RIGA TECHNICAL UNIVERSITY

Inga Vagale

DEVELOPMENT OF INTERNET SERVICE QUALITY ASSESSMENT AND MONITORING METHODOLOGY

Summary of the Doctoral Thesis

RTU Press
Riga 2022

RIGA TECHNICAL UNIVERSITY

Faculty of Electronics and Telecommunications
Institute of Telecommunications

Inga Vagale
Doctoral student of the Study Programme "Telecommunications"

DEVELOPMENT OF INTERNET SERVICE QUALITY ASSESSMENT AND MONITORING METHODOLOGY

Summary of the Doctoral Thesis

Scientific supervisors

Professor Dr. sc. ing.
ĢIRTS IVANOVS

Professor Dr. sc. ing.
VJAČESLAVS BOBROVS

RTU Press
Riga 2022

Vagale I. Development of Internet Service Quality Assessment and Monitoring Methodology. Summary of the Doctoral Thesis. – Riga: RTU Press, 2022. – 32 p.

Published in accordance with the decision of Promotion Council “RTU P-08” of 4 March 2022, Minutes No. 7

https://doi.org/10.7250/9789934227738
ISBN 978-9934-22-773-8 (pdf)

DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 3 June 2022 at 11:00 at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Āzenes Street, Room 201.

OFFICIAL REVIEWERS

Professor Dr. sc. ing. Jurģis Poriņš
Riga Technical University

Researcher Dr. sc. ing. Aleksejs Udaļcovs
RISE Research Institutes of Sweden AB, Sweden

Professor Dr. habil. sc. comp. Juris Borzovs,
University of Latvia, Latvia

DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Science (Ph. D.) is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Inga Vagale …… (signature)

Date: ……

The Doctoral Thesis has been written in Latvian. It consists of 5 chapters, Conclusions and Summary, 91 figures, 27 tables, 3 appendices; the total number of pages is 161. The bibliography contains 116 titles.

ANNOTATION

Today, a large number of services of public importance are accessible and usable via the Internet, thus increasing the role of the availability of internet services in promoting the consumers' social and economic participation in society. Studies and forecasts for the use of the Internet service suggest a significant increase in the amount of data transmitted in the coming years, which will be influenced, inter alia, by the development and introduction of new content services. Given both the importance of the internet service and the trends in its use, a strategy has been developed at the European Union level and relevant requirements have been implemented to promote the availability and quality of broadband Internet.

In the Doctoral Thesis the framework for monitoring and promoting quality and development of broadband Internet has been evaluated, as well as related shortcomings and problems of its actual applicability have been identified. An assessment of end-user's centric Internet quality indicators has been performed and based on mathematical analysis, a concept for determining and reflecting the actual internet service quality values has been developed. Special emphasis is placed on determination of the objective methods for the evaluation of connection speed indicators and definition of measurement principles. The Thesis provides suggestions of determining the areas of insufficient broadband Internet coverage, based on the information obtained within the geographical survey, which in turn can be used to plan the deployment of broadband networks, thus facilitating the availability of universal service in the country. Study results related to the quality of broadband internet services have been summarised in this Thesis. In addition, it contains suggestions for the implementation of a practical methodology that evaluates the quality of the internet service that is being provided.

CONTENTS

ABBREVIATIONS

4G – 4th generation mobile network
5G – 5th generation mobile network

A
ADSL – asymmetric digital subscriber line

B
BEREC – Body of European Regulators for Electronic Communications

C
CN – core network

D
DSL – digital subscriber line
DSM – digital single market

E
E2E – end-to-end
EC – edge computing
ETSI – European Telecommunications Standards Institute

F
FTTH – fibre to the home
FWA – fixed wireless access

G
GPS – Global Positioning System
GSMA – Global System for Mobile Communications Association

I
ITU – International Telecommunication Union
IXP – Internet exchange point

M
MOB – mobile network

O
OAM – operations, administration and management
OECD – Organisation for Economic Cooperation and Development

Q
QoE – quality of experience
QoS – quality of service

R
RAN – radio access network

S

SPRK – Public Utilities Commission of Latvia

T

TCE – Trace Collection Entity

TCP – Transmission Control Protocol

GENERAL DESCRIPTION OF THE DOCTORAL THESIS

Relevance of the topic

Nowadays, access to the Internet has become an integral part of everyday life. Internet access has a significant impact on people's social and economic participation in society. Internet services play an important role in improving the overall quality of life of citizens, ensuring equal opportunities for all to participate in different areas of society. For example, access to an internet service enables people to get an education, learn new skills, find a job, communicate with others, use e-services, make purchases and do business online, etc. In this way, everyone, regardless of their location, financial means and other factors, has the same opportunities. The feasibility of the above aspects is particularly important for people with fewer opportunities. In addition, Internet access supports all sectors of the economy, boosting their performance and creating high-skilled jobs. Broadband connectivity promotes transnational economic integration and raises people's living standards. Inclusive access to Internet services contributes to increased flexibility and productivity among small businesses, as well as to the more transparent functioning of public authorities.

Looking at the dynamics of fixed and mobile broadband connections over more than 10 years, mobile connections are growing rapidly globally. Latvia has seen a sevenfold increase in mobile broadband connections in the last 10 years, while fixed broadband connections have even seen a slight decline in recent years [2]. This trend may be due to the development of mobile technologies, which provide increasingly faster data transmission speeds and more stable services, as well as their availability, which in some cases ensures the substitutability of fixed Internet (e.g., in sparsely populated areas, fixed internet connections may not be available and are costly to install).

Over the last decade, there have been significant changes in the need for Internet service, in data consumption, and in the range of connected devices, which have seen a marked increase in demand, thus contributing to changes in Internet usage trends. With the development of data transmission technologies and the availability of the Internet, the variety of services and applications provided over the Internet is increasing, as is the demand for higher quality of service, resulting in continuously increasing volumes of data transmitted [1], [2] and an increasing demand for the capacity of the electronic communications network on which they are provided.

As broadband Internet becomes more important in people's daily lives, the quality of broadband is becoming particularly important. A number of performance indicators reflect the quality of broadband and have an impact on the services users receive, such as connection speed, data delay or latency, packet loss rate and others. As networks and technology evolve, services are emerging where a certain level of quality assurance is critical [4], [5].

In order to define a clear vision of the indicators to be pursued, the 2010 European Commission prepared the “EUROPE 2020 strategy. A strategy for smart, sustainable and inclusive growth”. The Strategy was the first document to set clear targets for Internet speed and penetration figures to be achieved in the foreseeable future. The Global Strategy's objective

“to prepare the EU economy for the next decade” only set priorities for action and established flagship initiatives aimed at catalysing the implementation of each thematic priority [6]. The Digital Agenda for Europe, therefore, aimed to accelerate the take-up of high-speed internet services and to reap the benefits of the Digital Single Market for households and businesses [6]. The Europe 2020 and Digital Agenda for Europe strategies, therefore, set a target of basic broadband for all Europeans by 2013, **Internet access above 30 Mbps for all Europeans by 2020, and 50 % or more of European households to have an internet connection above 100 Mbps by 2020 [6], [7].**

To achieve all these objectives, the Digital Agenda for Europe strategy outlined the areas of action that should be applied at both the European and national level to deliver the desired economic growth and sustainable economic and societal benefits from a Digital Single Market based on fast and ultra-fast Internet. [7]

In 2015 and 2016, strategies on the Digital Single Market in Europe [8] and moving towards a European gigabit society [9] were developed, continuing the drive towards a Digital Single Market and the development of communication services, taking into account the changes in the use of digital services that have taken place over the years. These strategies clarified and complemented the strategic lines of action already identified to meet the current use of digital services and their future needs, and recommended improving and adapting the regulatory framework by merging the requirements of the 2002 Directives into a consolidated European Electronic Communications Code. The new strategies also set out the quality requirements for the future Internet. As digital technologies are evolving at a rapid pace, the high-speed Internet speeds and availability required to achieve a technology fit for the digital society were also specified. The strategy for moving towards a gigabit society in Europe thus set a target that **by 2025, all European households in both rural and urban areas should have access to an Internet connection with download speeds of at least 100 Mbps, upgradable to gigabit speeds.** In addition, all urban areas and all land transport routes must have uninterrupted 5G coverage by 2025 [9].

While strategic objectives have been set and conditions, including certain quality requirements, have been included to contribute to the achievement of these objectives, no mechanism has been developed to infer the actual state of progress and to provide a common set of benchmarks to measure progress. This is confirmed both by the Commission's statement in its Communication on the Digital Agenda that **consumers lack confidence in the actual speed of the services provided to them [11]** and by BEREC's guidance on geographic network surveys, which states that **the information that will be collected through the geographic survey initiative is a general indicator and not relevant to the user experience** and that this **information needs to be validated. [10]**

Aim and objectives

Taking the importance of the availability of the internet service and the need for an objective assessment of broadband penetration and its quality indicators into account, **the aim of the Doctoral Thesis** is to evaluate and propose a mechanism for monitoring broadband

development and to develop a mathematically sound methodology for assessing Internet quality indicators.

To achieve the objective, the following **key tasks** were set:

1. To assess the parameters characterising the quality of an Internet access service and to identify a set of parameters that provide comprehensive information on the level of quality of service to be provided to the end-user, as well as to assess the minimum required performance of these parameters for the use of different Internet-based services, thus allowing conclusions to be drawn on the expected quality of user experience (QoE).
2. To research the possibilities of assessing broadband evolution in different quality monitoring levels (QoS-1, QoS-2, QoS-3), to assess their main differences and to identify their applicability aspects for monitoring broadband evolution.
3. To research and evaluate the factors influencing the evaluation of the internet service and the aspects of the Internet principles that need to be taken into account in defining the functional requirements of the measurement system and in analysing and presenting the quality indicators.
4. Using mathematical calculations and experimental measurements, to define a sample of Internet geographic measurement sites to estimate broadband penetration.
5. Using mathematical calculations and experimental measurements, to develop a methodology for measuring Internet quality to reflect broadband evolution at the QoS-2 level.
6. To develop an algorithm for assessing and monitoring insufficient broadband development.
7. Using mathematical calculations and experimental measurements, to determine the minimum quality parameters for adequate broadband Internet, taking into account the level of internet service quality used by the majority of consumers in the country.
8. To evaluate and develop a model for obtaining information on Internet quality indicators using data held by service providers, thus minimising the long-term involvement of human resources in the experimental evaluation, analytical processing, preparation, submission and validation of broadband development indicators.

Research methodology

Experimental measurements, mathematical calculations, statistical data evaluation and numerical simulations have been performed in order to carry out the tasks and analyse the problems set out in the Doctoral Thesis. For experimental measurements, the Public Utilities Commission (PUC), Internet Access Service Quality Measurement system ITEST, based on Visualware Inc. software solution, allows the assessment of Internet quality parameters such as download and upload speed, latency, jitter and packet loss rate. Mathematical calculations using various statistical analysis methods have been performed to define optimal measurement methods based on the obtained measurement results. The R and Phyton programming languages are used for data analysis and numerical simulation. Wireshark software was used to monitor

the measurement data flow. To model the Big Data analytics algorithm, the Hadoop MapReduce paradigm was explored.

Research results and scientific novelty

Practical value and new contributions

- Concepts have been developed, which will be used in the development of regulatory acts of the Public Utilities Commission and its monitoring of the quality of internet service, implementing the defined principles in the methodology for assessing the quality of internet service, as well as through participation in working groups of the Body of European Regulators for Electronic Communications, the defined principles will be proposed for implementation in the relevant documents developed by the Authority, ensuring a common approach to Internet quality monitoring at the European level.
- The aspects and principles related to the measurement of the quality of internet service identified in the research have been taken into account in the technical documentation for the development and implementation of the new system for measuring the quality of internet service of the Public Utilities Commission.
- Principles and monitoring options for assessing actual broadband penetration and quality of service are explored and proposed, depending on available resources and future technological developments.
- The principles of data provision for the geographical survey information and comparability tool and a schematic prototype for the implementation of the aggregated representation have been developed, providing comprehensive information on broadband Internet availability in Latvia.

Key conclusions of the Doctoral Thesis

- An assessment of the regulatory framework for the electronic communications sector shows that it is possible to establish a consistent and uniform mechanism for the implementation and application of monitoring methods.
- In order to measure broadband penetration and promote its further extension and the availability of an adequate quality of internet service, an algorithm should be applied to identify geographical areas where the population is not sufficiently and adequately connected to the Internet. The designation of such areas will enable planning and financial investment in the development of the electronic communications network and will facilitate wider access to internet services for citizens.
- Evaluating Internet quality indicators is essential to obtain a numerical measure for interpreting quality. They allow the level of development of electronic communications networks to be assessed and compared at the national and international level, ensure the assessment of service compliance with technology standards, set reasonable requirements for electronic communications undertakings, and ensure the protection of

users' rights. Consequently, a mechanism was developed to measure quality indicators that will provide objective, meaningful and comparable information.

- To assess the performance of an electronic communications network and broadband penetration, it is not sufficient to use data at the QoS-1 level, which includes theoretical information about the internet service provided. In conclusion, the theoretical assessment of the quality of internet service parameters may differ significantly from the actual indicators.
- Monitoring and mapping Internet quality in mobile electronic communications networks at the QoS-2 level requires the identification of a numerical and geographic sample of measurements against which to plan and conduct Internet quality measurements, thus ensuring a true reflection of the situation at a given geographic scale.
- In order to obtain and report correct and unbiased results when measuring Internet quality parameters, it is essential to ensure that the measurements are carried out during the time of day with the smallest deviation of the connection speed values from the daily average connection speed value. It was found that the period between 9:00 and 15:00 has the smallest deviation from the daily average download speed and most accurately represents the average download speed at a given location.
- To ensure adequate access to broadband Internet, it is necessary to set minimum speeds for internet service to ensure an adequate level of social inclusion and participation in the digital economy and society. It concludes that for fixed internet service and mobile internet service provided at a fixed location, the minimum download speed to be provided is at least 6 Mbps and the upload speed is at least 2 Mbps.
- In the future planning of Internet quality monitoring, with the widespread deployment of 5G technology, and in order to ensure that the actual quality parameters are reflected in the 100 m × 100 m polygon according to the geographic survey requirements, it is necessary to apply a quality assessment methodology that will be based on mobile operators' data analytics.

Use of the Doctoral Thesis results

The results obtained during research and reflected in the Doctoral Thesis have been used in 3 international projects, 3 transnational seminars in the field of electronic communications, as well as in the development and improvement of 3 Latvian regulatory frameworks.

Theses to be defended in the Doctoral Thesis

1. The development of a common methodology for monitoring internet service can provide complete, objective, comparable and factual information on broadband internet penetration, availability and quality, which can be used to meet the needs of a wide range of information users.
2. The paper shows that there is a direct correlation between the measurement time of a mobile internet service and the values of certain quality of service parameters, and

determines the most appropriate time of day for quality measurements, which provides the most objective representation of the measurement results.

3. The actual assessment of the quality of the internet service needs to be based on a mathematically sound measurement approach, thus ensuring the reliability and objectivity of the measurement results.

Approbation of the Doctoral Thesis results

The main results of the Doctoral Thesis have been presented at 4 international scientific conferences, as well as included in 2 publications in scientific journals, 4 articles in conference proceedings, and 1 publication submitted to a scientific journal at the end of 2021.

Reports at International Scientific Conferences

1. Lipenbergs, E., Stafecka, A., Ivanovs, Ģ., **Smirnova (Vagale), I.** Quality of Service Measurements and Service Mapping for the Mobile Internet Access. In: 2017 Progress in Electromagnetics Research Symposium – Spring (PIERS 2017), Russia, Petersburg, 22–25 May 2017.
2. Lipenbergs, E., **Smirnova (Vagale), I.**, Stafecka, A., Ivanovs, Ģ., Gavars, P. Quality of Service Parameter Measurements Data Analysis in the Scope of Net Neutrality. In: 2017 Progress in Electromagnetics Research Symposium – Fall (PIERS 2017), Singapore, Nanyang, 19–22 November 2017.
3. **Smirnova (Vagale), I.**, Lipenbergs, E., Bobrovs, V., Gavars, P., Ivanovs, Ģ. Network Slicing in the Scope of Net Neutrality Rules. In: Progress In Electromagnetics Research Symposium – Spring (PIERS 2019), Italy, Rome, 17–20 June 2019.
4. **Smirnova (Vagale), I.**, Lipenbergs E., Bobrovs V., Ivanovs Ģ., "The Analysis of the Impact of Measurement Reference Points in the Assessment of Internet Access Service quality"// Proceedings of Progress in Electromagnetics Research Symposium PIERS 2019 – Fall, PIERS, Xiamen, China, 17–20 December 2019.

Publications in Scientific Magazines

1. **Smirnova (Vagale), I.**, Lipenbergs, E., Bobrovs, V. "Mathematical algorithm for processing measurement results of internet access service in the scope of net neutrality"// Proceedings of LATVIAN JOURNAL OF PHYSICS AND TECHNICAL SCIENCES, LV, 2018, No. 3, pp. 63–69.
2. **Vagale (Smirnova), I.,** Lipenbergs, E., Bobrovs, V., Ivanovs, G. Development of Internet Measurement Principles for Representation of Measured Provision of Service (QoS-2). Journal of Information and Telecommunication, 2021, Vol. 5, No. 2., pp. 267–277.

Publications in Conference Proceedings

1. Lipenbergs, E., Stafecka, A., Ivanovs, Ģ., **Smirnova (Vagale), I.** Quality of Service Measurements and Service Mapping for the Mobile Internet Access. In: 2017 Progress

in Electromagnetics Research Symposium – Spring (PIERS 2017), Russia, Saint Petersburg, 22–25 May, 2017. pp. 2526–2532.

2. Lipenbergs, E., **Smirnova (Vagale), I.**, Stafecka, A., Ivanovs, Ģ., Gavars, P. Quality of Service Parameter Measurements Data Analysis in the Scope of Net Neutrality. In: 2017 Progress in Electromagnetics Research Symposium – Fall (PIERS 2017), Singapore, Nanyang, 19–22 November, 2017, pp. 1230–1234.
3. **Smirnova (Vagale), I.**, Lipenbergs, E., Bobrovs, V., Gavars, P., Ivanovs, Ģ. Network Slicing in the Scope of Net Neutrality Rules. In: Progress in Electromagnetics Research Symposium – Spring (PIERS 2019), Italy, Rome, 17–20 June, 2019, pp. 1516–1521.
4. **Vagale (Smirnova), I.**, Lipenbergs, E., Bobrovs, V., Ivanovs, Ģ. The Analysis of the Impact of Measurement Reference Points in the Assessment of Internet Access Service Quality. No: Progress in Electromagnetics Research Symposium – Fall (PIERS – Fall): 2019 Photonics & Electromagnetics Research Symposium, China, Xiamen, 17–20 December 2019. Piscataway: IEEE, 2019, pp. 2972–2977.

Scope and structure of the Doctoral Thesis

The Doctoral Thesis is 161 pages long. The Thesis consists of an introduction, five chapters, a list of references and an appendix.

C**hapter 1** of the Doctoral Thesis examines trends in broadband development and use. The role of broadband penetration and widespread accessibility in boosting social and economic growth is assessed. European strategies and frameworks to promote broadband development are analysed, as well as the requirements and procedures for their application and existing national and European projects to monitor broadband development and the quality of broadband provision. Gaps and shortcomings in the existing regulatory framework and in the principles contained in the projects are analysed, which hinder objective and comparable information on the actual quality of broadband provision, as well as the full achievement of the European objectives.

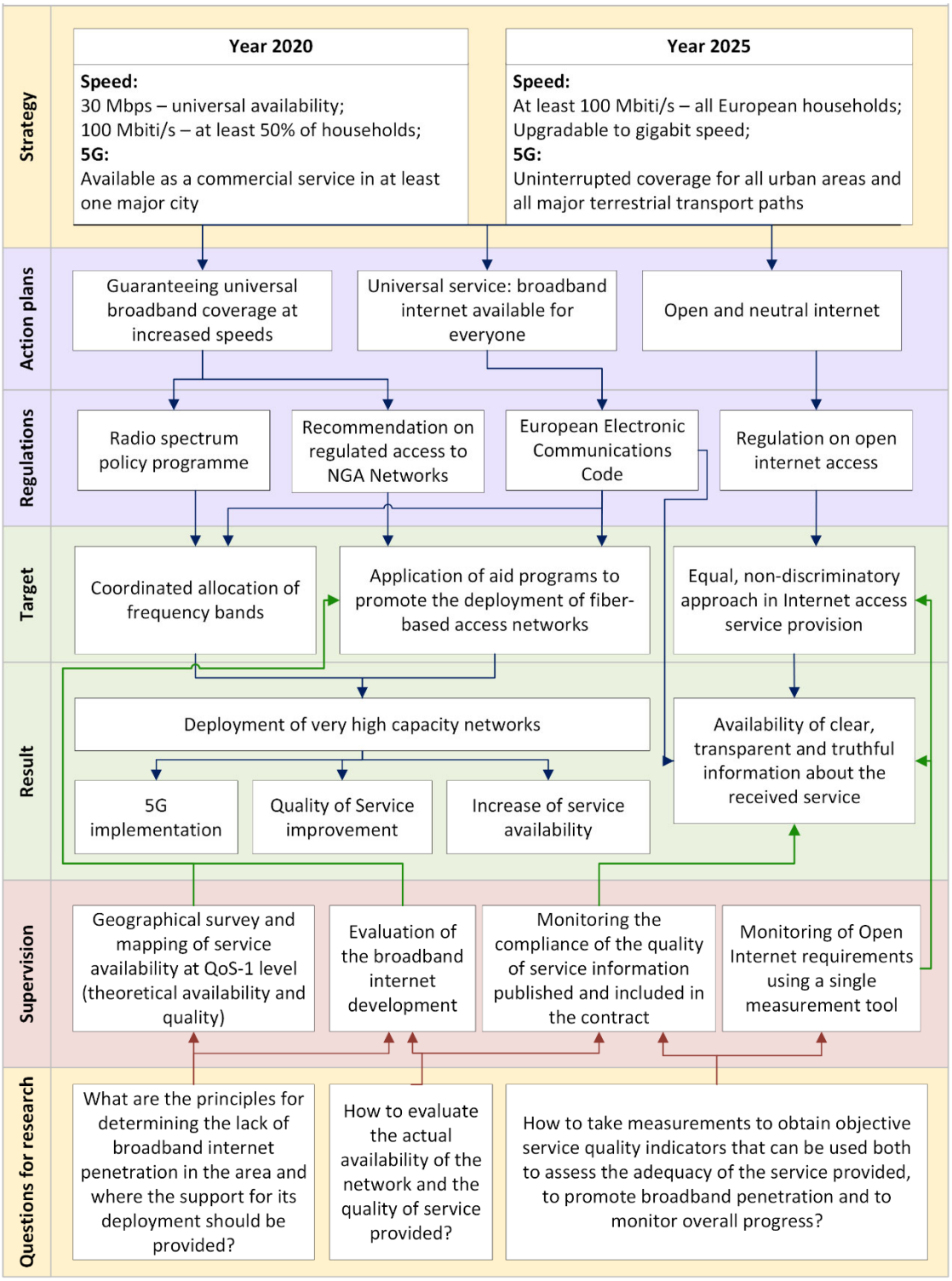

Fig. 1. A schematic summary of the lines of action, legislation, objectives and expected results, as well as the necessary monitoring measures and identified gaps, stemming from the European strategic objectives

C**hapter** 2 of the Doctoral Thesis analyses the parameters characterising the quality of the internet service depending on the point of view of its evaluation. A number of international recommendations have been analysed for a set of parameters to be assessed depending on the aspect of service provision. The quality parameters that provide information on the technical

quality of service have been studied in depth, and the minimum set of quality parameters that most comprehensively describe the level of quality received, reflecting not only network and service performance but also indicating the QoE experience of potential users, has been identified. Internet connection phase and measurement principles are assessed to ensure that quality indicators are assessed from the user's perspective and provide objective and comparable measurement results.

Chapter 3 of the Doctoral Thesis provides an in-depth study of the operation and algorithms of the Transmission Control Protocol (TCP), which is particularly important to consider when designing an internet measurement system and providing internet quality measurements to obtain true and unbiased throughput measurements. Other factors influencing the measurement results are analysed and taken into account when defining the measurement approach and methodology.

Chapter 4 analyses the results of the measurement of the internet service, defining the measurement principles and developing the measurement methodology. The potential impact on the measurement of quality parameters is assessed and the possibility of mitigating these impacts is analysed. The most appropriate statistical measures to characterise the measurement results are analysed. Principles have been set out on how these measurement results should be presented in relation to the requirements of the European framework.

Chapter 5 analyses an alternative option for practical measurements of the quality of internet service – the MDT solution. Options for its application are assessed, and the advantages, disadvantages and main obstacles to its use are analysed. Future research directions are assessed, analysing the cost-effectiveness and relevance of such a solution for monitoring broadband penetration and quality in line with common European objectives.

The Doctoral Thesis concludes with a summary of the results of the completed research. Finally, the main conclusions of the Thesis are summarised and justified. Appendices contain lists of scientific conferences and publications.

OUTLINE OF DOCTORAL THESIS SECTIONS

Chapter 1

This chapter deals with the assessment of broadband internet service indicators and availability by international organisations such as OECD, European Commission, Body of European Regulators for Electronic Communications (BEREC) and Public Utilities Commission (SPRK) in Latvia, as well as forecasts regarding the Internet usage trends and volumes by assessing information provided by international companies such as Ericsson, GSMA, Cisco Systems, Inc. An overview of the use cases defined for 5G technology, their corresponding quality indicators, as well as the basic conditions for technology development, in line with the recommendations of the International Telecommunication Union (ITU) [5], [6], [7], is also provided.

The EU strategies developed by the European Commission have been assessed, as have the directives and regulations of the European Parliament and the Council that define the requirements for achieving the objectives set out in the strategies (see Fig. 1). The transposition of the requirements into Latvian legislation is summarised, introducing the relevant provisions and laying down conditions to protect the interests of users.

In addition, the framework for reflecting broadband internet availability introduced in the European Broadband Mapping Project and defined in the BEREC Guidelines for Geographic Network Surveys, which aims to provide information on broadband internet performance at the scale of different territorial units [10], [12], [13], is analysed. Thus, the mapping of fixed broadband is designed according to the service to be provided at specific address points, while the mapping of mobile broadband is designed to provide information on service availability on a 100 m × 100 m grid. The levels defined for broadband data representation (QoS-1, QoS-2, and QoS-3) are also discussed, which classify the data to be represented according to the way it was obtained (theoretical calculations or measurements), as well as according to the stage of service provision being evaluated (see Fig. 2). In addition, the applicability of theoretical calculations to the assessment of broadband internet quality indicators is analysed, as well as the differences in practical measurement results and the reasons for them.

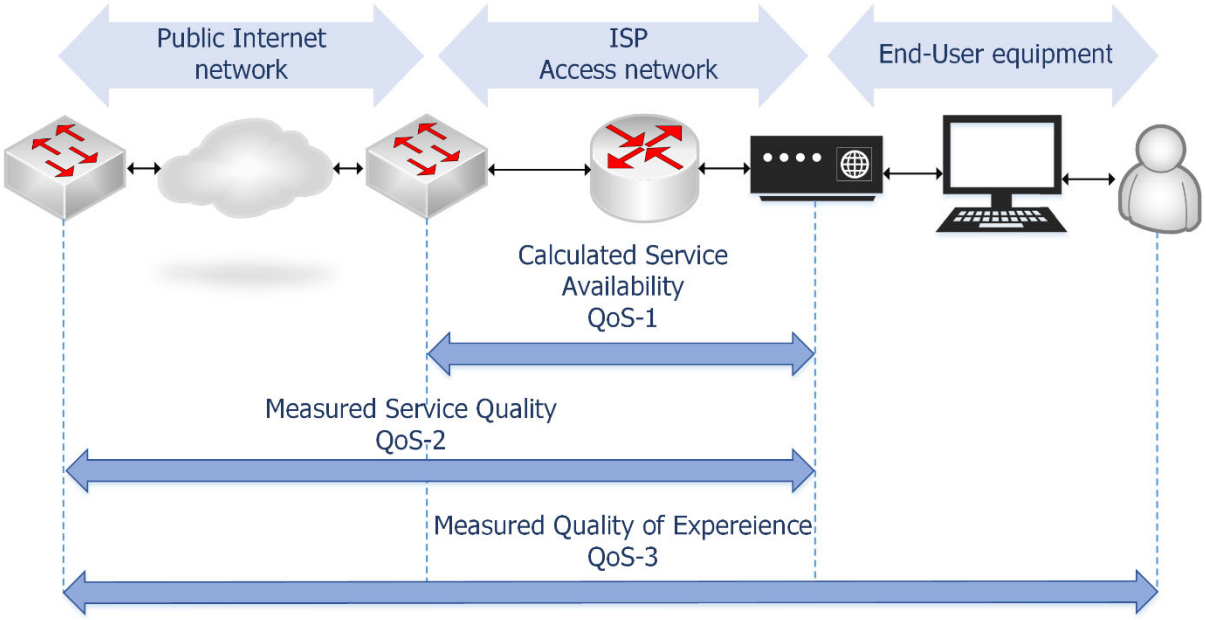

Fig. 2. Schematic representation of the quality of service assessment levels implemented in the broadband mapping project [11]

It is, therefore, concluded that, in line with the trends and foreseeable volumes of internet use, the strategic objectives of the European Commission to promote broadband internet access are relevant and important in supporting various social and economic aspects. In order to achieve these objectives and raise user awareness, it is essential to provide universally accessible, meaningful and objective information on the availability of broadband internet and the level of quality to be ensured. However, it has been concluded that while existing laws and regulations outline lines of action and aspects of supervision, they do not set clear and uniform requirements for supervisory methods. Consequently, it cannot be guaranteed that the results of the monitoring reflect the actual situation, thus affecting both public awareness and the validity of decisions in the application of the various State aid programmes.

Chapter 2

This chapter analyses various parameters characterising the quality of the internet service, their interpretation depending on the stage of connection and on different aspects of service provision or use. Quality of service (QoS) always describes the E2E testing link, i.e., user-to-user or user-to-content. Quality of service (QoS) is thus measured at the E2E stage in terms of objective (quantitative) or subjective (qualitative) parameters. Consequently, a binding assessment of the quality of the Internet for users should be carried out in the E2E phase.

.

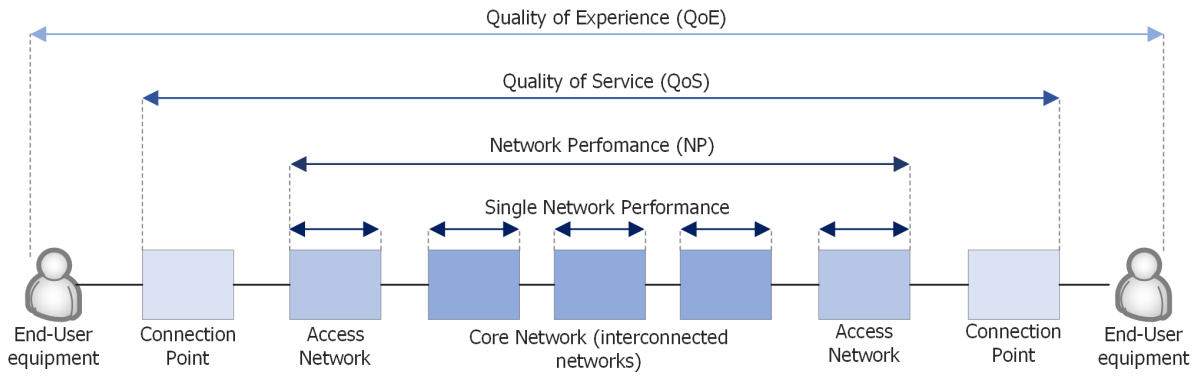

Fig. 3. Schematic representation of the assessment of service delivery phases for network performance, quality of service (QoS) and quality of experience (QoE) [14]

The technical quality of service indicators that are relevant to the user, which characterise the user's experience when using the Internet, are assessed, as well as the quality parameters that affect these indicators. In addition, key parameters such as data rate, latency, delay and packet loss are summarised, the assessment of which allows one to draw a conclusion on the overall level of quality provided and to predict user satisfaction. The level at which the OSI protocol stack needs to be evaluated in order to characterise the level of quality available to the user has been analysed [14], [16], [17], [18].

Chapter 3

The chapter analyses the principles and algorithms of the Transmission Control Protocol (TCP) and the necessity to follow them when designing and setting up a measurement system in order to obtain an objective and realistic throughput assessment, discusses other aspects related to internet service quality measurements that may affect the measurement results, as well as defines criteria for the placement of the measurement system reference point in order to ensure comparable and unbiased measurement results.

Several factors can affect TCP throughput and its measurement results. There are factors that arise independently of TCP's operating principles and settings, such as cross traffic (UDP or TCP), the number of competing TCP connections, overload on the transmission path, as well as the size of router buffers, and the capacity and load of each channel. These factors may also be present when the user is using the internet service, so in general, they do not affect the objectivity of the results, and their influence on the measurement results can be minimised by taking measurements at the appropriate time, quantity and location.

However, there are factors that depend directly on the specifics of TCP operation that must be taken into account in the design of the measurement system itself, as well as in the TCP settings. For example, TCP throughput can be affected by factors such as the size of TCP buffers on both the sender and receiver side, the number of parallel TCP connections established in the measurement, the duration of the measurement and the amount of data to be transmitted, differences in TCP specifications (e.g., Tahoe, Reno, NewReno), and several other parameters [19], [20], [21]. The location of the reference server and its connection capacity are also

important. The studies have shown that when measured against different measurement servers located relatively close to each other (within the city of Riga), the difference in measurement results reaches 8 %. On the other hand, when measured against different servers spread across Europe, the results can vary by up to 70 %. It follows that in order to assess the quality indicators available in a given country, measurements need to be made at a national level. Connecting the metering server to a national or regional Internet Exchange Point switching facility is considered to be the most appropriate solution. This reference point location provides objective information on the connection quality indicators available to the user [22], [23].

Chapter 4

In the chapter, based on the actual results of internet quality measurements, obtained by taking several thousands of measurements per day over a week, the dynamics of changes in download speeds for different internet connection technologies in fixed (FTTH 100 Mbps connection and ADSL connection) and mobile (4G connection) networks are assessed.

Analysing the dynamics of download speed changes during the day in a fixed network shows that both ADSL and fibre networks provide relatively stable connection speed values regardless of the time of day.

In the measurements of the FTTH connection in the fixed network, where the maximum connection speed is contractually set at 100 Mbps, it was observed that the 2.5 percentile of the measurement sample was 63.95 Mbps, i.e., in 97.5 % of the measurements the connection speed was not lower than this value. It was also observed that in most cases (75 %) the reduction in connection speed was no more than 15 % of the maximum value specified in the contract. In half of the measurements, download speeds were close to the maximum value. The conclusion is that the fibre network is delivering robust download speeds and in most cases the drops are not significant.

An analysis of the measurements made over a fixed ADSL connection shows that 97.7 % of the measurements are close to the maximum observed value – the differences are measured in kilobits, which shows the remarkable stability of the download speeds provided.

The results of the measurements on the mobile electronic communications network show that download speed values vary over a wide range of values throughout the day. Given the significant variation in quality indicator values for a service provided over a mobile network, it is concluded that a defined measurement approach is essential for obtaining objective quality indicators [24].

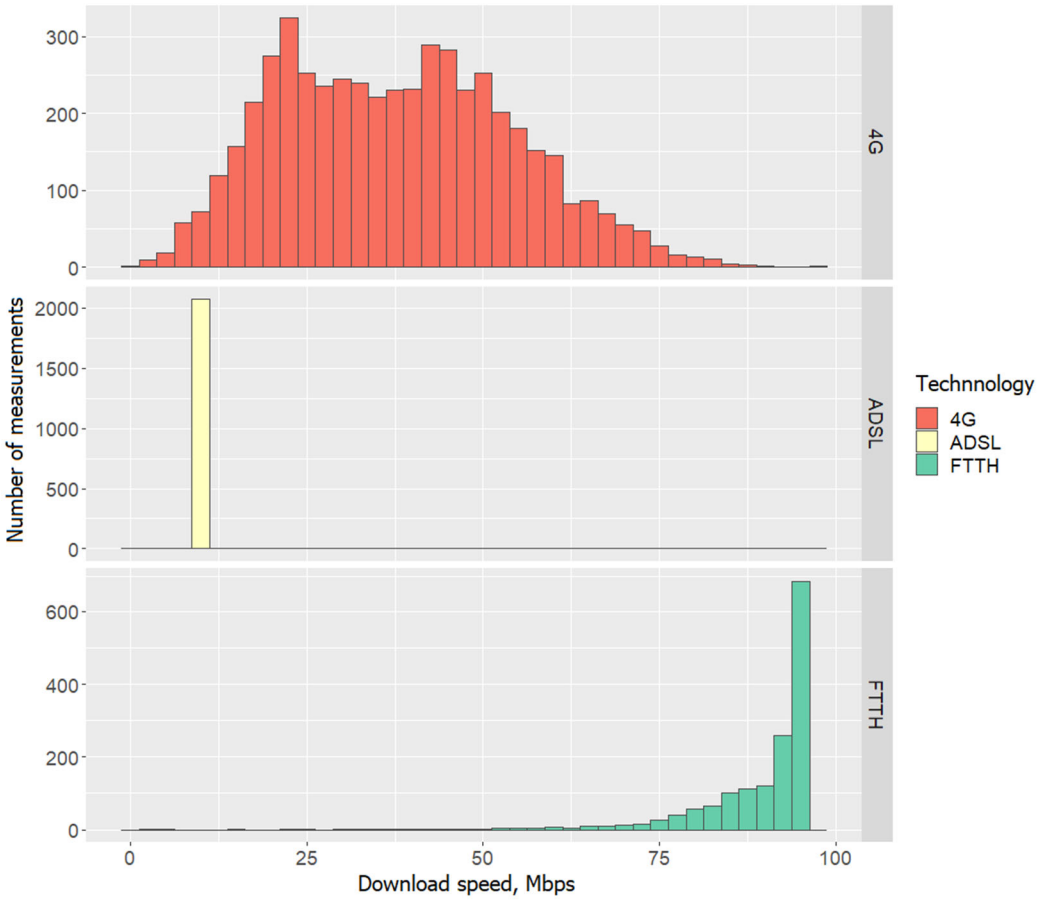

Fig. 4. Distribution of measured download speed values on the fixed FTTH 100 Megabits/s connection network, on the fixed ADSL connection network, and on the mobile 4G connection network

In order to assess the influence of the time of day on the measurement results and to develop a measurement methodology taking this influence into account, a study was carried out to assess whether there is a correlation between the measurement time and the values of the quality parameters, as well as between the different quality parameters. In total, the correlation assessment analyses more than 530 000 measurement results from a long series of measurements at 45 different locations in Latvia in 2019 and 2020. The calculations show that the results of the download speed measurements are statistically significantly negatively correlated with the time of day of the measurement (at a significance level of $\alpha = 0.05$). Thus, on average, the later the measurement, the lower the download speed observed.

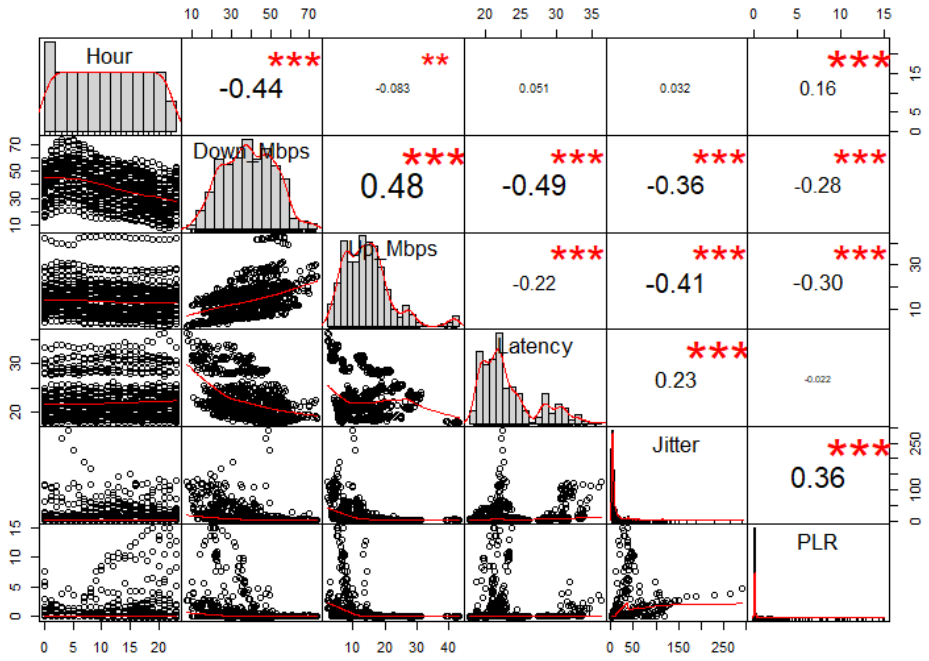

Fig. 5. Correlation graph between hourly averages of quality parameters and time of day

It was, therefore, assumed that the measurements should be carried out over a period of time that ensures that the values of the measurement results are numerically equivalent to the daily average. To test this assumption, calculations were made by comparing the average download speed per hour with the average download speed per day (see Fig. 6). The result was the time of day with the smallest difference between the measurements taken at a particular hour of the day and the overall daily values [25].

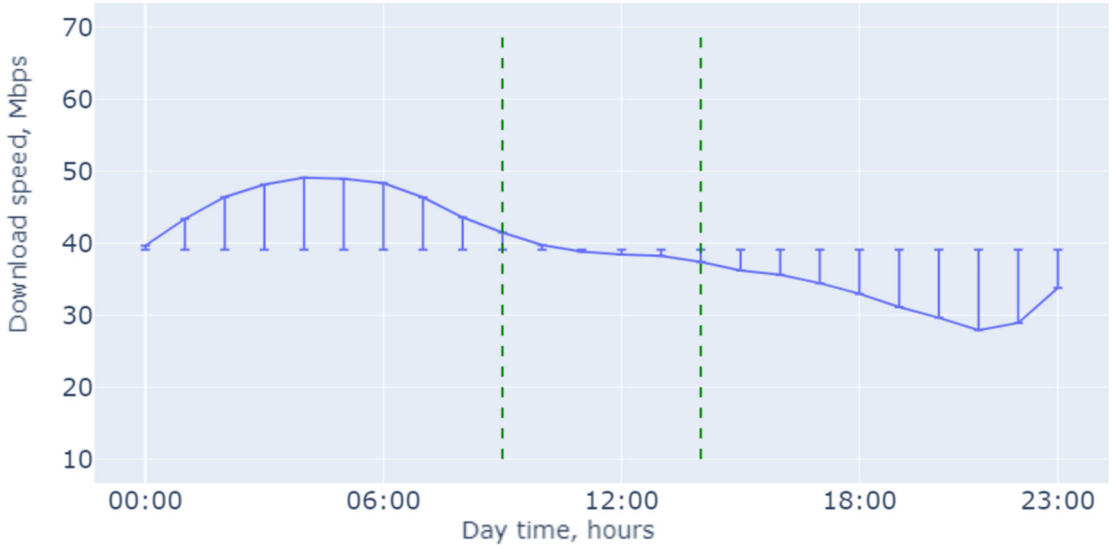

Fig. 6. Difference between hourly average download speed values and daily average download speed values

Figure 7 shows the distribution of average download speeds. The figure shows that the distribution of morning (00:00–08:00) and evening (16:00–23:00) results differs from the

distribution of daily values. On the other hand, the day (from 09:00–15:00) values look visually equivalent.

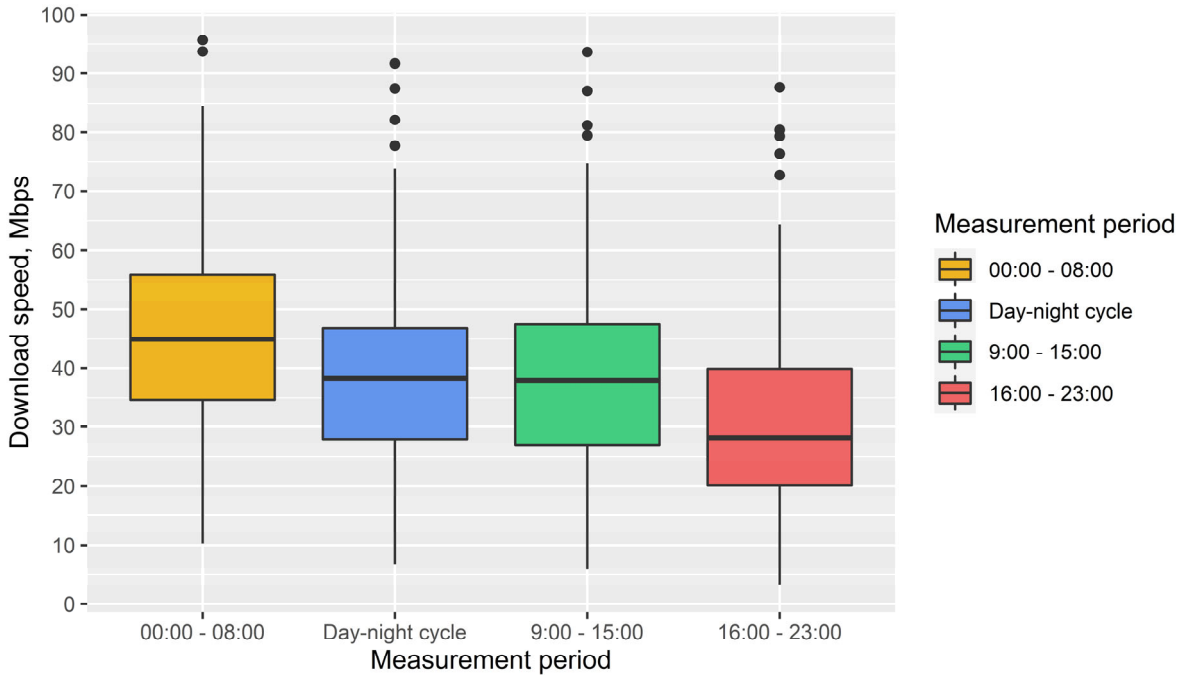

Fig. 7. Scatter of measured download speed values at different times of the day

Based on these observations, the hypothesis H_0: $\mu_0 = \mu$ against H_1: $\mu_0 \neq \mu$ was put forward that the average download speed measured between 9:00–15:00 (μ) is equal to the average download speed measured throughout the day (μ_0).

To compare the average download speeds between the four sampled daily periods, an analysis of variance test and a so-called post-hoc test was performed.

Table 1

Testing the Equality of Means Between Different Groups with a Post-hoc Test Using R Roftware

```
require(PMCMRplus)
posthoc.kruskal.nemenyi.test(x=dati$Down_Mbps, g=dati$M_period,
dist="Tukey")
```

	00:00–08:00	16:00–23:00	9:00–15:00
16:00–23:00	9.2e-07	-	-
9:00–15:00	0.059	0.031	-
24 hours	**0.078**	**0.023**	**1.000**

The calculated data show that at a significance level of α = 0.05, the equality between the day-night and evening (16:00–23:00) averages is rejected (*p*-value < 0.05). Comparing the day-night and morning (00:00–08:00) mean values, it can be concluded that at a significance level

of α = 0.05, the equation cannot be rejected. However, given the calculated *p*-value (0.078), it can be concluded that this equality between the means of the two groups cannot be considered statistically significant. It may be possible to observe values equivalent to the daily mean during some hours in this period, but the probability is too small and the potential bias too large to be of practical use. However, when the day-night cycle averages are evaluated against the day (09:00–15:00) averages, there is a highly statistically significant equality between these groups (*p*-value 0.999536). Consequently, it was hypothesised that the average values of the download speed measurements taken between 09:00–15:00 are equal to the average values of the download speeds evaluated over the whole 24-hour period, and this time of day was recommended for the measurements.

The number of replicate measurements required at a given measurement location is calculated to ensure that the mean values of the assessed quality of service parameters fall within the specified limits of the mean value of the hypothetical set with 95 % confidence. The following formula is used to calculate the required number of measurements or sample size [26]:

$$n = \frac{{z_{\alpha/2}}^2 \cdot \sigma^2}{e^2}, \quad (1)$$

where $z_{\alpha/2}$ corresponds to the desired confidence level; σ is standard deviation; and e is margin of error.

Calculations were performed separately for connection speed and latency.

As the quality of internet service parameters is assessed simultaneously, **a minimum of 63 measurements** per site are required to ensure that the average download and upload speeds assessed at each measurement site during the period from 9:00–15:00 are within ±5 Mbps with 95 % confidence and the average latency is within ±2.5 ms with 95 % confidence. On the other hand, to ensure that under the same conditions the average download and upload speeds are within ±10 Mbps with 95 % confidence and the average latency within ±5 ms with 95 % confidence, **a minimum of 16 measurements** per site must be taken.

Given the distribution of the jitter and packet loss coefficient measurements, it can be concluded that a different approach is needed to monitor them. The assessment of these parameters over a short period of time by a single series of measurements at a specific measurement site cannot be presented as a site-specific reading, as this is likely to give a false impression of the overall quality level of these parameters. However, it is important to monitor these parameters and, in the case of repeated high readings of these parameters, to carry out additional measurements over a longer period of time in order to ascertain their impact on the overall quality level and the user experience of the internet service.

The Doctoral Thesis assesses the minimum number of measurement sites required for the overall national mean values of the quality parameters to fall within a specified range of the mean value with 95 % confidence. While the overall national average internet quality score does not provide information on the level of quality available to a given user, it is an important measure for objectively assessing the overall evolution of mobile network performance, as well as for comparing it between different operators and with those provided in other countries.

Thus, it was calculated that at least 1756 different measurement locations would need to be measured across the country to ensure that, with 95 % confidence, the sample mean download speed value would be within ±2 Mbps of the hypothetical cluster mean value. The average upload speed will then fall within ±0.5 Mbps of the hypothetical cluster mean with 95 % confidence, while the average latency will fall within ±1 ms of the hypothetical cluster mean with 95 % confidence.

In addition, the distribution of the results of the measurements of the quality parameters according to population size and density has been assessed and, on this basis, a principle for selecting the number of measurement sites in different areas has been defined. Taking the minimum number of measurement sites required to ensure that the mean values of the parameters fall within the specified limits of the mean value of the hypothetical set with 95 % confidence into account, and based on the defined principle of distribution of the number of measurement sites, the corresponding number and distribution of measurement sites within the territory of Latvia has been calculated.

Similarly, the assessment of the measurement results over a six-year period has assessed how often the measurement cycle needs to be repeated to ensure that the quality parameter values reported are representative of the current performance of broadband networks. It can be concluded that it is optimal to repeat the measurement cycle once a year within the national territory.

In addition, a possible mechanism for assessing areas of broadband undersupply is defined, based on information from a geographical survey. The theoretical indicators and the values of the connection speeds obtained from practical measurements have been assessed, which could indicate that the quality of broadband internet in the area is not provided at an adequate level. This provides a first extract of areas of insufficient broadband.

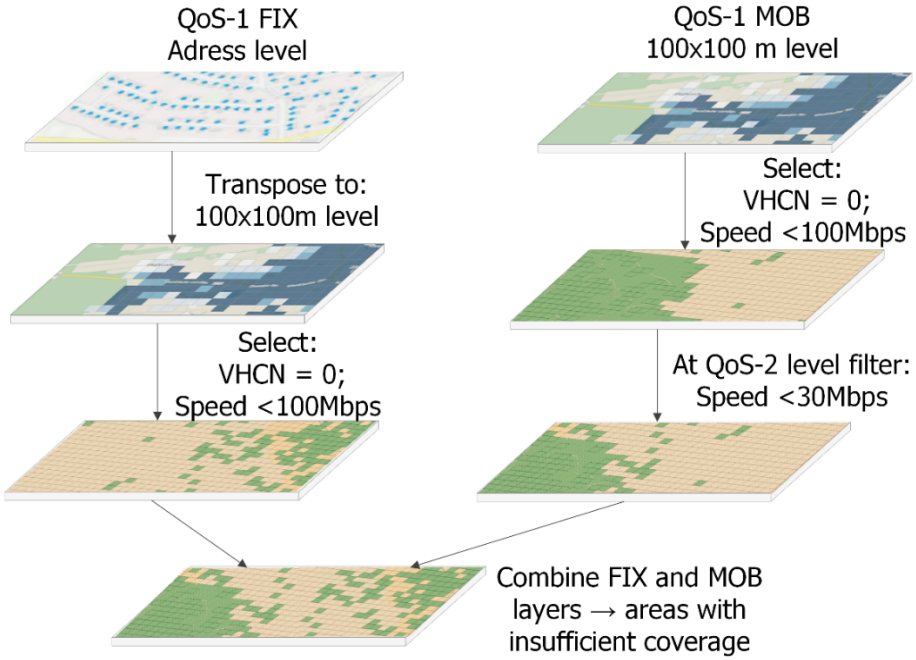

Fig. 8. Algorithm for identifying areas with insufficient broadband coverage based on geographic survey data

A framework is set out for an in-depth analysis of the identified areas that need to be assessed in order to plan future broadband investments in these areas. This in-depth analysis and the identification of more detailed principles may be a direction for **future research**.

Chapter 5

In this chapter, a method is proposed for estimating the actual quality of internet service indicators using MDT technology and thus providing a QoS-2 level representation of quality indicators in a 100 m × 100 m grid over a wide area.

MDT allows mobile operators to record radio parameter measurements using the user's terminal equipment, such as a smartphone, and the measurement results are read back together with the GPS coordinates of the location [29], [30], [31]. MDT ensures that the measurement reports are uploaded periodically or on demand by the end-user's device during the signalling phase, so that no additional software installation is required on the end-user's device and no additional costs are incurred [27], [28], [31], [32]. With regard to the quality of service (QoS), MDT provides functionality to measure the quality of service (i.e., throughput, latency, packet loss) experienced by the end-user, using the user's terminal, and to analyse it at a geographical scale, obtaining the measurement results together with the location of the end-user's terminal [27]. This can provide information on the actual throughput and connectivity aspects available to the user [29].

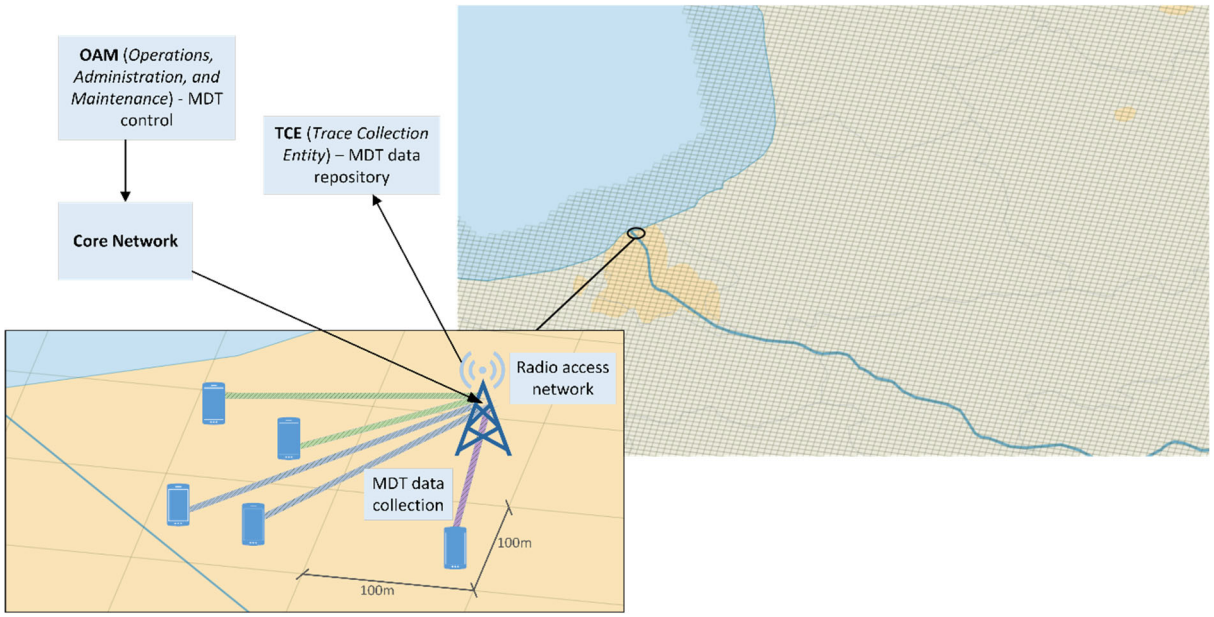

Fig. 9. Conceptual representation of MDT measurements and mapping of measurement results on a 100 m × 100 m grid scale

Given that active field measurements are practically impossible to carry out on such a dense spatial scale across the whole country, the following alternative method could be used. The Doctoral Thesis proposes a mechanism for aggregating measurement results using the Big Data analytics algorithm MapReduce, as well as a way to display the results on a 100 m × 100 m scale. As a result, on a large scale with a fine spatial distribution (100 m × 100 m grid), it would

be possible to measure and reflect actual data rates that are not reflected in the theoretical assessment of quality of service indicators and are practically impossible to provide by active measurements. This approach would be particularly relevant in 5G networks, assessing quality performance in different network segments where service servers are deployed closer to the edge of the network, enabling so-called *"edge computing"* (EC), which provides faster processing and storage capabilities. Consequently, in such cases, measurements up to the measurement server installed at the internet exchange would not reflect the actual quality performance [33].

The Doctoral Thesis also identifies the problem aspects of using such a method. First, MDT measurements are carried out on a specific operator's network, thus providing information on quality indicators within the service provider's network, without ensuring the same cross-section of measurement results with those obtained from active measurements. However, MDT measurements provide information on the quality of service experienced by the user, which is not reflected in the theoretical calculation of mobile network coverage. The MDT solution would, therefore, complement the theoretical information provided by operators by providing actual readings of network and quality parameters. However, active tests would still be relevant, especially in areas where MDT measurements cannot be obtained.

Secondly, MDT measurements reflect throughput at Layer 2 of the OSI protocol stack, or the data link layer, which refers to network performance metrics rather than the quality of service values available to the user.

Finally, as MDT measurements contain extensive information about the performance and usage of a mobile operator's network, mobile operators may not want to pass raw data to third parties (including public administrations). When providing data analytics on the mobile operator side, the question of the veracity of the reported values and the appropriateness of the measurement approach used remains. This still requires the verification of quality indicators by independent bodies.

Overall, the applicability of such a method for assessing and capturing internet service quality indicators may be an area **for future research**.

RESULTS OF THE DOCTORAL THESIS

In the course of carrying out the defined tasks, several main results and conclusions of the Doctoral Thesis have been obtained.

The assessment of the regulatory framework for the electronic communications sector concluded that it is possible to establish a consistent and uniform mechanism for the implementation and application of monitoring methods for assessing the quality of internet access service. Evaluating internet quality indicators is essential to obtain a numerical measure for interpreting quality. They allow the level of development of electronic communications networks to be assessed and compared at the national and international level, ensure the assessment of service compliance with technology standards, set reasonable requirements for electronic communications undertakings and ensure the protection of users' rights. In order to develop a common monitoring mechanism, existing monitoring requirements were assessed, aspects hindering the comparability and comprehensibility of monitoring results were identified, and principles were identified that are important to be taken into account to ensure that the assessment of internet quality indicators is objective, meaningful and applicable to the needs of a diverse range of users.

Given the critical importance of the internet service and Europe's strategic plans to make it more accessible, obtaining objective monitoring results is particularly important. The Thesis evaluated the role of practical measurements in the aspect of assessing the actual quality of internet service indicators, which, following the appropriate measurement principles, ensure the necessary objectivity of the results. Thus, the Doctoral Thesis developed a complete and mathematically sound methodology for monitoring and assessing the quality of internet service, which includes important conditions for different measurement conditions, the determination of the appropriate time of day and measurement sample size, as well as the number of measurement sites, their geographical distribution and the choice of the measurement repetition cycle.

Also, in order to ensure the assessment of broadband penetration and to promote its further spread and availability of adequate quality internet service, an algorithm was developed in the Doctoral Thesis to identify geographic areas where the population is not provided with an internet connection of sufficient quantity and quality. The designation of such areas will enable planning and financial investment in the development of the electronic communications network, including by facilitating the justification for investment through State aid programmes, and will facilitate wider access to internet services for citizens, thus ensuring compliance with universal service requirements.

In addition, the Doctoral Thesis assesses the importance of setting minimum quality requirements for adequate access to broadband internet and concludes that in order to ensure an adequate level of social inclusion and participation of citizens in the digital economy and society, it is necessary to set minimum internet service connection speeds. It concludes that for fixed internet service and mobile internet service provided at a fixed location, the minimum download speed to be provided is at least 6 Mbps and the upload speed is at least 2 Mbps.

In addition, the Doctoral Thesis outlines a possible future monitoring approach. In order to plan for the future monitoring of internet quality in the context of the widespread deployment of 5G connectivity, as well as to ensure that the actual quality parameters are reflected at the appropriate geographical scale, it is proposed to develop a quality assessment methodology based on mobile operators' data analytics.

The Doctoral Thesis summarises the results of completed research and defines possible future research directions.

1. Evaluate the use of MDT solutions in practice by assessing actual quality of service performance over a wide area, which could be particularly applicable to performance monitoring of 5G networks.
2. Develop and apply Big Data analysis algorithms to analyse geographic survey information and identify areas of broadband undersupply.

BIBLIOGRAPHY

[1] Ericsson, “Ericsson Mobility Report”, 2021 // https://www.ericsson.com/en/reports-and-papers/mobility-report/reports/june-2021, pp. 4–14, 20–24.

[2] OECD, "Broadband policy and technology developments", OECD Digital Economy Papers, No. 317, OECD Publishing, Paris, 2021 // https://doi.org/10.1787/e273ff77-en, pp. 50–51

[3] GSM Association – GSMA; “The Mobile Economy 2021”// https://www.gsma.com/mobileeconomy; GSMA Intelligence 2021, pp. 2–11, 19–33.

[4] Starptautiskā telekomunikāciju savienība (ITU), Starptautisko mobilo telekomunikāciju (IMT) attīstības mēķu vadlīnijas, Recomendācija ITU-R M.2083 “IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond”//2015, pp. 4–19.

[5] Starptautiskā telekomuinikāciju savienība (ITU), Pārskats ITU-R M.2410-0 “Minimum requirements related to technical performance for IMT-2020 radio interface(s)” // 2017, pp. 1–9.

[6] Komisijas Paziņojums “EIROPA 2020. Stratēģija gudrai, ilgtspējīgai un integrējošai izaugsmei” (Briselē, 3.3.2010 COM (2010), 2020), // https://ec.europa.eu/eu2020/pdf/1_LV_ACT_part1_v1.pdf .

[7] Komisijas paziņojums Eiropas Parlamentam, Padomei, Eiropas Ekonomikas un sociālo lietu komitejai un Reģionu komitejai, “Digitālā programma Eiropai” (Briselē, 19.5.2010. COM (2010)245).

[8] Komisijas paziņojums Eiropas Parlamentam, Padomei, Eiropas Ekonomikas un sociālo lietu komitejai un Reģionu komitejai, “Digitālā vienotā tirgus stratēģija Eiropai”, (Briselē, 6.5.2015. COM (2015) 192) // https://eur-lex.europa.eu/legal-content/LV/TXT/?uri=celex%3A52015DC0192.

[9] Komisijas paziņojums Eiropas Parlamentam, Padomei, Eiropas Ekonomikas un sociālo lietu komitejai un Reģionu komitejai, “Konkurētspējīga digitālā vienotā tirgus savienojamība. Virzība uz Eiropas Gigabitu sabiedrību”, COM (2016)587, 2016. // https://eur-lex.europa.eu/legal-content/LV/TXT/?uri=CELEX%3A52016DC0587.

[10] Body of European Regulators for Electronic Communications (BEREC) Guidelines on Geographical surveys of network deployments, BoR (20) 42, 2020, pp. 7–50.

[11] Komisijas paziņojums Eiropas Parlamentam, Padomei, Eiropas Ekonomikas un sociālo lietu komitejai un Reģionu komitejai, “Eiropas digitalizācijas programma – digitalizācijas virzīta Eiropas izaugsme”, (Briselē, 18.12.2012. COM (2012) 784), pp. 3–16.

[12] European Commission project “Mapping of Fixed and Mobile Broadband Services in Europe (SMART 2014/0016)” https://www.broadband-mapping.eu.

[13] Lipenbergs, E., Stafecka, A., Ivanovs, Ģ., **Smirnova (Vagale), I.** “Quality of Service Measurements and Service Mapping for the Mobile Internet Access”// Proceedings of Progress in Electromagnetics Research Symposium PIERS 2017, Saint Petersburg, RU, 2017, pp. 2526–2532.

[14] Body of European Regulators for Electronic Communications (BEREC) “A framework for Quality of Service in the scope of Net Neutrality”, BoR (11) 53, 2011, pp. 6–53.
[15] Eiropas Telekomunikāciju standartu institūts “Speech and multimedia Transmission Quality (STQ); Throughput Measurement Guidelines” (ETSI EG 203 165 V1.1.1), 2012, pp. 8–28.
[16] M. Mathis, M. Allman, “A Framework for Defining Empirical Bulk Transfer Capacity Metrics”, Internet Engineering Task Force IETF, RFC 3148, July 2001.
[17] Oueis, J., Strinati, E. “Uplink Traffic in Future Mobile Networks: Pulling the Alarm.”, International Conference on Cognitive Radio Oriented Wireless Networks, 2016, pp. 583–593.
[18] Sundaresan K., White G., Glennon S. “Latency Measurement: What is latency and how do we measure it?” Society of Cable Telecommunications Engineers (SCTE), International Society of Broadband Experts (ISBE), CableLabs, NCTA, Fall Technical Forum, October 2020, pp. 4–24.
[19] R. Prasad, C. Dovrolis, M. Murray, K. Claffy, "Bandwidth estimation: metrics, measurement techniques, and tools," IEEE Network, vol. 17, no. 6, Nov.-Dec. 2003, pp. 27–35.
[20] Kevin R. Fall, W. Richard Stevens, “TCP/IP Illustrated, Vol. 1: The Protocols” // Addison-Wesley Professional, ISBN: 9780321336316, 2011, pp. 579–793.
[21] Constantine B., Forget G., Geib R., Schrage R. “Framework for TCP Throughput Testing”, Internet Engineering Task Force IETF, RFC 6349, August 2011, pp. 5–26.
[22] Lipenbergs, E., Stafecka, A., Ivanovs, G., **Smirnova (Vagale), I.**, Gavars P. “Quality of Service Parameter Measurements Data Analysis in the Scope of Net Neutrality”// Proceedings of Progress in Electromagnetics Research Symposium PIERS 2017, Nanyang, SG, 2017, pp. 1–5.
[23] **Smirnova (Vagale), I.,** Lipenbergs, E., Bobrovs, V., Ivanovs, G. The Analysis of the Impact of Measurement Reference Points in the Assessment of Internet Access Service Quality, No: 2019 Progress in Electromagnetics Research Symposium (PIERS 2019), Ķīna, Ksiamena, 17–20 December 2019.
[24] **Smirnova (Vagale), I.**, Lipenbergs, E., Bobrovs, V. “Mathematical algorithm for processing measurement results of internet access service in the scope of net neutrality”// Proceedings of LATVIAN JOURNAL OF PHYSICS AND TECHNICAL SCIENCES, LV, 2018, No. 3, pp. 63–69.
[25] **Vagale, I.**, Lipenbergs, E., Bobrovs, V., Ivanovs, G. Development of Internet Measurement Principles for Representation of Measured Provision of Service (QoS-2). Journal of Information and Telecommunication, 2021, Vol. 5, No. 2, 267. 277 p.
[26] Weiers R. M. “Introduction to Business Statistics, Seventh Edition” // South-Western, Cengage Learning, 2011, pp. 293–294.
[27] 3GPP TS 37.320. V16.6.0 (2021-09) 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Universal Terrestrial Radio Access (UTRA) and Evolved Universal Terrestrial Radio Access (E-UTRA); Radio

measurement collection for Minimization of Drive Tests (MDT); Overall description; Stage 2 (Release 16), pp. 9–28.

[28] 3GPP TS 32.422 V12.6.0 (2021-03) 3rd Generation Partnership Project; Technical Specification Group Services and System Aspects; Telecommunication management; Subscriber and equipment trace; Trace control and configuration management (Release 12), pp. 11–140.

[29] J. Johansson, W. A. Hapsari, S. Kelley, and G. Bodog, "Minimization of drive tests in 3GPP release 11," in IEEE Communications Magazine, vol. 50, no. 11, November 2012, pp. 36–43.

[30] W. A. Hapsari, A. Umesh, M. Iwamura, M. Tomala, B. Gyula, and B. Sebire, "Minimization of drive tests solution in 3GPP," in IEEE Communications Magazine, vol. 50, no. 6, June 2012, pp. 28–36.

[31] Micheli D., Diamanti R. "Statistical Analysis of Interference in a Real LTE Access Network by Massive Collection of MDT Radio Measurement Data from Smartphones," 2019 PhotonIcs & Electromagnetics Research Symposium – Spring (PIERS-Spring), 2019, pp. 1906–1916.

[32] Po-Chiang Lin, "Minimization of Drive Tests using measurement reports from user equipment," 2014 IEEE 3rd Global Conference on Consumer Electronics (GCCE), 2014, pp. 84–85.

[33] **Smirnova (Vagale), I.**, Lipenbergs, E., Bobrovs, V., Gavars, P., Ivanovs, Ģ. Network Slicing in the Scope of Net Neutrality Rules. In: Progress in Electromagnetics Research Symposium – Spring (PIERS 2019), Italy, Rome, 17–20 June 2019.

Inga Vagale was born in 1990 in Riga. She holds a Bachelor's degree in Electrical Science and a Master's degree in Engineering in Telecommunications from Riga Technical University (RTU). She has been working in the field of telecommunications since 2012. Currently Inga Vagale is Chief Service Quality Expert in the Service Quality Division of the Electronic Communications and Postal Department of the Public Utilities Commission. Inga Vagale is a researcher with the Institute of Telecommunications of RTU Faculty of Electronics and Telecommunications.