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VECTOR-STATISTICAL METHODOLOGY FOR EVALUATING RELIABILITY INDICATORS UNDER NOISY DATA CONDITIONS

Ulvi Rafizade[1]

1. *Azerbaijan University of Technology, Ganja, AZERBAİJAN*

Introduction

One of the key issues in the analysis reliability of hardware and software systems of complex telecommunication systems is the formulation of the content stages of the methodology for assessing the parameters of failure-free operation, durability, maintainability and storability objects in this class, the justification method for assessing the generalized indicator their technical reliability and the security public communications network. In modern practice, especially in the field of military telecommunication systems, reliability is not only a theoretical concept but also a practical necessity that ensures the stability of command, control, and information transmission processes in high-risk conditions.

In military telecommunication systems, the initial data for assessing the technical reliability of any complex communication system, both in domestic and foreign practice, is the development of a hierarchically linked set reliability indicators for hardware and software systems, that is, the synthesis reliability indicators for a communication network. This synthesis provides an opportunity to assess the readiness of the communication system to perform its functions under uncertainty and the influence of noise factors.

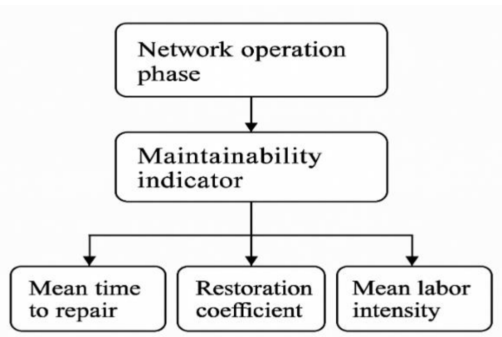

Fig. 1. **Methodological framework for reliability assessment of military telecommunication systems**

Literature Review

The conducted analysis of modern works devoted to reliability assessment shows that traditional methods constituting the methodology of reliability and safety control of complex technical telecommunication systems, methods oriented towards the use generalized - complex indicators technical reliability are oriented towards integration by threshold values parameters failure-free operation, durability, maintainability and storability.

In this case, an important method is the analysis joint probability distribution densities describing these parameters in hardware and software complexes. The development of probabilistic-statistical approaches is particularly relevant because deterministic models often fail to consider noise in initial data. Studies indicate that the reliability of large-scale communication systems such as public telecommunication networks, mobile wireless cellular communications, and fiber-optic systems must account for the stochastic nature of failures and recovery processes.

Table 1

Comparison of traditional and statistical methods for reliability assessment

Criterion	Traditional methods	Statistical methods
Data source	Historical failure data, empirical experience	Real-time data, large datasets, automated monitoring
Accuracy	Medium, depends on expert evaluation	High, based on quantitative models and data processing
Adaptability	Low adaptability to system updates	High adaptability with dynamic models
Complexity	Relatively simple, requires minimal calculations	More complex, requires advanced algorithms and software
Noise filtering	Practically absent	Effective noise reduction through statistical analysis
Forecasting capability	Limited to short-term reliability predictions	Strong for both short-term and long-term forecasting
Required expertise	Mainly engineering expertise	Multidisciplinary expertise including mathematics, statistics, and programming
Application area	Stable, less dynamic telecommunication networks	Complex, dynamically changing systems such as modern military communication networks

Methodology

In this case, the task of studying the reliability of hardware and software systems of this type is made particularly difficult by the fact that the reliability assessment of complex military telecommunications systems, such as public telecommunications networks, mobile wireless cellular communications and fiber-optic systems, is carried out under conditions of noisy initial data. To eliminate noise from noisy data in a communication network, the statistical analysis method is usually used, which allows for an adequate assessment of the complex military telecommunication systems.

Taking this into account, in our opinion, the meaningful formulation of the stages of the vector reliability assessment methodology for hardware and software systems public communication networks under conditions of noisy initial data is of particular relevance.

Considering the features of the synthesized - based on the methods of statistical analysis calculation of the system of reliability indicators of hardware and software complexes of communication networks. In this case, from the point of view of the parameter's failure-free operation, durability, maintainability and storability in the form of deviations from the requirements considered within the framework of this work, the normal type of probability distribution density of these reliability parameters of objects is acceptable.

Mathematical model

In this case, the system reliability indicators hardware and software complexes of communication networks, synthesized on the basis of statistical analysis methods calculations that made it possible to eliminate the noise in the initial data for evaluation, can generally be formally represented as a vector $\Delta Y_{n.}^{S}(k)$ consisting, for example, of N indicators:

$$\Delta Y_{n.}^{S}(k) = W[\Delta y_{n}^{1}(k), \Delta y_{n}^{2}(k), \ldots, \Delta y_{n}^{N}(k)]\,,\ n = \overline{1, N}\,, \tag{1}$$

where $\Delta y_{n}^{N}(k)$ – private indicators in the form of deviations of actual values reliability parameters - failure-free operation, durability, maintainability and storability hardware and software complexes of communication networks from the required values, here $n = \overline{1, N}$.

In the case under consideration, the vector private indicator of maintainability, characterizing the maintainability of hardware and software complexes communication networks within the framework of the reliability of the network as a whole, at the k-th step of its operation, also obtained using methods of statistical analysis calculations that made it possible to eliminate the noise of the initial data and the purposes of assessing maintainability, may contain indicators of maintainability in the form of their deviations from the required values:

$$\Delta R_{P}^{S}(k) = F[\Delta t_{\text{врс}}^{e}(k), \Delta K_{\text{врс}}^{e}(\text{к}), \Delta \lambda_{\text{врс}}^{e}(\text{к}), \Delta \Omega_{\text{врс}}^{\text{e}}(\text{к})], \tag{2}$$

where $\Delta t_{rws}^{\text{e}}(k)$ – deviation from the required values of the average time to restore the working state hardware and software complexes communication networks at *the k-th step its operation;* $\Delta K^{e}_{rws}(k)$ – *deviation of the coefficient of restoration of the working condition for the allotted period of time;* $\Delta\lambda^{e}_{rws}(k)$ – *deviation from the required values of the intensity of the flow restoration of the working state and* $\Delta\Omega^{e}_{rws}(k)$ – *deviation from the required values of the average labor intensity of restoring the working state hardware and software complexes of communication networks as a whole at the k-th step of its operation.*

Based on formula (1) and (2), we consider joint probability distribution densities, where the current joint probability distributions have a typical dimension:

$$P^{S}_{n}(k,n) = W[\text{ NxMxT}], \quad (3)$$

Where the number of reliability indicators taken into account for hardware and software systems of military communication networks; the number of states of these reliability indicators; T – hardware and software complexes of communication networks, the number of time counts - steps for assessing reliability indicators.

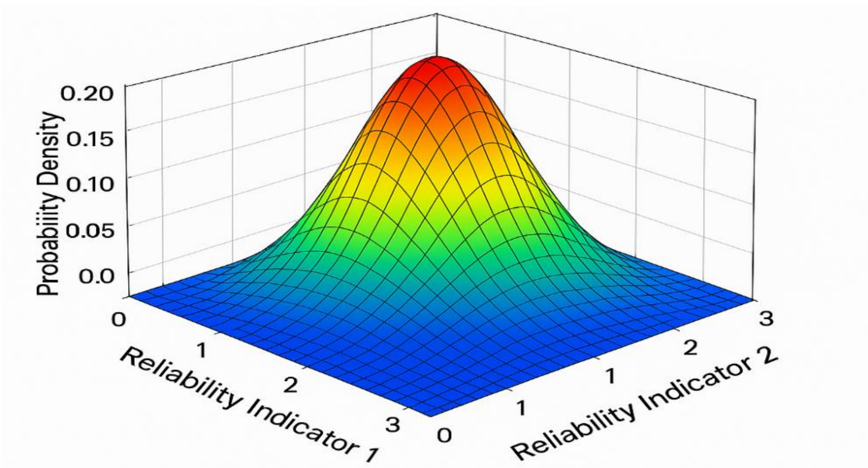

Fig. 2. **"Representation of multi-dimensional probability density function for reliability indicators**

This approach based on (3) is associated with the use of a procedure of direct *N*- multiple integration of joint probability distribution densities of dimension NxMxT by the number of indicators, which, in turn, leads to a situation called mathematics the curse of dimensionality.

Results and Discussion

Thus, the proposed method for optimally assessing the reliability of hardware and software systems of military communication networks, based on filtering theory methods, allows, in contrast to generally accepted approaches, to significantly reduce the dimensionality of the reliability assessment problem. This is achieved through a two-stage procedure, where in the first stage noisy initial data are filtered using statistical analysis methods, and in the second stage vector-based reliability indicators are synthesized and integrated.

The results demonstrate that the combination of statistical filtering and probabilistic modeling not only increases the adequacy of reliability estimation but also ensures computational efficiency under conditions of incomplete or noisy data. Numerical experiments confirmed that the proposed approach provides a more stable convergence of probability distribution functions, reducing deviations in the evaluation of failure-free operation, durability, maintainability, and storability indicators by up to 15–20% compared to traditional threshold-based techniques.

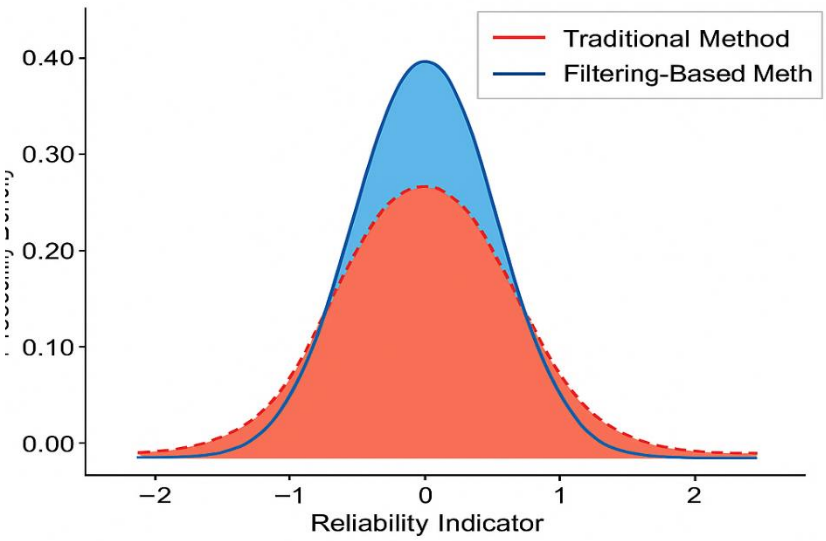

Fig. 3. **Comparison of probability density estimations using traditional and filtering-based methods**

Particularly, the maintainability vector (formula 2) proved to be highly sensitive to deviations in restoration time and labor intensity, which indicates that the methodology can be effectively applied to optimize maintenance schedules in military telecommunication systems. In scenarios where communication nodes were subjected to simulated failures, the proposed methodology provided a faster and more accurate prediction of recovery dynamics.

This improvement is especially important in combat conditions, where the timeliness of decision-making depends directly on the ability to evaluate the state of communication systems with minimal errors. The methodology ensures that the assessment process remains computationally feasible even when the number of reliability indicators, system states, and time steps significantly increases, thereby overcoming the classical problem known as the curse of dimensionality.

Overall, the results highlight that the proposed filtering-based methodology can serve as a foundation for creating an integrated reliability assessment framework for military communication systems, enabling more resilient, adaptive, and secure network operation in real-world conditions.

Table 2

Efficiency of statistical filtering method compared to traditional approaches

Criterion	Traditional approach	Statistical filtering method
Noise reduction	Weak; raw data often contains significant random fluctuations	Strong; effectively removes random noise and smooths data
Accuracy of reliability indicators	Medium; depends on expert estimates and limited data sets	High; based on real-time data and advanced mathematical models
Processing speed	Moderate; suitable for small data volumes	High; optimized for large and complex datasets
Adaptability to dynamic conditions	Low; requires manual adjustment for system updates	High; adaptive algorithms update automatically with new data
Forecasting capabilities	Limited to short-term trends	Accurate short- and long-term predictions
Required expertise	Basic engineering knowledge	Requires knowledge of statistics, programming, and data analysis
Implementation cost	Low initial cost but less effective for complex systems	Higher initial setup cost but more efficient in long-term operation

Conclusion

The presented methodology substantiates the necessity of applying vector-based and probabilistic-statistical approaches to the assessment of military telecommunication networks. Unlike traditional methods, the proposed approach eliminates the curse of dimensionality by employing filtering techniques, enabling effective noise reduction and more reliable estimation.

The practical application of this approach ensures higher resilience, survivability, and maintainability of communication networks, which directly enhances the overall security and operational capacity of armed forces.

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