

ANNOTATION
for the dissertation of Nurakhov Yedil
submitted for the degree of Doctor of Philosophy (PhD)
in the educational program 8D06102 – Computer Engineering
on the topic: " Development of methods for forecasting quality indicators in 5G
Standalone networks using machine learning "

Relevance of the research topic.

Fifth-generation 5G Standalone (5G SA) networks represent a new stage in the development of telecommunications systems, characterized by a high degree of software manageability, virtualization of network functions, and extensive use of service-oriented architecture. Unlike previous generations of mobile communications, the 5G SA architecture provides the ability to flexibly manage network resources, dynamically adapt operating parameters, and implement intelligent network monitoring and management mechanisms in near-real-time mode.

Simultaneously with the expansion of functionality, the complexity of network behavior increases significantly. The state of 5G SA is determined by the combined influence of a large number of factors, including the number of active users, the nature of generated traffic, the distribution of radio resources, transport network parameters, and management mechanisms. As a result, network quality metrics such as data latency, bandwidth, and packet loss can change in a non-linear fashion, and performance degradation often develops as a complex transient process.

According to the 3GPP TS 23.501 and TS 38.300 specifications, network status monitoring is an integral part of the 5G System architecture and includes monitoring of latency parameters, data transfer rates, congestion information, and other quality of service indicators. The development of Open RAN and software-defined network concepts further enhances the role of network data mining, since modern architectures involve the use of automated decision-making and adaptive management mechanisms based on the observed network state.

In recent years, machine learning methods have been actively considered as a promising tool for analyzing and predicting the behavior of telecommunications systems. A significant amount of research is devoted to predicting individual indicators of network quality, network traffic, and load. However, most of the existing works are based either on data from carrier networks containing a large number of uncontrolled factors, or on simulation models that do not always reproduce the features of the functioning of the real 5G Standalone software stack.

The use of data from commercial networks limits the ability to conduct reproducible experiments and identify cause-and-effect relationships between system parameters and observed quality indicators. In turn, simulation models often simplify the mechanisms of functioning of the transport layer, buffering, resource allocation, and interaction of network components, which reduces the reliability of the results obtained.

In this regard, the creation of controlled reproducible experimental environments that make it possible to conduct multiple network studies under identical conditions, control load parameters, and obtain reliable experimental data for analyzing system behavior is particularly relevant. The development of open software platforms Open5GS and srsRAN makes it possible

to build such research stands without using expensive specialized equipment, which opens up new opportunities for studying the behavior of 5G Standalone networks.

An additional scientific interest is the study of the state of the network as a dynamic process. In most works, individual quality indicators are predicted, while the task of forming an integral representation of the network state, studying transitions between different operating modes, and analyzing the predictability of these states is presented in a limited way. At the same time, the ability to detect the approach of congestion or degradation in advance is one of the key prerequisites for building intelligent monitoring and management systems for next-generation networks.

Thus, the relevance of the thesis is due to the need to develop methods for analyzing and predicting the state of the 5G Standalone network based on controlled reproducible experimental data, to study the patterns of network degradation under multi-user load conditions, and to determine the possibilities of using machine learning methods for short-term forecasting of the network state.

Purpose of the dissertation work

Development of methods for predicting 5G Standalone network quality indicators based on machine learning using data obtained in a controlled experimental environment.

Research objectives:

- Develop a controlled experimental 5G SA environment that provides a reproducible study of network performance in various load modes
- Determine the quality indicators of the 5G SA network and investigate their dependence on load parameters and network operation conditions
- Generate a structured set of experimental data containing network parameters and corresponding quality indicators, suitable for subsequent analysis and training of models
- Develop and research methods for predicting 5G SA network quality indicators based on machine learning and evaluate the possibility of detecting network degradation in dynamic load scenarios

Research methods:

Systematic literature review, analysis of 3GPP and O-RAN standards, construction of a reproducible 5G Standalone experimental environment, network measurements and monitoring, time series analysis, statistical data analysis, machine learning, regression models, classification methods, neural networks for processing time sequences, network state prediction.

Research object

Methods for analyzing and predicting the state of 5G Standalone networks based on controlled experimental data and machine learning methods.

Subject of the study

Methods for predicting the state and quality indicators of 5G Standalone networks.

Scientific novelty of the obtained results:

1. A reproducible environment of controlled experiments for studying the state of the 5G Standalone network is implemented.
2. An approach to forming a data set for analyzing and predicting the network state, including experimental parameters, network quality indicators, and an aggregated network state indicator, is proposed

3. Based on the obtained experimental data, the predictability of the state of the 5G Standalone network is revealed and the working forecast horizon is determined, which makes it possible to detect the development of network degradation before the transition to a critical state.

Provisions submitted for defense:

4. A reproducible environment of controlled experiments is implemented, which provides the ability to study the state of the 5G Standalone network under repeated experimental conditions.
5. An approach to the formation of a data set is proposed, which includes an aggregated indicator of the network state and a classification of network states, which provides a reproducible study of network transitions between different states.
6. It is established that the state of the 5G Standalone network and the aggregated indicator of the network state have predictability, the working forecast horizon depends on the nature of the dynamics of changes in network parameters.

Theoretical and practical significance of the study

Theoretical significance

This study contributes to the development of methods for analyzing and predicting the state of 5G Standalone networks based on controlled experimental data. In this paper, the network is considered as a dynamic system, the state of which is formed under the influence of multi-user load, configuration parameters, and operating conditions. An approach to the aggregated representation of the network state is proposed, which makes it possible to study transitions between different modes of its operation. The results obtained expand our understanding of the patterns of performance degradation of 5G Standalone networks and the features of predictability of their state in a controlled experiment. The results of the study can serve as a basis for further development of methods for intelligent monitoring, forecasting and management of new-generation networks.

Practical significance

The practical significance of the work lies in the development of a reproducible 5G Standalone experimental environment based on Open5GS, srsRAN Project and ZeroMQ, which provides controlled multi-user experiments without the use of specialized radio frequency equipment. The developed environment allows us to study the influence of load parameters on network quality indicators, generate experimental datasets, and evaluate machine learning methods in conditions close to the actual functioning of the network.

The developed methods of analysis and forecasting can be used to create network state monitoring systems, intelligent decision support tools, and advanced control mechanisms in software-defined networks and Open RAN architectures. The results obtained can also be used in scientific research, educational purposes, and in the development of experimental platforms for studying 5G networks and subsequent generations of mobile communications.

Scope and structure of the dissertation work

The dissertation consists of an introduction, four main chapters, a conclusion, and a list of references. The total volume of the work is about 110 pages, including tables, figures and formulas. The list of references includes more than 50 titles.

The dissertation consists of an introduction, four main chapters, a conclusion, and a list of sources used.

The first chapter provides an overview of the 5G Standalone network architecture, the Open RAN concept, network quality indicators, and modern methods for analyzing and predicting the state of telecommunications systems. The analysis of existing approaches is performed, the relevance of the research is justified, and the main scientific tasks of the work are formulated.

The second chapter describes the developed reproducible experimental 5G Standalone environment based on Open5GS, srsRAN Project and ZeroMQ. The stand architecture, multi-user emulation methods, organization of telemetry collection, and formation of an experimental dataset are considered.

The third chapter presents the results of a study of network behavior under changing load conditions. Dependencies between system parameters and network quality indicators are analyzed, an approach to the aggregated representation of the network state is proposed, and performance degradation processes are investigated.

The fourth chapter discusses methods for predicting the state of a network based on machine learning. Various forecasting models are compared, the predictability of the network state in different operating modes is investigated, and the working horizons of short-term forecasting for controlled and stochastic scenarios are determined.

In conclusion, the main results of the study are presented, conclusions are formulated and directions for further research are determined.

Testing the work

The results of the work were discussed at scientific seminars of the Faculty of Information Technologies and Artificial Intelligence of the Al-Farabi Kazakh National University, and were also presented at international conferences:

- Қазақстан математиктерінің бірінші конгресі (Алматы, Қазақстан, 2025);

Publications.

6 scientific papers have been published on the topic of the dissertation, including 5 articles in peer-reviewed scientific journals indexed in the international databases Scopus and Web of Science, and 1 article in a journal recommended by the Science and Higher Education Quality Assurance Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan.

– Nurakhov, Y., Mukhanbet, A., Aibagarov, S., & Imankulov, T. (2025). A Machine Learning Approach to Investigating Key Performance Factors in 5G Standalone Networks. *Electronics*, 14(19), 3817. <https://doi.org/10.3390/electronics14193817>

– Nurakhov, Y., Kassymbek, N., Marlambekov, D., Mukhanbet, A., & Imankulov, T. (2026). Bridging the Semantic Gap in 5G: A Hybrid RAG Framework for Dual-Domain Understanding of O-RAN Standards and srsRAN Implementation. *Applied Sciences*, 16(7), 3275. <https://doi.org/10.3390/app16073275>

– Nurakhov, Y., Aibagarov, S., Kassymbek, N., Mukhanbet, A., Kumalakov, B., & Imankulov, T. (2026). The Impact of Generative AI on 6G Network Architecture and Service. *Electronics*, 15(7), 1345. <https://doi.org/10.3390/electronics15071345>

– Nurakhov, Y., Kyzirkanov, A., Otarbay, Z., & Lebedev, D. (2025). Adaptive Software-Defined Network Control Using Kernel-Based Reinforcement Learning: An Empirical Study. *Applied Sciences*, 15(23), 12349. <https://doi.org/10.3390/app152312349>

- Kyzyrkanov, A. E., Nurakhov, Y. S., Otarbay, Z., & Lebedev, D. V. (2026). Log-Driven Proximal Policy Optimization for Adaptive Traffic Control in Software-Defined Networks. *Applied Sciences*, 16(9), 4424. <https://doi.org/10.3390/app16094424>
- Nurakhov, Y., & Marlambekov, D. (2025). Implementation of a Reproducible 5G Standalone Testbed Using Open-Source Components. *Journal of Problems in Computer Science and Information Technologies*, 3(4), 39–47. <https://doi.org/10.26577/jpcsit202544>