Study of the Telecommunication Networks Performance and Reliability Indicators

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Abstract: - It is currently urgent to improve the technical characteristics and increase the efficiency of telecommunication networks because of the global problem of ensuring the reliable transmission, processing and protection of commercial information in telecommunication networks. The aim of this study is to assess the reliability indicators of telecommunication networks and analyse the level of their development. The aim was achieved through the methods that were used to assess the reliability of the entire network: the generalized method of analytical assessment of the telecommunication network reliability; connection-based metrics; scaling of telecommunication networks, and application of unified reliability indicators to routine control, operation and maintenance. As a result of the research, the indicators of telecommunication networks were studied with and without using connection-based metrics. As a result, the network metrics were also divided into distribution and generation/transmission reliability and telecommunication network metrics – into connection-, performance-, and condition-based metrics, which showed improvements in network performance and reliability. As a prospect for further research, studying and improving the telecommunication network reliability indicators is suggested.

Key-Words: - metrics, transmission system, power grid efficiency, information security.

Received: October 8, 2022. Revised: May 12, 2023. Accepted: June 14, 2023. Published: July 19, 2023.

1 Introduction

Critical infrastructure, such as telecommunication networks, is an important driving force for sustainable social and economic development. Demand for telecommunication services is growing with the continuous progress of society. As a result, telecommunications permeate almost all aspects of daily life in most parts of the world. Besides, they play an increasingly important role in our society.

Failure of a telecommunications network can entail huge losses — from economic to human lives, depending on the reliability category.

Additionally, these crucial networks are consistently exposed to inevitable risks, encompassing natural calamities like earthquakes, tsunamis, and volcanic eruptions, as well as human-induced disruptions such as malicious cyberattacks, terrorist incidents, and accidents.

The current and relevant example is the problem with the electricity supply in Ukraine caused by the military operations on its territory. Since the autumn of 2022, the unified energy system of Ukraine has been regularly subject to missile attacks, which has led to high unreliability and instability of telecommunication networks. In October 2022, tens of millions of consumers faced a blackout, and they are still subject to stabilization and sometimes emergency power outages, which entails the problem of access to telecommunications networks.

During the ice disaster in southern China in 2008, [1], ice on overhead power lines and facilities caused power outages in some cities and districts, leaving about 30 million people without electricity. The Wenchuan earthquake occurred in southwest China in the same year, [2]. Eight districts were completely disconnected during a specific period, 28,765 kilometers of optical cables were damaged,

and 142,078 electric poles collapsed. In 2013, two transmission lines in the Arkansas power system were cut, and one was disconnected by one person, which caused a disconnection of electricity for 10,000 customers, [3]. In 2015, the Black Energy malware hacked the Ukrainian power system, leaving 700,000 households without electricity, [4].
The given examples indicate the need to ensure the reliable operation of telecommunication networks. Measurement of reliability is the main and critical issue for the implementation of quantitative management to prevent and mitigate potential losses or damage. Reliability cannot be quantified without metrics. Consequently, quantitative management cannot be achieved. Clearly defined indicators of network reliability enable quantifying, understanding and reporting failure probabilities. Besides, the system has the purpose of operation and maintenance, [5], [6].

Research on telecommunication network reliability indicators began several decades ago. A system of reliability indicators and indicator standards were established.
The aim of this study is to assess the reliability indicators of telecommunication networks and analyse the level of their development.

The research objectives are the following:
The development of a methodology for assessing the telecommunication network's structural and topological indicators will allow the evaluation of the structural and topological indicators of the telecommunication network. This will be achieved by normalizing the structural reliability of the network and decomposing the network into information directions.

Analysis of the dependence of structural reliability indicators on the structure of information directions. The study involves the analysis of the assessment of the dependence of structural reliability indicators of information directions on their structure, in particular, on the length and number of paths included in the information direction.

Identification of the main directions for further research. The study also aims to identify the main directions for further research in the field of reliability of telecommunication networks.

2 Literature Review

In the 1980's, researchers began to study the reliability of energy distribution. In, [3], the authors wrote two fundamental books. They formally defined various reliability indices such as SAIFI, SAIDI, CAIFI, CAIDI, and ASAI in these two books, as shown below (Formulas 1-5).

$$SAIFI = \frac{CI}{N_T} \text{(interruptions/customer)}, \quad (1)$$

$$SAIDI = \frac{CMI}{N_T} (duration/customer), \quad (2)$$

$$CAIFI = \frac{CI}{CN} (interruptions/customers\ interrupted) \quad (3)$$

$$CAIDI = \frac{SAIDI}{SAIFI} (duration/interruption), \quad (4)$$

$$ASAI = \frac{8760 N_T - CMI}{8760 N_T}, \quad (5)$$

In the formula, CI is the total number of customers interrupted, N is the total number of customers served, CMI is the total duration of customer interruptions, and CN is the total number of customers continuously interrupted during the reporting period. In ASAI, the required customer time is defined as the average number of clients served over 12 months multiplied by 8760.

Besides, were summarized other indicators of distribution reliability, such as the Average System Interruption Frequency Index (ASIFI), the Average System Interruption Duration Index (ASIDI), the Customer Total Average Interruption Duration Index (CTAIDI), Customers Experiencing Multiple Interruptions Index (CEMIn) and Momentary Average Interruption Frequency Index (MAIFI), expressed as follows (Formulas 6-10), [3].

$$ASIFI = \frac{\sum L_e}{L_T} \quad (6)$$

$$ASIDI = \frac{\sum r_e L_e}{L_T} \quad (7)$$

$$CTAIDI = \frac{CMI}{CN} (duration/customers\ interrupted) \quad (8)$$

$$CEMI_n = \frac{CN_{(k \geq n)}}{N_T} \quad (9)$$

$$MAIFI = \frac{TMI}{N_T} \quad (10)$$

where L_e — load of kVA connections interrupted because of each disconnection e, L_T is the total serviced load of kVA connections, r_e is the recovery time for one disconnection event, $CN_{(k \geq n)}$ is the total number of consumers who had n or more stable disconnections, and TMI is the total number of momentary interrupted customers.

Later, Brooks noticed that many consumers were negatively affected by more subtle voltage disturbances, such as dips and surges. They propose four indicators for estimating the magnitude of the root mean square (rms) change and the combination of magnitude and duration:

1) the System Average RMS Variation Frequency Index ($SARFI_x$);
2) the System Instantaneous Average RMS Variation Frequency Index ($SIARFI_x$);
3) the System Momentary Average RMS Variation Frequency Index ($SMARFI_x$);
4) System Temporary Average RMS (Variation) Frequency Index ($STARFI_x$) (Formulas 11-14).

$$SARFI_x = \frac{S_x}{N_T} \quad (11)$$

$$SIARFI_x = \frac{S_{x(0.5c-30c)}}{N_T} \quad (12)$$

$$SMARFI_x = \frac{S_{x(30c-3s)}}{N_T} \quad (13)$$

$$STARFI_x = \frac{S_{x(3s-60s)}}{N_T} \quad (14)$$

where x – rms voltage threshold value, S_x – the total number of consumers experiencing short-term voltage deviations, $S_{x(0.5s-30s)}$ – the total number of consumers experiencing momentous voltage deviations within 0.5–30 cycles, and $S_{x(30c-3s)}$ – the number of consumers experiencing transient voltage deviations during the set duration, $S_{x(3s60s)}$ represents the total number of consumers experiencing transient voltage deviations during 3–60 seconds.

In, [7], the authors classified the above indicators into three categories: by users, load, and system quality indicators. The first category includes SAIFI, SAIDI, CAIFI, CAIDI, ASAI, CTAIDI, CEMIn and MAIFI. The second category contains ASIFI and ASIDI. The third category includes $SARFI_x$, $SIARFI_x$, $SMARFI_x$ and $STARFI_x$.

While reliability metrics continue evolving in academic circles, utilities and professional associations work closely with academic researchers to standardize metrics. In the late 1980's, the IEEE (Institute of Electrical and Electronics Engineers) created the Working Group on Distribution Reliability (WGDR). IEEE keeps updating this standard. Currently, the standard is used by many network operators in several countries.

We use the examples described in, [4], to clarify the previously described measures. These indicators can be illustrated by considering a part of a power distribution system with six load point buses. This basic system displays only the data (Table 1) necessary to explain the metrics calculation. The number of customers connected to these buses and the average load is shown in Table 1, which serves 4,000 customers with a total load of 8 MW. The consequences of downtime are shown in Table 1, considering four system failures in a given calendar year.

Table 1. Detailed information about the distribution system

Loading point	Number of consumers	Average connected load
1	1000	5000
2	800	3600
3	600	2800
4	800	3400
5	500	2400
6	300	1800
Total	4000	19000

The above data are the basis for direct calculation of some of the above indicators, as shown below:

$$SAIFI = \frac{CI}{N_T} = \frac{3100}{4000} = 0.775 \quad (interruption/customer)$$

$$CAIFI = \frac{CI}{CN} = \frac{3100}{2200} = 1.409$$

Where

$$CN = 800 + 600 + 300 + 500 = 2200$$

$$SAIDI = \frac{CMI}{N_T} = \frac{6600}{4000} = 1.650$$

$$CAIDI = \frac{SAIDI}{SAIFI} = 2.129 (duration/interruption)$$

$$ASAI = \frac{8760 N_T - CMI}{8760 N_T} = \frac{8760 \times 4000 - 6600}{8760 \times 4000} = 0.999812,$$

$$CTAIDI = \frac{CMI}{CN} = \frac{6600}{2200} = 3.000 (duration/customers\ interrupted)$$

$$ASIFI = \frac{\sum L_e'}{L_T} = \frac{14200}{8000} = 1.775,$$

$$ASIDI = \frac{\sum r_e L_e}{L_T} = \frac{31900}{8000} = 3.988.$$

These simple numerical examples are used to illustrate the application of reliability indicators. It is recommended to refer to, [4], for a more detailed introduction and application.

The energy system is evolving from centralized production to distributed production with the development of power electronics technologies and the popularization of renewable energy sources, [4]. Besides, micro networks are also gradually developing. However, the above indicators of the distribution network still apply. In, [8], [9], the authors used SAIDI and ASAI in AC and DC distribution networks to create reliability models for transformer stations, DC transformers, and DC circuit breakers. In, [5], the authors used SAIFI, SAIDI and CAIDI to assess microgrids, which are distribution networks that include various distributed generators (DG) and energy storage systems (ESS) with the ability to operate in an autonomous mode.

3 Materials and Methods

Various indicators are used to assess the structural reliability of the network, which to one degree or another, indicate the stability of the network's functioning against the failure of its elements — nodes or cable connections.

Three groups can represent all characteristics of the communication network:

- morphological characteristics;
- operational characteristics;
- economic characteristics.

Characteristics describing these properties and used to evaluate the construction and operation of a telecommunications network can be classified in a similar way. The indicators of any of the specified groups are divided into exogenous and endogenous when setting the task.

Exogenous indicators can be considered primary, predetermining certain concepts, requirements, and conditions. As a rule, these indicators are set on the communication network from the outside when formulating the task and describing or evaluating its construction and operation.

Endogenous indicators are formed from exogenous ones due to the description of the process of building and functioning the communication network. In this sense, they can be considered derived from the initial set of indicators.

In general, the division of indicators of the communication network into exogenous and endogenous may not have a clear limit, being determined by the nature of the task to be fulfilled. This division is, however, convenient when performing operations that reveal the physical essence of processes or phenomena taking place in a network, especially because endogenous indicators are interconnected with exogenous direct or reverse links, and exogenous ones —do not have an inverse effect within one task.

Morphological indicators characterize the construction of any communication network. Exogenous indicators of this type primarily include the size of the network N, which is determined by the number of switching centres included in it. Switching centres are connected by branches. Their number — M — describes the ability of the network to ensure the establishment of connections, as well as for the endogenous characteristics of the structure and operation of this communication network.

The communication network's functional morphological element is the communication direction (information direction). The number of communication directions is set by the control system provided by this network. The number of paths πi of the establishment of connections characterizes each i^{th} communication direction. It determines the structural reliability, bandwidth and other indicators of this network, together with several performance indicators.

The length of each path l can be expressed by the total number of switching centres included in it — n_i, or by the number of transit switching centres — b_i, by the number of branch paths — m_i.

Some exogenous probabilistic indicators estimate communication reliability, the types of communication network reliability are structural — W(G) and functional — W(F). Structural and functional reliability are the main exogenous indicators of this type: W(G) and W(F), respectively.

It is necessary to use methods that calculate the probability W(G) of failure-free service of applications in the specified communication directions to assess the structural reliability of a telecommunications network. Only independent paths should be used as possible information transfer paths to calculate this probability.

3.1 Adequacy of the Production/Transmission System

Capacity margin (CM) is another important adequacy indicator that is widely used in the energy sector and by regulatory bodies. It was first defined as the difference between a set of specific system conditions and actual system limitations, [10]. Consequently, it can also describe network adequacy. This definition is qualitative, mainly because of the high network CM. Therefore, practitioners have few incentives for quantitative assessment (Formula 15).

$$CM = Available\ generated \rightleftarrows\ power - Peak\ demand\ (MW) \tag{15}$$

We use the data in Table 1 and Table 2 to briefly describe the use of some indicators.

Table 2. Load data

Daily peak load (MW)	34	41	46	52	57
Number of events	47	116	107	83	12

$$ENS = \sum_j L_{a(j)} U_j = 31900(kV)$$
$$EENS = \sum_k ENS_k p_k = 9650(kV)$$
$$AENS = \frac{ENS}{N_T} = \frac{31900}{4000} = 7.975(kV/customer)$$
$$ACCI = \frac{ENS}{N_a} = \frac{31900}{2200} = 14.500(kV/customer\ interrupted)$$

The second system, with a capacity of 100 MW can be used to calculate LOLE and other indicators. Table 2 provides the load data for 365 days.

$$LOLE = 12\,Pr(100-57) + 83\,Pr(100-52) + 107\,Pr(100-46) + 116\,Pr(100-41) + 47\,Pr(100-34) = 2.151(day/year)$$

$$CM = 100 - 57 = 43(MW)$$

These straightforward numerical examples are used to demonstrate the practical implementation of reliability indicators. Researchers often use EENS and LOLE among the above indicators. In, [11], the authors used a two-state model to simulate a wind turbine generator (WTG) system and used EENS and LOLE to estimate the WTG. In, [12], the researchers considered distribution networks with renewable generators and calculated LOLE and EENS using the DG system.

3.2 Mathematical model for Calculating Structural Reliability

The mathematical model for calculating the structural reliability of a communication network involves determining various parameters that describe the requirements and characteristics of the network. These parameters are used to assess the network's ability to maintain reliable communication. The model considers the following parameters:

- Number of sources (consumers) of information recognized by the PU (Processing Unit). This parameter, denoted as N, represents the total number of sources or consumers of information in the network.
- Number of directed communications between the PU. Denoted as I, this parameter represents the total number of directed communications or connections between the Processing Units in the network.
- Normalized values of structural reliability of communication network elements. The structural reliability of communication network elements, such as PU and cable communication, is represented by normalized values. These values provide a measure of the reliability of individual network elements.

According to the definition of the structural reliability $W(\pi_i)$ of the i^th^ path, its value can be determined as (Formula 16):

$$W(\pi_i) = \prod_{j\in\pi_i} W_j(\pi_i) \qquad (16)$$

$W_j(\pi_i)$ – the probability of the existence of the j^{th} element sequentially included in the i^{th} path.

Revealing this parameter and taking into account that the CC and the branches forming the i^{th} path are connected sequentially, the probability of survival of the entire path is equal to (Formula 17)

$$W(\pi_i) = \prod_{j=1}^{N-1} Wm_{jh}(\pi_i) \prod_{L=1}^{N-2} Wn_L^T(\pi_i) \qquad (17)$$

$Wm_{jh}(\pi_i)$ — the probability of the existence of the branch *jh*, which makes up the i^{th} path;

$Wn_L^T(\pi_i)$ – the probability of the existence of transit CCs entering the i^{th} path.

The above expressions defining the structural reliability parameters and the main relationships between these parameters can be considered:

- at the stage of network synthesis as initial data and requirements for its structural reliability;
- at the stage of network analysis as the result of ensuring the set reliability indicators of this network and its main components — directed communication.

Optimizing morphological indicators (for example, the structure of the network) makes it possible to achieve compliance of the obtained result with the requirements put forward with minimal material and technical costs.

We will use graph theory, which is a convenient way to formally represent the structure of communication networks, for the morphological description of TCM.

We will present the TCM's structure through an undirected graph $G = \{N, M\}$. The graph's structure $G = \{N, M\}$ is presented in the form of the connectivity matrix $A = \{a_{ij}\}$.

The set of paths from one graph vertex to other forms the direction of communication, and independent paths are defined in the model.

When describing the communication system, it is necessary to consider not only the morphological but also the functional features of the communication network, determined, for example, by the procedures for choosing and making connections. Using Dijkstra's algorithm when solving the TCM research problem is appropriate.

Considering that when determining the structural reliability of the i^{th} path, the reliability of the elements that make up this path is used, it is convenient to describe the value of the reliability of network elements with matrices of a certain size.

So, the main indicators of this model were determined: the telecommunication network connectivity and reliability matrices.

One or several communication lines can form each network, for example, Figure 1(a). Each communication line is characterized by its survival probability $Wm_{ij}^{(k)}$. The communication channels of each communication line on the branch are connected in parallel, forming a multi-line (a single-line with one communication line) edge of the graph $G(N, M)$, as shown in Figure 1(b). In this regard, assuming the independence of the failure events of each type of connection, and consequently the independence of the probabilities $Wm_{ij}^{(k)}$, the reliability probability of the branch m_{ij} can be determined as (Formula 18):

$$Wm = \prod_{k=1}^{L}(Wm_{ij}^{(k)}), \qquad (18)$$

where L – is the number of independent communication lines, the channels of which are included in the branch m_{ij}. Values of the probability determined by the expression are matrix elements.

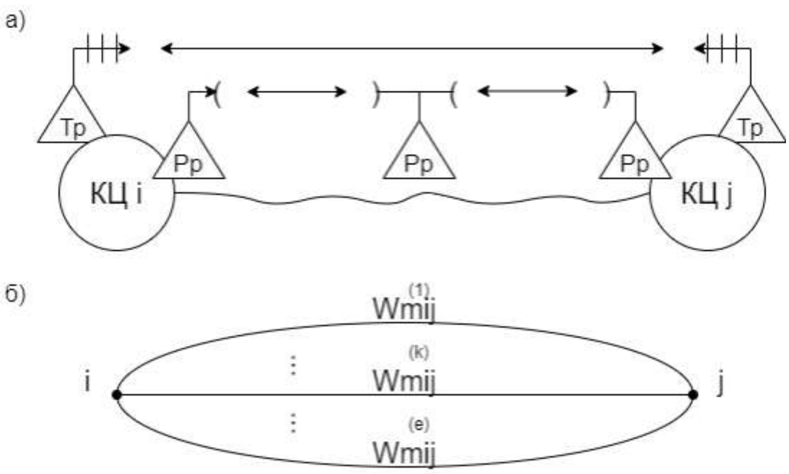

Fig. 1: Example of a branch: a) with several communication lines; b) multiline edge of the graph

4 Results

Publications discussing the conventional concept of network reliability can be categorized into three primary groups. The first category encompasses connectivity-based metrics, prioritizing network node connectivity. The second category comprises performance-based metrics, which evaluate network reliability based on network attributes and predefined thresholds. The third category involves state-based metrics linked to specific network state measurements. Table 3 contains a list of subgroups and corresponding publications in each group.

Table 3. Consequences of interruption in the 2022 calendar year

Interruption event	Probability	Affected load point	Number of interrupted customers	Reduced load (kW)	Break duration (time)	Reduced customer working hours	Unsupplied energy (kWh)
1	0.3	2	800	3,600	3	2,400	10,800
		3	600	1,800	3	1,800	8,400
2	0.4	6	300	1,800	2	600	3,600
3	0.2	3	600	2,800	1	600	2,800
4	0.3	5	500	2,400	1.5	750	3,600
		6	300	1,800	1.5	450	2,700
Total			3,100	14,200	12	6,600	31,900

In summary, the interruptions in the communication network affected 3,100 customers, reduced the total load by 14,200 kW and interrupted working hours by 6,600. As a result of these interruptions, 31,900 kWh of energy was not used.

These findings emphasize the importance of communications network reliability and its impact on load, customer hours, and energy consumption.

4.1 Connection-based Metrics

Two special cases are important for the probability of connection to the K-terminal: 1) the reliability of a connection with 2 terminals (ST), where K = 2, one node in K is designated as the source node, and the second is the receiver node; 2) general reliability (full ultimate reliability).

4.2 Performance Indicators

We illustrate these metrics by using the network example in Figure 2. In this context, every edge within the network has a particular probability of failure, and there are limitations on the amount of data each edge can transmit. In this scenario, reliability refers to the probability that a minimum of *d* units of data can be successfully transmitted from source point *s* to destination point *t*.

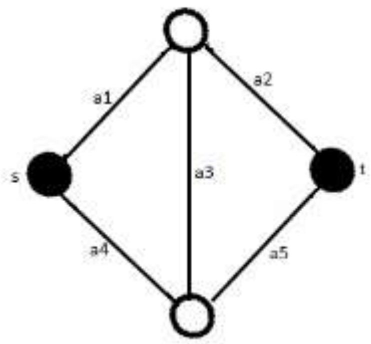

Fig. 2: Network example, [3]

In addition to service reliability based on network traffic, performance-based reliability also includes time-based reliability. In this case, reliability represents the probability that the time required to move from point s to point t is less than τ.

The signal/interference/noise ratio (SINR) is another important factor in the telecommunication network performance. Signal quality interruption characteristics are crucial for meeting strict reliability requirements. Performance indicators are expressed as follows (Formula 19):

$$R_s = Pr\{SINR > T\}, \quad (19)$$

where T — threshold for SINR. This indicator is widely used in telecommunication networks, [13].

4.3 State-based Metrics

Besides, some new metrics classify the state of the function in the network. Was proposed a new index that combines efficiency and connectivity. The telecommunication network reliability is expressed as follows (Formula 20):

$$R_s = \sum Pr\{x\} \cdot \phi(x), \tag{20}$$

where $Pr\{x\}$ represents the probability of state *x* and $\phi(x)$ represents the system's efficiency. In this study, reliability is referred to the maximum number of channels of state x. Similarly, the number of nodes with which this node can interact is used as a reliability measure, [14].

Similar to energy losses in the network — EENS — traffic losses in telecommunication networks are also considered. In [15], [16], the authors defined reliability as the probability of the network being operational at any given time. One measure related to reliability is the expected lost traffic, which refers to requests that cannot be delivered due to failures in the network. The researchers also consider routing and rerouting strategies that come into play after a failure occurs. Their model comprises two layers: the physical network layer, which represents the physical channels, and the logical network layer, which captures the traffic requirements of source and receiving nodes. This indicator can be expressed as follows (Formula 21):

$$Expected\ lost\ traffic = \sum Pr\{x\} \cdot \phi(x) \tag{21}$$

Here, $\phi(x)$ represents the lost flow in state x.

These network reliability parameters make the network reliability measurement more user-oriented and intuitive, significantly contributing to the study of network reliability.

4.4 Practical Reliability Indicators

There is, however, a certain gap between reliability indicators in practical applications and academic circles. The first commercial 1G network was launched in Japan in 1979. This is an analogue system that does not provide for data transmission. In 1991, the first 2G network based on the new GSM (Global System for Mobile Communications) standard was launched in Finland. Until the 2000's, telecommunication networks were mainly limited to wired networks with relatively simple network functions, mainly for telephone or telegraph services. The call setup success rate (CSSR) and call drop rate (CDR) are the relevant indicators (Formula 22-23).

$$CSSR = \frac{S_c}{T_c}, \tag{22}$$

$$CDR = \frac{N_d}{N_s} \tag{23}$$

S_c is the number of successful call connections, T_c is the total number of call requests, N_d is the number of dropped calls, and N_s is the number of successful connections. However, these indicators were extrapolated from data records and user complaints at an early stage.

After the 2000's, telecommunication networks began to play an increasingly important role in everyday life with the rapid development of 3G and 4G networks. Telecommunication networks still use the reliability of all terminals, [17]. The telecommunication network gradually became a heterogeneous wireless and wired network with the development of wireless technology. In addition to traditional indicators, social demand for the network has grown, and such indicators as unified connectivity can no longer satisfy demand. The QoS concept was gradually applied to the telecommunication network services, [18].

According to previous studies, [19], [20], [21], in the context of network analysis, several fundamental metrics are commonly utilized, including delay, reliability, throughput, jitter, and loss probability. It's important to note that while reliability is one of these metrics, it is primarily a low-level metric and should not be confused with overall network-level reliability. In other words, while reliability focuses on the performance and dependability of individual network components or links, overall network-level reliability considers the collective behaviour and performance of the entire network. Some researchers represent reliability by the frequency of bit errors, [13].

More specific key performance indicators (KPI) appeared based on QoS and became more widespread. Besides, many companies, for example, Huawei will use early warning indicators (EWI) in real work. Key performance indicators of the network are grouped into the following subcategories: availability, retention, mobility, integrity, and accessibility, [13], [14], [15]. In [20], the author, [18], classified KPIs according to the following categories in the METIS project, co-financed by the European Commission: traffic density, empirical user throughput, delay, reliability, and energy consumption. Table 4 shows key performance indicators.

Table 4. KPIs for the LTE (Long Term Evolution) network

Category	KPI	Description	Calculation Method	Measurement Unit
Accessibility	Successful installation of RRC (Radio Resource Control)	Measures the availability of successful RRC signaling establishment	Number of successfully established RRC divided by the total number of RRC establishment attempts	Percentage (%)
	Successful installation of E-RAB (E-UTRAN Radio Access Bearer)	Measures the availability of successful E-RAB establishment	Number of successfully established E-RAB divided by the total number of E-RAB establishment attempts	Percentage (%)
Retention	Call drop rate	Measures the proportion of dropped calls	Number of dropped calls divided by the total number of calls	Percentage (%)
	Service call drop rate	Measures the proportion of dropped service calls	Number of dropped service calls divided by the total number of service calls	Percentage (%)
Mobility	Inter RAT Handover Outgoing Success Rate (Radio Access Technology)	Measures the success rate of outgoing handovers between different access technologies	Number of successful outgoing handovers between different access technologies divided by the total number of handovers	Percentage (%)
	Handover Success Rate (from LTE to WCDMA)	Measures the success rate of handovers from LTE to WCDMA	Number of successful handovers from LTE to WCDMA divided by the total number of handovers	Percentage (%)
Integrity	Average uplink/downlink bandwidth	Measures the average throughput in the uplink/downlink direction	Average uplink/downlink bandwidth	Bytes per second (Bps)
	Bit error ratio	Measures the ratio of erroneous bits to the total number of transmitted bits	Number of erroneous bits divided by the total number of transmitted bits	Ratio
	SINR (Signal-to-Interference plus Noise Ratio)	Measures the ratio of signal power to the combined interference and noise power		Measured in decibels (dB)
	Packet error rate	Measures the proportion of packets with errors in the total number of transmitted packets	Number of packets with errors divided by the total number of transmitted packets	Percentage (%)
Latency	User-plane latency	Measures the delay experienced by end users during data transmission		Measured in milliseconds (ms)
	Control plane delay	Measures the delay at the control plane of the network		Measured in milliseconds (ms)
	End-to-end delay	Measures the delay across the entire data transmission path from sender to receiver		Measured in milliseconds (ms)
	One-way delay	Measures the one-way delay from sender to receiver		Measured in milliseconds (ms)
Availability	Radio Network Unavailability Rate	Measures the proportion of time when the radio network is unavailable	Time when the radio network is unavailable divided by the total time	Percentage (%)
	Cell availability	Measures the proportion of time when an individual cell is available	Time when the cell is available divided by the total time	Percentage (%)
Traffic	Radio carriers	Measures the number of active radio carriers	Number of active radio carriers	
	Inbound/outbound traffic volume	Measures the volume of inbound/outbound traffic passing through the network	Number of transmitted bytes of inbound/outbound traffic	
Energy Efficiency	Spectral efficiency	Measures the number of transmitted bits per unit of the frequency spectrum	Number of transmitted bits divided by the frequency spectrum width	Bits per Hertz (bps/Hz)
	The energy efficiency of E-UTRAN data transmission	Measures the number of transmitted bits per unit of energy consumed for data transmission	Number of transmitted bits divided by the energy consumed	Bits per Joule (bps/J)

As the 5G era approaches, the telecommunications network carrying this advanced technology has turned into a giant. It constantly grows, from simple calls/communications to increasingly complex messaging capabilities. Enjoying the convenience of a telecommunications network, every user wonders about the reliability and stability of the network, the completeness of data, and the timely transmission. Society is becoming increasingly dependent on telecommunication networks with the transition to 5G. The International Telecommunication Union (ITU) identifies the following main use cases for the 5G era:

- Enhanced Mobile Broadband (eMBB), which is mainly determined by the need for high data transfer speed and high bandwidth;
- Massive Machine-Type Communications (mMTC), which requires energy consumption, provides efficient communication and wide coverage;
- Ultra-Reliable Low Latency Communications (URLLC), where high reliability and low latency are critical.

The 3GPP Radio Access Network (RAN) Working Group (3GPP, 2018) determined design goals for next-generation requirements as shown in Table 5.

The aforementioned Key Performance Indicators (KPIs) serve as valuable tools for network monitoring, where the metrics obtained through monitoring are compared to target values to assess whether the current network meets the specified requirements. For instance, peak speed assumes greater significance in enhanced Mobile Broadband (eMBB) scenarios due to clear downloading and uploading requirements. The peak download speed should not fall below 20 Gbit/s, while the peak upload speed should not exceed 10 Gbit/s. However, peak speed is not mandatory for Massive Machine-Type Communications (mMTC) and Ultra-Reliable Low-Latency Communications (URLLC) scenarios. In the case of URLLC, latency emerges as a critical factor, with user-level latency needing to be below 0.5 ms. It should be noted that these metrics, in practical applications, are predominantly deterministic values acquired through network testing, diverging from the probabilistic indicators of reliability explored within academic circles.

Table 5. The 3GPP Radio Access Network (RAN) Working Group (3GPP, 2018)

Usage scenarios	KPI	Goal	
		Download	Upload
EMBB	Peak data transfer rate	20 Gbit/s	10 Gbit/s
	Peak spectral efficiency	30 bit/s/Hz	15 bit/s/Hz
	Control level delay (same as URLLC)	10 ms	
	User level delay	4 ms	
	Average spectral efficiency (bps/Hz)	Three times higher than IMT (International Mobile Telecommunication)-advanced	
	Zone bandwidth	10 Mbit/s/m^2	
	Data transfer speed for the user	100 Mbit/s	50 Mbit/s
	The efficiency of using the 5% user spectrum (bit/s/Hz/user)	Three times higher than IMT-advanced	
	Target maximum speed (same as in URLLC and mMTC)	500 km/h	
	Mobility interruption time (same as URLLC and mMTC)	0 ms	
	Network energy efficiency (similar to URLLC and mMTC)	No quantitative requirements	
	User equipment energy efficiency (similar to URLLC and mMTC)	No quantitative requirements	
	Bandwidth	Not less than 100 MHz; Up to 1 GHz for operation in higher frequency ranges (for example, above 6 GHz)	
mMTC	Coverage	Max. communication loss 140 dB	
	User equipment battery Service life	older than 10 years, preferably 15 years	
	Connection density	1,000,000 devices/km^2	
	Infrequent small packets delay	10 s	
URLLC	User plane delay	0.5 ms	
	Reliability	$1*10^{-5}$ success probability for 32 bytes within 1 ms with a user plane delay	

Nevertheless, there are certain drawbacks to many existing KPIs. For instance, numerous key performance indicators generate an overwhelming influx of early warning alerts. Consequently, operators are inundated with a high volume of KPI alerts daily, necessitating increased maintenance resources and augmenting the burden of operations and maintenance. As mentioned earlier, several practical metrics are deterministic monitoring values lacking statistical significance, making it challenging to estimate the probability of network satisfaction. Therefore, the advancement and operation of communication networks encounter obstacles. In contrast to electrical networks, there is an urgent need to investigate unified reliability indicators for telecommunication networks in academic and industrial settings.

5 Discussion

The assessment and forecasting of the structural reliability of complex multi-service communication networks cause many difficulties in practice because of their large size. This is why a method of assessing a telecommunication network's structural and topological indicators when normalizing its structural reliability is proposed. Its main objective is decomposing the network, that is the division into information directions.

The proposed methodology was the basis for analying the results of the assessed dependence of the structural reliability indicators of information channels on their structure (length and number of paths included in the information channel).

In other words, the study determined how the structure of information channels affects structural reliability indicators. At the same time, such factors as the length of the paths and the number of paths included in each information direction were taken into account. This analysis will help to understand which aspects of the information direction structure affect the telecommunications network's reliability.

The process of developing the reliability of telecommunication networks began with industry. Later, the researchers started working on it. The problems studied in academic circles are closely related to production practice, and the gap between these two areas is relatively small. Academic studies are also successfully applied in industrial practice. However, the scientific community began to study telecommunication network reliability in the early days theoretically. It took the industry a long time to pay attention to the telecommunication network reliability and develop several indicators. The indicators previously developed in academic studies were not used in the industry. This missing application has created a big gap between academia and industry.

It is possible to single out universal methods and models for assessing the network structural reliability among their multitude, which would be suitable for the analysis of arbitrary network structures and specialized ones that take into account certain network features and thus enable obtaining more accurate estimates for them than in [18]. Most of these methods are intended for analysing networks with a certain topology. The indicators for assessing the structural reliability of complex systems and networks are much better than in [22], [23]. The works, [20], [21], deal with the problems of assessing the structural reliability of TCM. In contrast to [19], a method of obtaining structural reliability based on basic structural characteristics is presented for networks with a certain topology. The paper, [20], considered the possibility of using structural characteristics to assess the reliability of a network with an undetermined topology, while this article presents a method for obtaining the upper and lower limits of structural reliability for a single link in the network.

The power system's reliability concept has evolved into two distinct categories: distribution reliability and generation/transmission adequacy. The network reliability index, represented by the Equivalent Energy Not Served (EENS), can be applied to the entire power network and evaluate end-to-end network reliability for multiple services. In telecommunication networks, traditional reliability indicators are typically categorized as connection-based or performance-based. Theoretically, these indicators provide a global assessment of the network's reliability. However, in practical terms, there is a lack of metrics capable of assessing the end-to-end reliability of the entire network for multiple services offered within the telecommunications domain, [24], [25], [26], [27].

The number of network reliability indicators is appropriate, as IEEE standards were established to determine these indicators. Besides, many countries' network operators and regulatory authorities often use several reliability indicators. However, there are many KPIs for telecommunications networks, as different telecommunication operators use different KPIs. A standard set of metrics for different operators has not yet been established, [28].

The results of the analysis of the structural parameters of TCM and, in particular, the influence of the CC ranks of this network on the parameters of its operation are also confirmed when evaluating the morphology of the studied network from the perspective of structural reliability. In other words, it can be argued that when choosing an option of the communication network structure (where the general topology of this network corresponds to the independence of the paths of establishing connections with a given number of CCs and branches), the option with the minimum number of CC ranks of this network will be more reliable than any other. It is characteristic that the tendency to preferentially choose the option with a certain (minimum) number of CC ranks for the assessment of its morphological characteristics, both in terms of throughput and reliability, coincide, [14], [29], [30].

The influence of the number of CC ranks of the communication network on its structural reliability is actually the only “hidden” factor that determines the network performance according to a given parameter. Summarizing the influence of other parameters on reliability indicators, it can be noted that the reliability of the information direction is higher:

- the shorter the path (this is determined by kilometer length for cable and fiber-optic lines, by the number of transmission and reception sections for radio relay and tropospheric communication lines);
- the more independent paths of established connections;
- the more linear connections ("parallel") form one branch of the network;
- the higher the reliability of each element of the communication network included in this information direction.

Therefore, the discussed issues and proposed methods for investigating the structural reliability of multiservice communication networks significantly contribute to this field's advancement. The results of these studies can be used both in production and the academic environment, fostering the improvement of telecommunications systems and their reliability.

6 Conclusions

This study provides a systematic assessment of reliability indicators in telecommunications networks. The findings reveal that the reliability of telecommunications networks is still in the developmental stage compared to other infrastructure networks.

To address the challenges associated with evaluating and predicting the structural reliability of complex multiservice communication networks, a methodology for assessing the structural-topological indicators of a telecommunications network is proposed. The main objective is to decompose the network into informational directions, enabling a more comprehensive evaluation of its structural reliability.

Simultaneously, the importance of reliability in telecommunications networks is growing. Based on the current state of research in this field, several key areas for future investigation are suggested.

Researchers should establish a unified measurement system among the multitude of reliability indicators. As different users have diverse requirements in various network scenarios, it is essential to determine the relationship between network requirements and reliability indicators and establish a common reliability standard.

Telecommunications networks are complex systems composed of multiple subnetworks with different properties, each processing different components. Further research should focus on the methods for evaluating the reliability of the entire network based on the reliability of its subnetwork components.

The scale of telecommunications networks is constantly expanding, with node counts ranging from millions to hundreds of millions. Further studies should determine efficient and rapid approaches to network reliability assessment.

The establishment of reliability indicators is intended for management and supervision purposes. Future research should investigate the widespread application of standardized reliability indicators in routine monitoring, operation, and maintenance.

In conclusion, this study emphasizes the need for further research in telecommunications network reliability. Developing a unified measurement system, studying the reliability of network components, and devising fast and efficient evaluation methods are key areas for further studies in this area.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare.