents the proportion of non-real-time traffic, $Rsp2$ represents the processing speed of satellite for non-real-time services, Br represents the capacity of satellite

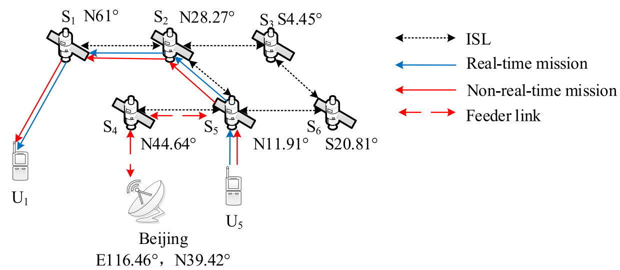

FIGURE 6. Topology of LEO satellite communication network.

receiving buffer. The non-real-time services packet is transmitted transparently by the visual satellite through the satellite network to the landing ground station, which increases the upper and lower satellite-ground delay, average delay increases with p_{nr} as shown in Fig. 7(a). When the processing time $Tsp2$ of layer 1 is small, the occupancy of on-board processor resources by real-time services is the main factor of satellite node congestion. So, as shown in Fig. 7(b), The higher the proportion of non-real-time services is, the greater the throughput. In Fig. 7(c), with the increase of the $Tsp2$, the maximum throughput moves to the right gradually, while the network utility increases first and then decreases with the increase of the average delay. This shows that for different processing time (such as packet length and encoding mode), the optimal network utility requires different proportion of real-time non-real-time service. The packet is stored in the common waiting queue or buffer when the satellite is blocked in all directions. In Fig. 7(d), the network throughput and blocking rate tend to a constant [39] with the increase of buffer due to limited on-board resources, while the delay increases gradually, and the network utility decreases slowly when it reaches a certain upper limit. Therefore, the reduction of blocking rate is partly at the cost of increasing delay [30], buffer are not the bigger the better.

B. IMPORTANCE ANALYSIS

As shown in figure 8(a) and figure 8(c), the importance of satellite nodes and links will also be affected by different service arrival rates due to the population density of satellite coverage in different latitudes and longitudes. Satellite node v_2, v_4 and v_5 with higher population density is the key node affect network effectiveness, while the importance of link e(1,2) in Non-Hotspot area decrease. As shown in figure 8(b) and figure 8(d), if the traffic of each satellite is evenly distributed, the importance of satellite v_4 and feed link e(4,7) connected with the ground station increases with the increase of non-real-time traffic, while the importance of satellite v_2, v_3 and v_6 decreases with the increase of non-real-time traffic. From the perspective of graph theory, compared with satellite v_5, satellite v_5 and link e(4,5) are the most important transit satellites for non-real-time service processing, although the node degree and point-to-point number of satellite v_5 are the same. It's necessary to evaluate the importance of satellite network nodes and links in terms of service type, traffic and service utility.

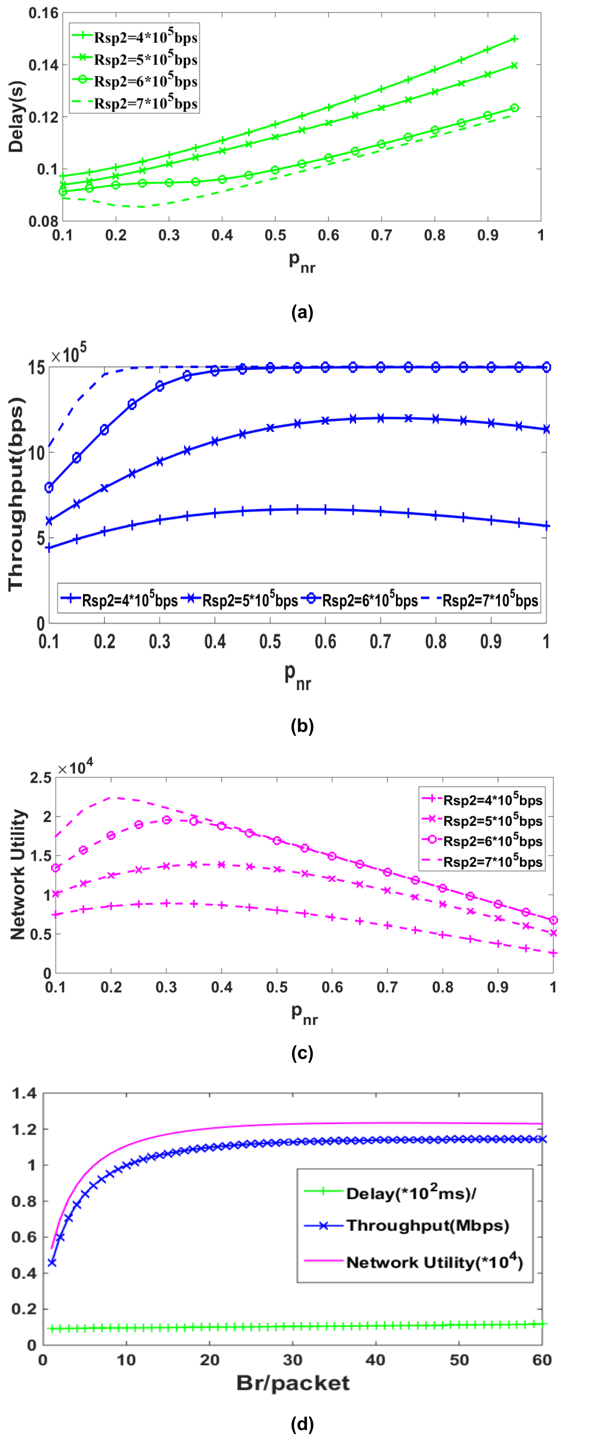

FIGURE 7. **(a) The variation of delay with non-real-time mission proportion and satellite processing rate. (b) The variation of throughput with non-real-time mission proportion and satellite processing rate. (c) The variation of utility with non-real-time mission proportion and satellite processing rate. (d) The variation of delay, throughput and utility with buffer capacity.**

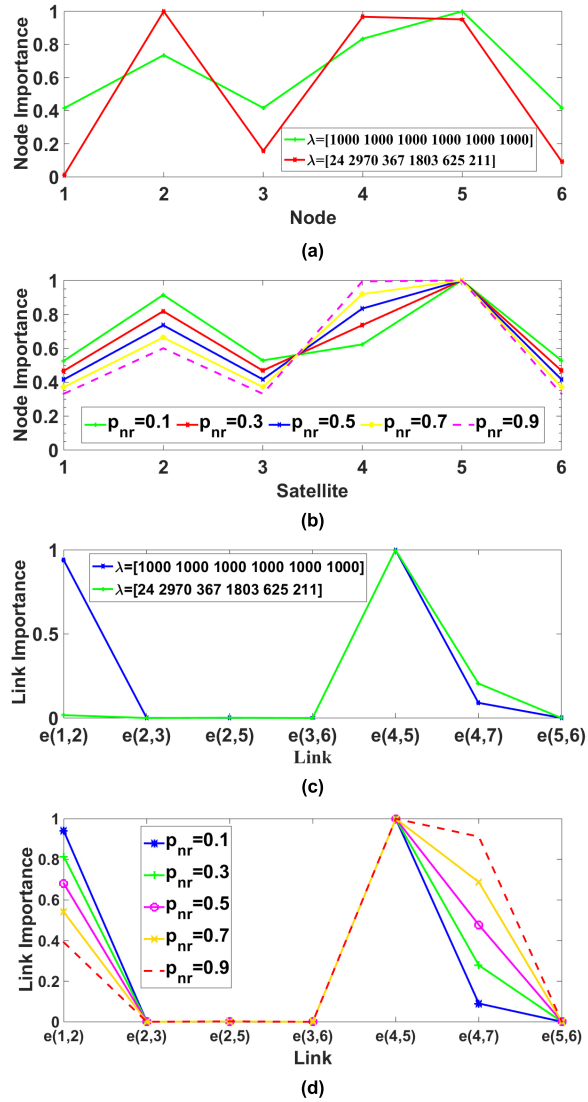

FIGURE 8. **(a) The rule of I_v (node importance) changing with λ. (b) The rule of I_v (node importance) changing with p_{nr}. (c) The rule of I_e (Link Importance) changing with λ. (d) The rule of I_e (link importance) changing with p_{nr}.**

C. SURVIVABILITY

Figure 9(a) shows the survivability of LEO satellite networks for different failure modes. The greater the failure arrival rate, the faster the network utility decreases; assuming that the satellite lifetime is guaranteed at a probability of 0.95 for five years when $\alpha = 3.2529993912{*}10^{-10}$, the satellite network needs to run for 3790 days, the network utility decreases by half; the impact of node arrival rate and edge arrival rate on the network effectiveness is different, and the same failure arrival rate; at the same time, the link failure makes the network decline faster, the survivability of satellite network against node failures is lower than link failures. As shown in figure 9(b), the more nodes or links were attacked randomly, the more the network utility will decrease; the remaining network utility will be less than half of the initial network utility except for less than three links or less than two satellites were attacked; when $c_v = c_e$, there are two ways to reduce the network utility to the threshold ($n_v = 1, n_e = 1$) and ($n_v = 2$), $\min f_{ra}^{*} = 0.3333$; when $c_v = 2\ c_e$, there are two ways to reduce the network utility to the threshold ($n_v = 1, n_e = 1$)

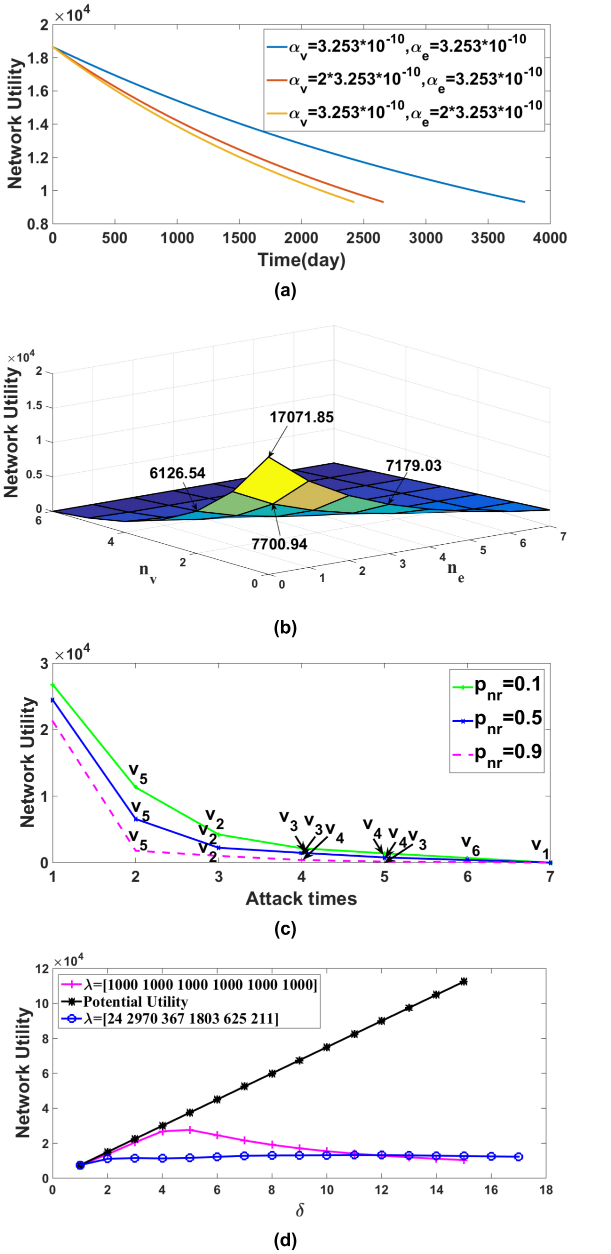

FIGURE 9. (a) Natural failure survivability. (b) Random attack survivability. (c) Calculated attack survivability. (d) Saturation attack survivability.

and ($n_e = 3$), $\min f_{ra}^* = 0.25$; when $c_v > 2c_e$, there is only one way to reduce the network utility to the threshold (ne $=$ 3). From figure 9(c), the LEO satellite network is vulnerable to deliberate attacks, and attack node 5 can can halve network utility, $\min f_{ca}^* = 0.1667$; after attacking node 5 and node 2 in turn, node 4 should be attacked priority if the proportion of real-time traffic p_{nr} is high, otherwise node 3. The actual utility of the network keeps approaching the potential utility at the initial stage of the increase of saturated attack intensity δ in figure 9(d); when δ exceeds a certain value, the actual utility of the network keeps away from the potential utility; when the network load distribution is balanced, the network utility decreases relatively slowly in the initial stage; when δ exceeds a certain value, all nodes in the network with balanced load distribution are in congestion state, and some satellite nodes in Non-Hotspot areas with unbalanced load distribution still have idle channels, which makes the overall network utility the highest.

V. SUMMARY

The communication performance of resource-constrained LEO satellite system is studied by using queuing birth and death principle, and the network utility function is constructed by using network efficiency to further study the survivability of LEO satellite networks in four scenarios. Simulation results show that the network utility maximization needs to consider how to manage and allocate limited satellite resources and different types of services, this proposed survivability method can provide some reference for network attack and defense, backup strategy, establishment of Ground Station and mobile coverage planning.

APPENDIX

We present major steps in computing the reliability function of the queuing birth and death model of section II:

A. QUEUING LOSS M/M/m/m MODEL FOR ACCESS TO LOW EARTH ORBIT SATELLITE NETWORK

According to Figure 2, the equilibrium equation of the system is

$$\begin{cases} \sum_{n=0}^{m_1} p_n = 1 \\ \lambda_{ui} p_{n-1} = n\mu_{upi} p_n, \quad n = 1, 2, \cdots, m_1 \\ p_n = p_0 (\frac{\lambda_{ui}}{\mu_{upi}})^n \frac{1}{n!}, \quad n = 1, 2, \cdots, m_1 \end{cases}$$

We solve the above equation and obtain:

$$p_0 = [\sum_{n=0}^{m_1} (\frac{\lambda_{ui}}{\mu_{upi}})^n \frac{1}{n!}]^{-1}$$

$$p_n = \frac{(\rho_{upi})^n}{n!} P_0$$

Access blocking rate is the probability that there is no idle channel in m1 user link during call request access stage, that is to say, there is no idle channel in m_1 user link.

$$P_{ci}^{block} = P_{m_1} = \frac{(\frac{\lambda_{ui}}{\mu_{upi}})^{m_1}}{m_1!} \Bigg/ \sum_{n=0}^{m_1} \frac{(\frac{\lambda_{ui}}{\mu_{upi}})^n}{n!}$$

Effective arrival rate of user terminals transmitted to satellite processing front-end via m1 channel.

$$\begin{aligned} \lambda_{usi} &= n_s \left[(1 - P_{ci}^{block}) \right] \lambda_{ui} \\ &= n_s \lambda_{ui} \left[1 - \frac{(\frac{\lambda_{ui}}{\mu_{upi}})^{m_1}}{m_1!} \Bigg/ \sum_{n=0}^{m_1} \frac{(\frac{\lambda_{ui}}{\mu_{upi}})^n}{n!} \right] \end{aligned}$$

B. M/M/1/m QUEUING MODEL FOR LEO SATELLITE SIGNAL PROCESSING

State transition equation is

$$\begin{cases} \mu_{spi}p_{n-1} = \lambda_{si}p_0, & n = 0 \\ \mu_{spi}p_{n+1} + \lambda_{si}p_{n-1} = (\lambda_{si} + \mu_{spi})p_n, & n \le B_r \\ \mu_{spi}p_n = \lambda_{si}p_{n-1}, & n = B_r + 1 \end{cases}$$

$$\rho_{spi} = \frac{\lambda_{si}}{\mu_{spi}}$$

$$P_0 = \begin{cases} \frac{1-\rho_{spi}}{1-\rho_{spi}^{B_r+1}}, & \rho_{spi} \ne 1 \\ \frac{1}{B_r+1}, & \rho_{spi} = 1 \end{cases}$$

$$P_n = \frac{1-\rho_{spi}}{1-\rho_{spi}^{n+1}}\rho_{spi}^n, \quad n = 1, 2, \cdots, B_r$$

$$P_0 = \begin{cases} \frac{1-\rho_{spi}}{1-\rho_{spi}^{B_r+2}}, & \rho_{spi} \ne 1 \\ \frac{1}{B_r+2}, & \rho_{spi} = 1 \end{cases}$$

$$P_n = \frac{1-\rho_{spi}}{1-\rho_{spi}^{n+1}}\rho_{spi}^n, \quad n = 1, 2, \cdots, B_r + 1$$

Receiving buffer, i.e. satellite input blocking rate is

$$P_{bri}^{block} = P_{B_r+1} = \frac{1-\rho_{spi}}{1-\rho_{spi}{}^{B_r+2}}\rho_{spi}{}^{B_r+1}$$

The effective arrival rate of the user terminal processed by the processor and transmitted to the satellite transmission buffer is achieved

$$\lambda_{spi} = \lambda_{si}(1 - P_{B_r+1}) = (1 - P_{bri}^{loss})\lambda_{si}$$

The queue length is

$$L_{spi} = \sum_{n=0}^{B_r+1} nP_n = \begin{cases} \frac{\rho_{spi}}{1-\rho_{spi}} - \frac{(N_{br}+2)\rho_{spi}{}^{B_r+2}}{1-\rho_{spi}{}^{B_r+2}}, & \rho_{spi} \ne 1 \\ \frac{B_r+1}{2}, & \rho_{spi} = 1 \end{cases}$$

The average queue length of the receiving buffer is

$$L_{q^{spi}} = \sum_{n=0}^{B_r+1} (n-1)P_n = \begin{cases} \frac{\rho_{spi}}{1-\rho_{spi}} - \frac{(B_r+1)\rho_{spi}{}^{B_r+1}}{1-\rho_{spi}{}^{B_r+2}}, & \rho_{spi} \ne 1 \\ \frac{B_r \cdot (B_r+1)}{2(B_r+2)}, & \rho_{spi} = 1 \end{cases}$$

Average waiting time in processing phase is

$$w_{q^{sp}} = \frac{L_{q^{sp}}}{\lambda_{sp}}$$

$$T_{sp}(y) = \frac{1}{\mu_{sp}(y)}, \quad y = 1, 2$$

Satellite processing time for different services is

$$T_{spi} = \frac{1}{\mu_{spi}}$$

Average sojourn time is

$$W_{sp} = w_{q^{sp}} + \frac{1}{\mu_{sp}}$$

C. M/M/s/k QUEUING MODEL FOR LEO SATELLITE SIGNAL TRANSMISSION

If the set of neighbor nodes of s_i is set Λ_i and the satellite is within the visual range of the gateway station, the output grouping satisfies the following formula

$$\lambda_{s_i} = \lambda_{s_iu_i} + \sum_{j\in\Lambda_i}\lambda_{s_is_j} + \lambda_{s_igk}$$

When the total queue length of the transmit buffer is longer than the transmit buffer capacity Bs, the channel will be congested.

$$P_n = \begin{cases} \frac{\rho_{ss_i}{}^n}{n!}P_0, & n = 0, 1, \cdots, m_2 \\ \frac{\rho_{ss_i}{}^n}{m_2!m_2{}^{n-m_2}}P_0, & m_2 < n \le k \end{cases}$$

Channel idle probability

$$P_0 = \begin{cases} \left[\sum_{n=0}^{m_2-1}\frac{\rho_{ss_i}{}^n}{n!} + \frac{\rho_{ss_i}{}^{m_2}(1-\rho'_{ss_i}{}^{B_{ss}+1})}{m_2!(1-\rho'_{ss_i})}\right]^{-1}, & \rho'_{ss_i} \ne 1 \\ \left[\sum_{n=0}^{m_2-1}\frac{\rho_{ss_i}{}^n}{n!} + \frac{\rho_{ss_i}{}^{m_2}(B_{ss}+1)}{m_2!}\right]^{-1}, & \rho'_{ss_i} = 1 \end{cases}$$

The average queue length is

$$L_q^{ss} = \sum_{n=m_2}^{m_2+B_{ss}}(n-m_2)P_n = \begin{cases} \frac{P_0\rho_{ss_i}{}^{m_2}\rho_{ss_i}{}'}{m_2!(1-\rho_s)^2}\left[1-\rho'_{ss_i}{}^{B_{ss}+1} - (1-\rho'_{ss_i})(B_{ss}+1)\rho'_{ss_i}{}^{B_{ss}}\right], & \rho'_{ss_i} \ne 1 \\ \frac{P_0\rho_{ss_i}{}^{m_2}B_{ss}(B_{ss}+1)}{2m_2!}, & \rho'_{ss_i} = 1 \end{cases}$$

The queue length is

$$L^{ss} = L_q^{ss} + m_2 + P_0\sum_{n=0}^{m_2-1}\frac{(n-m_2)\rho_{ss_i}{}^n}{n!}$$

Queuing delay of send buffer is

$$w_{q^{s_is_j}} = \frac{L_q^{s_is_j}}{\lambda_{es_is_j}}$$

ISI transmission delay

$$T_{ISL} = \frac{1}{\mu_{ISL}}$$

Similarly, the queuing delay and congestion rate of satellite-to-ground user links are consistent with the above methods. Effective achievement rate of group is

$$\lambda_{es_is_j} = \lambda_{s_is_j}(1 - P_k) = \lambda_{ssi}p_{ij}(1 - \frac{{\rho_{s_is_j}}^k}{m_2!m_2^{B_s}}P_0)$$

D. GROUND STATION M/M/1 QUEUING MODEL FOR ORIENTED NON-REAL-TIME SERVICE

State transition equation is

$$\lambda_{gpi}p_n = \mu_{gpi}p_{n+1}$$
$$P_n = {\rho_{gpi}}^n(1 - \rho_{gpi}) \quad n = 0, 1, 2, \cdots$$

Using Little theorem, the average waiting delay of each user group at the ground station is

$$w_{q^{gp}} = \frac{\rho_{gpi}}{\mu_{gpi}(1 - \rho_{gpi})}$$

Processing delay is

$$T_{gp} = \frac{1}{\mu_{gp}}$$

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