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RESEARCH ARTICLE

The operational readiness factor of satellite communication networks

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Abstract
Objectives. The most important distinguishing feature of satellite communication networks (SCNs) is topology, which consolidates the scheme for combining nodes and communication channels into a single structure and largely determines the main characteristics of communication systems. The following topologies are used in SCNs: fully connected, tree-like, ring-shaped, and radial ("star" type). The topology can be changed depending on the tasks being solved; for example, to ensure high reliability rates. The most frequently used indicator characterizing the reliability of communication networks is the readiness factor. Considering the SCN as a complex recoverable system, it is advisable to analyze the operational readiness factor along with the readiness factor. This paper investigates the influence of the network topology on the reliability of the SCN.
Methods. Queuing theory was used to analyze the flow of events, that is, the flow of failures and recoveries.
Results. Assuming that the exponential Mean Time Between Failures (MTBF) model can be used for a central node with a radial network topology, the time dependences of the operational readiness factor were obtained. The reliability of networks with ring and radial topology was compared in terms of the operational readiness factor.
Conclusions. To achieve a higher reliability, it is necessary to use an SCN with a radial structure. For example, on a time interval of 12000 h, the operational readiness factor of a two-node SCN with a radial structure is 0.9, and for an SCN with a ring topology with the number of nodes 2, 3, 4, it is 0.7, 0.59, and 0.5, respectively. The study also showed that radial topology is more efficient even with less reliable nodes, that is, with higher failure rates. The advantage of a radial network topology increases as the number of nodes increases. However, in an SCN with a radial topology, failure of the central unit leads to complete degradation of the entire system.

Keywords: reliability, satellite communication, communication network, network topology, operational readiness factor

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НАУЧНАЯ СТАТЬЯ

Коэффициент оперативной готовности спутниковых сетей связи

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Резюме
Цели. Важнейшим отличительным признаком спутниковых сетей связи (ССС) является топология, характеризующая схему объединения узлов и каналов связи в единую структуру и во многом определяющая основные характеристики систем связи. В ССС используются следующие топологии: полносвязная, древовидная, кольцевая и радиальная (типа «звезда»). Топологию можно изменять в зависимости от решаемых задач, например, для обеспечения высоких показателей надежности. Общим, наиболее часто применяемым показателем, характеризующим надежность сетей связи, является коэффициент готовности. Рассматривая ССС как сложную восстанавливаемую систему, целесообразно наряду с коэффициентом готовности анализировать коэффициент оперативной готовности. В работе исследуется влияние топологии сети на надежность ССС.
Методы. Используется теория массового обслуживания для анализа потока событий, то есть потока отказов и восстановлений.
Результаты. Полагая, что для центрального узла при радиальной топологии сети можно использовать экспоненциальную модель наработки до отказа, получены зависимости коэффициента оперативной готовности от времени. Выполнено сравнение надежности сетей с кольцевой и радиальной топологией по коэффициенту оперативной готовности.
Выводы. Показано, что для достижения более высокой надежности необходимо использовать ССС с радиальной структурой. Например, на интервале времени 12000 часов коэффициент оперативной готовности двухузловой ССС с радиальной структурой равен 0.9, а для ССС с кольцевой топологией при количестве узлов 2, 3, 4 соответственно равен 0.7, 0.59, 0.5. Исследование также показало, что радиальная топология эффективнее даже при менее надежных узлах, то есть при увеличении интенсивности отказов. Преимущество радиальной топологии сети возрастает по мере увеличения числа узлов. Однако в ССС с радиальной топологией выход из строя центрального узла приводит к полной деградации всей системы.

Ключевые слова: надежность, спутниковая связь, сеть связи, топология сети, коэффициент оперативной готовности

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INTRODUCTION

It is extremely difficult to increase the reliability of satellite communication networks (SCNs) during operation. This is due to the fact that expected reliability is mainly based on the design of networks and the manufacture of equipment. During operation, reliability only decreases [1, 2]. The rate of decrease in reliability depends on the operating methods, the qualifications of the maintenance personnel, and the operating conditions.

There are effective methods to improve the reliability of communication networks:

- redundancy [3, 4],
- simplification of the system,
- use of the most reliable elements,
- standardization and unification of elements and assemblies,
- built-in checks,
- automation of checks.

The effectiveness of these methods lies in that they allow building reliable systems from unreliable elements. These techniques can reduce system failure rates, decrease mean time to recovery, and increase the system's duration of continuous operation. The issues of assessing the reliability of communication networks and analyzing the effectiveness of methods for increasing reliability are relevant for INFOCOM communication networks [5–9].

The general indicator characterizing the reliability of any equipment (including communication networks) is the readiness factor—the limit of the instantaneous readiness factor when the considered moment of time tends to infinity. The instantaneous readiness factor (readiness function) is the probability that an object will be in a working state at a given time[1]. The readiness factor is one of the main reliability indicators of the communication network [10]. When formulating the requirements for the reliability indicators of communication networks, the readiness factor is usually standardized [11].

Considering the SCN as a complex recoverable system, it is advisable, along with the readiness factor, to analyze the operational readiness factor—the probability that the object will be in a working state at an arbitrary point in time, except for the scheduled periods during which the use of the object for its intended purpose is not provided, and, starting from this moment in time, will work flawlessly for a specified time interval[1].

The operational readiness factor K_{or} is determined by the formula [1]:

$$K_{\mathrm{or}}(t) = K_{\mathrm{r}} P(t), \tag{1}$$

where K_{r} is the readiness factor; $P(t)$ is the probability of failure-free operation of the system at time t, provided that the system is ready for operation at an arbitrary moment in time.

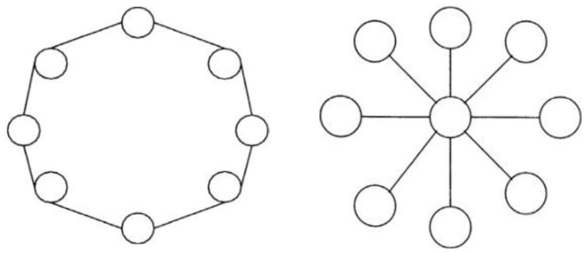
The most important distinguishing feature of a communication network is the network topology[2], the properties of which can be changed during the operation depending on the tasks being solved, for example, ensuring high reliability indicators [12]. The following network topologies are used in the SCN [13].

Fully coupled topology provides the highest reliability of the SCN functioning, since in case of a dedicated communication channel failure, information can be transmitted along bypass paths through intermediate nodes. However, the implementation of such technology requires the organization of direct communication among all nodes, which leads to an increase in the cost of SCN.

The tree topology is characterized by low reliability, since the failure of even one of the communication channels can lead to separation of the network into two isolated subnets. Therefore, the most commonly used topologies are the ring and radial topologies.

The ring topology (Fig. 1a), like the tree topology, has low reliability, since the failure of any one channel leads to a network failure. However, redundancy can improve the reliability of a ring topology by using multiple rings.

The radial topology ("star" type) (Fig. 1b) has a fairly high reliability compared to other topologies, since the peripheral nodes operate independently of each other. The failure of the central node leads to the failure of the entire network. Therefore, it is necessary to use the redundancy of this node.



(a) (b)

Fig. 1. Main SCN topologies: (a) ring, (b) radial ("star")

If a node or communication channel fails, the system should automatically recover in a set (usually very short) time. In this case, one of the backup routes of data delivery from the sender to the recipient should be used. Redundancy of communication channels allows you to minimize delays in data transmission, while at the same time significantly increase the values of the system's MTBF parameters.

Let us compare the reliability of the ring and radial topologies in terms of the operational readiness factor.

DETERMINATION OF THE OPERATIONAL READINESS FACTOR FOR THE "STAR" STRUCTURE

An SCN with radial topology is operational if at least one peripheral node is working while the central node is working. If all nodes or the central node fail, the network is inoperative.

As an example of a star structure SCN, consider a network consisting of a central node and 2 peripheral nodes. Then the operational readiness factor is determined according to the basic structural diagram of reliability by the following expression [1]:

[1] GOST 27.002–2015. *Nadezhnost' v tekhnike. Terminy i opredeleniya* (*Dependability in technics. Terms and definitions*). Moscow: Standartinform; 2016. 30 p. (in Russ.).

[2] Gol'dshtein B.S., Sokolov N.A., Yanovskii G.G. *Communication networks:* textbook for universities. St. Petersburg: BHV-Petersburg; 2010. 400 p. (in Russ.). ISBN: 978-5-9775-0474-4

$$K_{\text{or star}}(t) = \frac{2T_f}{T_r + 2T_f} P_{cn}(t)[2e^{-\lambda t} - e^{-2\lambda t}], \quad (2)$$

where $T_f = \frac{1}{\lambda}$ is the mean time between failures of the peripheral unit; $T_r = \frac{1}{\mu}$ is the average recovery time of the peripheral node; $P_{cn}(t)$ is the probability of failure-free operation of the central node; λ is the rate of failure of the peripheral node; μ is the rate of recovery of the peripheral node.

Assuming that an exponential model of MTBF can be used for the central node, we will transform expression (2) to the following form:

$$K_{\text{or star}}(t) = \frac{2T_f}{T_r + 2T_f} e^{-\lambda_{cn} t}[2e^{-\lambda t} - e^{-2\lambda t}], \quad (3)$$

where λ_{cn} is the failure rate of the central node. Usually, the central node is more reliable than the peripheral nodes, so we set $\lambda_{cn} = \lambda/2$.

The dependencies of $K_{\text{star}}(t)$ for $\mu = 0.04$ and different values of λ ($1.5 \cdot 10^{-5}$, $2.5 \cdot 10^{-5}$, and $5 \cdot 10^{-5}$) are shown in Fig. 2.

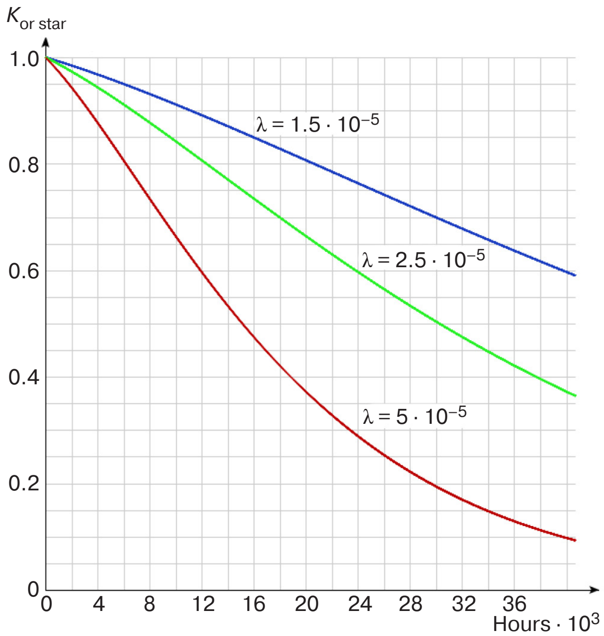


Fig. 2. Operational readiness factor of an SCN with radial topology

DETERMINATION OF THE OPERATIONAL READINESS FACTOR WITH A RING TOPOLOGY

An SCN with a ring topology is operational if all nodes are operational, which corresponds to a sequential reliability model. If one of the nodes fails, the network is inoperative.

The operational readiness factor of the SCN with the "ring" structure is determined by the following expression [1]:

$$K_{\text{or ring}}(t) = \frac{T_f}{T_r + T_f} e^{-n\lambda t}, \quad (4)$$

where n is the number of nodes.

The dependencies $K_{\text{or ring}}(t)$ for $\lambda = 5 \cdot 10^{-5}$, $\mu = 0.04$ and the number of nodes $n = 2, 3, 4$ are shown in Fig. 3.

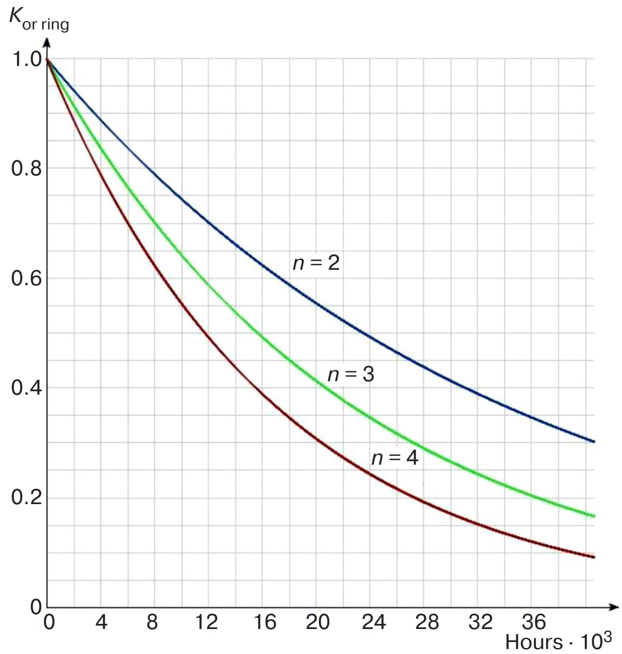


Fig. 3. Operational readiness factor of an SCN with ring topology

Figures 2 and 3 show that to achieve higher reliability, it is necessary to use an SCN with a "star" topology. For example, at $t = 12000$ h, the operational readiness factor of a network with a radial topology is 0.9, and for an SCN with a ring topology at $n = 2, 3$, and 4, it is 0.7, 0.59, and 0.5, respectively.

CONCLUSIONS

The operational readiness factor determines the probability that the network is in operational state during the given time interval starting from a certain moment in time. The comparison of the ring and radial SCN topologies made in terms of the operational readiness factor showed that the radial topology, even with less reliable nodes, features for any time interval higher reliability than that of the ring topology. The advantage of a radial network topology increases as the number of nodes increases.

Authors' contribution. All authors equally contributed to the research work.

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