



RIGA TECHNICAL  
UNIVERSITY

**Elmārs Lipenbergs**

# **LONG-TERM EVALUATION FRAMEWORK ELABORATION FOR THE BROADBAND INTERNET SERVICE QUALITY SUPERVISION**

Summary of the Doctoral Thesis



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**RIGA TECHNICAL UNIVERSITY**

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# **DOCTORAL THESIS PROPOSED TO RIGA TECHNICAL UNIVERSITY FOR THE PROMOTION TO THE SCIENTIFIC DEGREE OF DOCTOR OF ENGINEERING SCIENCES**

To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 19 December 2019 at the Faculty of Electronics and Telecommunications of Riga Technical University, 12 Āzenes Street, Room 201.

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## **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 Engineering Sciences is my own. I confirm that this Doctoral Thesis has not been submitted to any other university for the promotion to a scientific degree.

Elmārs Lipenbergs ..... (signature)

Date: .....

The Doctoral Thesis has been written in Latvian. It consists of Introduction; 3 chapters; Conclusions and Summary; 71 figures; 2 tables; 13 appendices; the total number of pages is 184, not including appendices. The bibliography contains 139 titles.

## ANNOTATION

Currently, electronic communication and content services available to users are mostly already obtainable by using an internet accessibility service, which gradually replaces various previously used types of communication and access to content. The research and internet usage forecasts predict that the total amount of data transmitted will grow threefold over the next five years. One of the most significant projects in the technology advancement field for the provision of transmission functions of electronic communication network is the introduction of 5G technology. Alongside access to the internet provided in fixed networks, the developments of mobile technology outline the 4G and 5G technology network development scenarios and suggest that by 2025 the number of mobile communication user connections among mobile operator networks worldwide will be close to 6 billion.

The Doctoral Thesis reflects the work performed within the framework of the study on implementation of a quality monitoring model that corresponds with the developments of technology for an internet access service. An assessment of an existing quality monitoring framework has been performed and suggestions have been provided for an engineering solutions concept of a methodology for sustainably adaptable broadband internet quality readings and of data mathematical analytics for the harmonisation of quality monitoring regulations. Study results linked to the quality of broadband internet services have been summarised in this Thesis by offering suggestions for the implementation of a fully functioning and complex quality monitoring model by providing the implementation of the components of the developed model in the regulatory documentation at an international level as well as a practical application in Latvia.

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## **ABBREVIATIONS**

2G – 2nd generation mobile network

3G – 3rd generation mobile network

4G – 4th generation mobile network

5G – 5th generation mobile network

### **B**

BEREC – Body of European Regulators for Electronic Communications

### **C**

CDN – content delivery network

CEPT – the European Conference of Postal and Telecommunications Administrations

### **D**

D2D – Device-to-Device

### **E**

ECC – Electronic Communications Committee

ETSI – European Telecommunications Standards Institute

### **F**

FTTH – fibre to the home

### **G**

GSMA – GSM Association

### **I**

ICT – information and communication

IoT – Internet of Things

ITEST – Internet Access Service Quality Measurement System of Public Utilities

Commission of Latvia

ITU – International Telecommunication Union

IXP – internet exchange point

### **L**

LIX – Latvian internet exchange

### **M**

M2M – machine-to-machine

**N**

NGN – next generation network

**O**

OECD – Organisation for Economic Cooperation and Development

**P**

PT TRIS – Project team Technical Regulatory Issues

**Q**

QoS – quality of service

**R**

RTT – round-trip delay time

**S**

SDN – software-defined networking

SPRK – Public Utilities Commission of Latvia

**W**

WG NaN – Working group Numbering and Networks



# GENERAL CHARACTERISTICS OF THE DOCTORAL THESIS

## Topicality of the Research

A range of electronic communications services and content services are already available to users through the Internet access service, which is gradually replacing different forms of communication and content access used previously. Global research and Internet usage forecasts suggest that the total amount of data transmitted will triple over the next five years. One of the major projects in the field of technological development for the provision of electronic communication network functions is the introduction of the fifth generation of technologies (5G technologies). The study by GSMA Intelligence and the forecasts contained in it (Fig. 1) demonstrate the most important steps in the development of the mobile communications industry in the years to come.

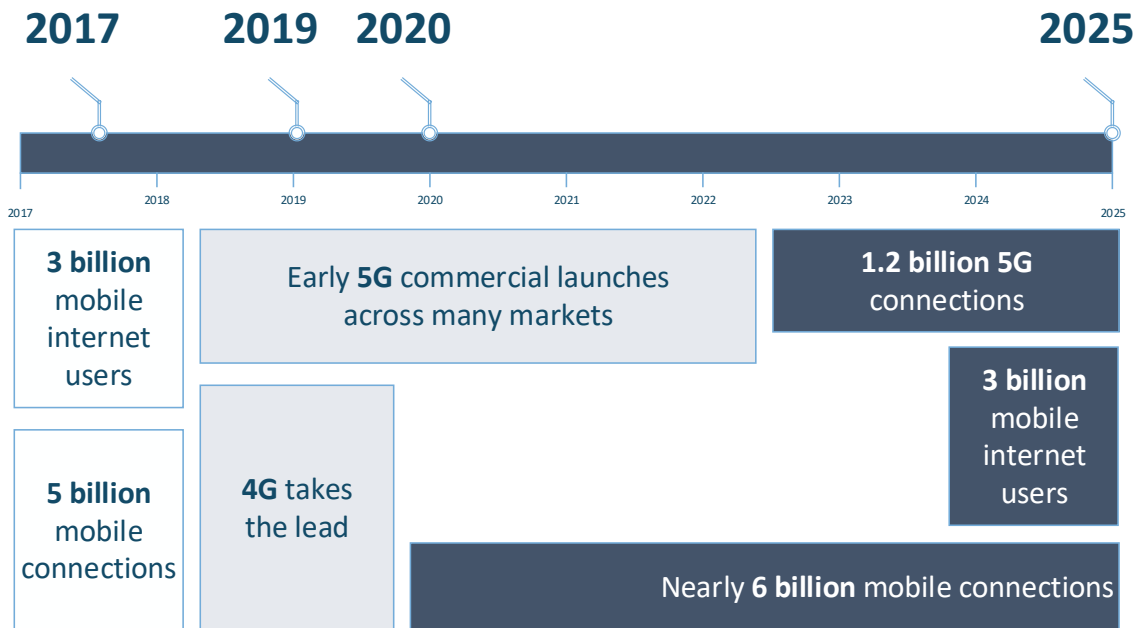


Fig. 1. Data from the study of GSMA Intelligence for mobile connections and usage forecasts for the period from 2017 to 2025 [16].

Along with internet access via fixed networks, mobile technology development trends are setting the scene for fourth-generation (4G) and fifth-generation (5G) technology network development scenarios by predicting that mobile operator networks worldwide could have close to 6 billion mobile user connections by 2025.

The Doctoral Thesis reflects the results of the study on the implementation of a model for monitoring the quality of the Internet access service in line with the technological development trends. An evaluation of the existing quality monitoring framework has been carried out and proposals have been made for a broadband Internet quality measurement

methodology and the concept for engineering solutions for mathematical data analytics to harmonize quality monitoring, applicable on a long-term perspective.

As part of the development of next generation (NGN) electronic communications “high-speed networks” characterized by end-user connection speeds of up to several gigabits per second, it is essential to ensure an appropriate quality of service when planning implementation of technological solutions for both global and European user range and geographical scope. There is a need to provide the user with understandable, transparent and comparable information on Internet access service quality indicators, such as factors affecting connection speed and content delivery [1].

The Internet access service effectively provides a transportation function and access to information, content and data exchange in the public Internet environment such as social networks, financial instruments, voice telephony services, video streaming and television program distribution services, and a significant number of other services and sites. Equally important Internet Protocol solutions already provide the data transmission environment for a substantially growing segment of machine to machine (M2M) and Internet of Things (IoT), especially in mobile 4G technology networks. Monitoring the quality of service is one of the most important activities to be implemented to achieve this goal from the point of view of businesses, regulators and users.

The subject of the Doctoral Thesis is topical in view of the still rapidly growing development of the electronic communications industry both in terms of technology dynamics and the volume of data usage in the world. Given the structure of today’s electronic communications networks with very different combinations of fibre-optic networks and other technological solutions, a range of services and user habits, the practical implementation of the legal framework for linking the technical and legal aspects of quality measurement by maintaining unity of the applicable measuring metrics in Internet service monitoring is one of the major challenges included in the study performed.

## **Aim and Tasks of the Work**

Considering the trends of development of technological solutions in the data transmission environment with a significantly progressive machine to machine communication and Internet of Things segment, as well as developing the environment advancing this solution, including evaluating the 5G technology concept and development trends, the following **aim of Doctoral Thesis** has been proposed: to assess and make proposals for a broadband Internet quality measurement methodology concept applicable in a long-term perspective for engineering and technical solutions for data analysis to harmonise quality monitoring regulations.

In order to achieve this aim, the following **key tasks** were set.

1. To evaluate and determine a set of the most significant parameters characterising Internet access service and rational use of relevant parameters to represent the most comprehensive information possible about the Internet service quality indicators, including those within the framework of principles defined for open Internet access.

2. To develop an analytical model for the evaluation of service quality for different purposes based on common principles and applicable on a long-term perspective, such as within the operator's network in various time sections, for comparisons between operators within a single country, and for relevant accounting or reference points for measurements to characterise information intended for a European or global scale. To optimize technical solutions and measurement methodology and applying to objectively evaluate the quality of the Internet access service in fixed and mobile electronic communications networks, both for services available at a certain location and at scattered points in the Internet environment, including for monitoring the quality of services provided within the 5G network segmentation.
3. To evaluate solutions for the visualization of parameters characterizing the quality of the Internet access service, such as connection speed, data transmission delay time, data transmission delay time unevenness, by displaying information in the form of a geographic map or graphical representation to provide comparable information.
4. To develop an optimal mathematical processing and calculation model for measurement results in order to produce comparable measurement data for broadband Internet access, such as connection speed and data delay time, by displaying measurement results for different purposes.
5. To develop a conceptual framework for the benchmarking and monitoring of the quality and quantity indicators of broadband Internet services and the aligning theoretical values, e.g., for quality of service declarations, connection parameters accounting and for contract speeds with technically achievable and measurable metrics.

Considering the conceptual and practical solutions for the implementation of the European-level and Latvian regulatory frameworks during the study, as well as the comparative information of quality monitoring, it is concluded that the main tasks of the Thesis have been successfully completed.

## **Research Methodology**

Experimental measurements, an evaluation of statistical data were performed and appropriate mathematical calculation methods were applied in the implementation of the tasks defined in the Doctoral Thesis. Analytical evaluation of problems was performed taking into account the need for mutual harmonisation of regulatory aspects, thus ensuring appropriate and coherent evaluation of the broadband internet service in various informational and analytical sections. Measurements were carried out by using ITEST, the Internet access service quality control system of the Public Utilities Commission, which has been developed by using a multi-module integrated solution of broadband internet measurement tool of Visualware Inc. MyConnection Server software.

# **RESULTS OF RESEARCH AND SCIENTIFIC NOVELTY**

## **Practical Value and Benefits of the Work**

- A comparative study has been carried out on the applied regulation for fixed and mobile internet access services. It was carried out through the preparation and conduct of surveys within the regulatory bodies of the European Union and the CEPT member states, active participation in preparation of two reports and in developing a recommendation within the CEPT ECC working group (WG) NaN project team (PT) TRIS in order to provide common technical regulation for a broadband internet service.
- The existing quality monitoring system in Latvia has been significantly improved by introducing interconnection of quality requirements, harmonisation of definitions and provision of a single approach to service quality declarations, quality requirements in electronic communications contracts as well as quality requirements for access to an open Internet within the scope of monitoring.
- Methodology and guidelines have been developed that are applicable and have been introduced for the evaluation of broadband Internet access service quality in Latvia, and the concept of mathematical processing and visualization of service quality measurement results in the SPRK, has been developed to include the measurement result analytics in the annual quality reports.

## **The Most Important Conclusions Gained During the Development of the Doctoral Thesis**

- Despite the extensive range of framework documentation and standardisation documents governing the electronic communications sector, and the often inadequate effectiveness of regulatory tools to successfully provide for monitoring the service quality due to the individual and unrelated implementation of many parallel regulations, it has to be concluded that it is possible to create a set of effectively functioning evaluation methodologies and technical solutions, thus ensuring the harmonisation of monitoring regulations without changing the framework of regulation.
- Data collection, processing and analytics on indicators characterising broadband Internet quality, e.g., connection speed or data transfer delay time, at the QoS-1 level, which includes a set of theoretical information, which can only be considered useful if such information is provided as an aggregate of information against which the results of systematic and verifiable measurements and quality indicators of services effectively provided to users obtained from measurements at the QoS-2 or QoS-3 level can be compared.

- For an objective and comparable long-term Internet quality assessment, it is necessary to select a set of systematic and uniform characteristics, as well as comparable and traceable reference points of the measurement tool.
- When evaluating the study on the range of characteristic parameters, evaluating the dynamics of indicators and their understandability for users, it is reasonable to apply similar principles of service quality assessment and measurement under specific conditions for a particular technological solution in case of both fixed and mobile connection points.
- Although the dynamics of the possible value or value change of fixed and mobile internet speed is very different, in order to provide end-users with comprehensible information and to ensure a unified access for the Internet service providers to requests for information and for the users to information, for the purpose of comparability as well as in order to implement the requirements included in the regulatory framework in the Regulation 2015/2120 on Open Internet Access, it has been concluded that it is possible to use a unified mathematical calculation model for mobile Internet services in both fixed and mobile electronic communications networks.
- There is a comprehensive solution for broadband internet service quality measurement possible to ensure quality monitoring for fifth-generation (5G) technology, by combining both a “central” reference point and scattered reference point architecture, providing the possibility to flexibly expand the measurement range across the specific services provided in the fifth-generation (5G) technology platform.

### **Use of the Results of the Doctoral Thesis**

- The results obtained during the development of Doctoral Thesis and reflected in the study have been used in 7 international projects related to the quality of electronic communications services, as well as in 4 international seminars of the electronic communications industry.
- The Doctoral Thesis summarises the results of the completed study related to the quality of broadband Internet service. The Thesis provides proposals for implementation of a fully functional complex quality monitoring model, which would ensure insofar as possible implementation of the developed model in the regulatory documentation of the CEPT on an international scale and its practical implementation in Latvia (ECC Report No. 195 – 2013; Draft ECC Report 312 – 2019; ECC Recommendation No. (15) 03 – 2015 & 2018; Quality Requirements (SPRK, No. 1/31 30.11.2017); Quality Measurement Methodology (SPRK, No. 1/30 23.11.2017); SPRK broadband Internet access measurement system ITEST – <https://itest.sprk.gov.lv/>).

## **Theses Defended Within the Doctoral Thesis**

1. The quality of the service monitoring framework, measurement principles and benchmarks or reference points for measurement provision should be implemented for the planned fifth generation (5G) technology solutions with network resource segmentation and dedicated or specialised services, as well as for fixed network solutions and the existing third generation (3G) and fourth generation (4G) technology mobile electronic communication networks, providing comparability of measurement results and relevant quality indicators between generations of technologies, while ensuring at the same time that the measurement methodology corresponds to the specifics of the actual range of services, terminal equipment and purpose of use of the services.
2. For the assessment of a broadband Internet access service, it is possible to implement and apply a sustainable evaluation methodology model that provides for obtaining objective and comprehensive information on quality indicators that is comparable in various analytical sections for different addressees or a different range of information users.
3. Broadband Internet connection speed values can be grouped into download and upload connection speed categories that provide comprehensive and complete information on the connection speed that is actually available and expected for the user in different situations, while providing for harmonised connection accounting, information quality declarations, determining terms and conditions of the Internet service contracts and their monitoring as well as comparative analytics of measurement data.

Both experimental measurements and the practical implementation of the concept of quality monitoring measurement methodologies developed by the study, and harmonisation of an open Internet access framework with other legal and regulatory enactments of technical regulation, allows to conclude that the theses have been proved by ensuring the effective use of indicators of quality and electronic communications industry in trend analytics and in the provision of Regulatory monitoring functions.

## **Approbation of Results of the Doctoral Thesis**

The main results of the Doctoral Thesis have been presented at 5 international scientific conferences as well as included in 3 papers published in scientific journals and 5 articles in full text conference proceedings. One publication was submitted and has been approved for presentation in a scientific conference at the end of 2019. Six of these publications are indexed in SCOPUS database with the citation index  $H = 2$ . Five publications are included in Web of Science database.

### **Reports at International Scientific Conferences**

1. **Lipenbergs, E., Bobrovs, V., Ivanovs, G.** Quality of Service Measurements References Investigation for the Mobile Internet Services in the Context of Net Neutrality Framework. In: 2016 Progress in Electromagnetics Research Symposium

- (PIERS 2016 Shanghai): Proceedings, China, Shanghai, 8–11 August 2016. [*SCOPUS, Web of Science*].
2. **Lipenbergs, E.**, Stafecka, A., Ivanovs, Ģ., Smirnova, 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. [*SCOPUS, Web of Science*].
  3. Stafecka, A., **Lipenbergs, E.**, Bobrovs, V., Sharashidze, T. Quality of Service Methodology for the Development of Internet Broadband Infrastructure of Mobile Access Networks. In: 2017 Electronics: Proceedings of the Conference, Lithuania, Palanga, 19–21 June 2017. [*SCOPUS*].
  4. **Lipenbergs, E.**, Smirnova, 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. [*SCOPUS, Web of Science*].
  5. 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.
  6. 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, China, 17–20 December 2019.

#### **Publications in Scientific Magazines**

1. Virtmanis, A., **Lipenbergs, E.**, Ķerņakovs-Neimarks, A./ “Система контроля качества услуг электронной связи в Латвии” (“The QoS Measurement System for the Electronic Communications Services Monitoring in Latvia”) Веснік сувязі, Belarus, 2015, No. 3–4, pp. 35–39.
2. **Lipenbergs, E.**, Bobrovs, V., Ivanovs, Ģ., “Quality of service measurements reference points investigation for the internet service on mobile networks”// Proceedings of LATVIAN JOURNAL OF PHYSICS AND TECHNICAL SCIENCES, LV, 2016, No. 5, pp. 65–73. [*SCOPUS, Web of Science*].
3. 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. [*SCOPUS, Web of Science*].

#### **Publications in Full-Text Conference Proceedings**

1. **Lipenbergs, E.**, Bobrovs, V., Ivanovs, Ģ. Quality of Service Measurements References Investigation for the Mobile Internet Services in the Context of Net Neutrality Framework. In: 2016 Progress in Electromagnetics Research Symposium (PIERS 2016 Shanghai): Proceedings, China, Shanghai, 8–11 August 2016, pp. 4248–4252. [*SCOPUS, Web of Science*].

2. **Lipenbergs, E.**, Stafecka, A., Ivanovs, Ģ., Smirnova, 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. [*SCOPUS, Web of Science*].
3. Stafecka, A., **Lipenbergs, E.**, Bobrovs, V., Sharashidze, T. Quality of Service Methodology for the Development of Internet Broadband Infrastructure of Mobile Access Networks. In: 2017 Electronics: Proceedings of the Conference, Lithuania, Palanga, 19-21 June 2017, pp. 61–65. [*SCOPUS*].
4. **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. 1–5. [*SCOPUS, Web of Science*].
5. Smirnova, 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. 1–7.

## **Volume and Structure of the Work**

The volume of the Doctoral Thesis is 184 pages. The work consists of the introductory section describing the general situation, three chapters presenting the research and proposals, conclusions and a summary, as well as a list of literature and appendices.

**Chapter 1** of the Doctoral Thesis provides a general overview and forecasts of broadband Internet service indicators by researching the available data of international companies such as Cisco Systems, Inc., GSMA, OECD, BEREC as well as the SPRK in Latvia. The major trend to note is the increasing availability of new services such as high and ultra-high definition video streaming, online games, telemedicine, video conferencing, online shopping, device to device (D2D) or machine to machine (M2M), Internet of Things (IoT), and other services provided in the IP environment. It contributes to a significant increase in the use of IP data and imposes ever new requirements on electronic communications companies to develop network infrastructure and ensure service quality.

**Chapter 2** of the Doctoral Thesis reflects and evaluates the regulatory framework applied in Latvia in relation to Internet service and its monitoring that derives from the European Digital Single Market Strategy and the connectivity strategy for the European gigabit society. The regulatory framework is defined by a set of directives that are incorporated into national laws and regulations, mainly the Electronic Communications Law. At the same time, open internet access or, as it is called in the previous terminology, the “network neutrality” regulation is in force and directly applicable in relation to the Internet service, especially in relation to open access to Internet. In addition, in connection with the set of directives as well as other directly or indirectly applicable regulatory documents, including national level laws and regulations for technical regulation, regulation of Internet service quality is influenced and determined by the guidelines of the ETSI, recommendations of the ITU as well as documents of the CEPT ECC on Internet access service.



**Chapter 3** of the Doctoral Thesis provides an overview of the research for service quality measurement methodologies, development of harmonised monitoring models and their implementation scenarios. In order to provide for what is defined in the regulatory framework in relation to service quality and relevant and up-to-date information about the quality indicators available to users, it is necessary that the national supervisory authorities determine the content, format and type of the information to be published to provide such information to users and consumers.

The Doctoral Thesis provides the outline that according to the research performed and assessment of practical implementation of the solutions, despite the variety and fragmentation of the currently existing Internet service-related laws and regulations, quality assessment and availability of meaningful information related to broadband Internet service indicators makes it possible to implement relevant regulation and conditions as well as to offer effectively functioning evaluation methodologies and concepts for technical solutions. A solution has been provided for the full functionality of the Internet service quality assessment system that ensures effective, non-duplicate monitoring of the Internet service within the existing legal framework and standardisation documentation.

**Chapter 4** of the Doctoral Thesis provides the results of the study and proposals for the providing of quality measurement results and the processing of measurement data, which provides for the definition of the principles of information analytics and visualization scenarios that are applicable to the presentation of different types of broadband internet indicators, such as connection speed in contracts, publicly or quality declarations. The proposals should also be used to achieve the objective of ensuring the widest possible, comprehensive and useful information for both users and service providers, in accordance with Regulation 2015/2120 on open internet access requirements for internet access services over a mobile network.

The most important **conclusions of the work** have been summarised, and substantiated achievements of the work, the development of a harmonised set of quality monitoring activities and directions for further research have been defined at the end of the Doctoral Thesis.

# OUTLINE OF THE DOCTORAL THESIS

## Chapter 1

**Chapter 1** assesses the broadband Internet service indicators and forecasts as included in the publications and overviews of Cisco Systems, Inc., GSMA, OECD, BEREC, European Commission and other European Economic Area and global institutions and companies, as well as evaluates and analyses the data available to the SPRK.

The Organization for Economic Cooperation and Development (OECD) is the leading organisation in reflecting global economic and technological development indicators as well as those in specific countries of the world. OECD research on the Internet access service covers, for example, the area of investment in information and communication technologies (ICT) that in general characterizes the purchase of equipment and computer software used in production or provision of services for more than one year and which includes information technology equipment – computers and related hardware, communication equipment and software. This indicator is measured as a percentage of the gross fixed capital formation in the entire manufacturing sector. At the same time, indicator assessment and economic indicator analytics are gathering and analysing information about broadband Internet access speeds of at least 256 kilobits per second, which include indicators of fixed and wireless mobile broadband connections as well as business and household user connections [8], [9].

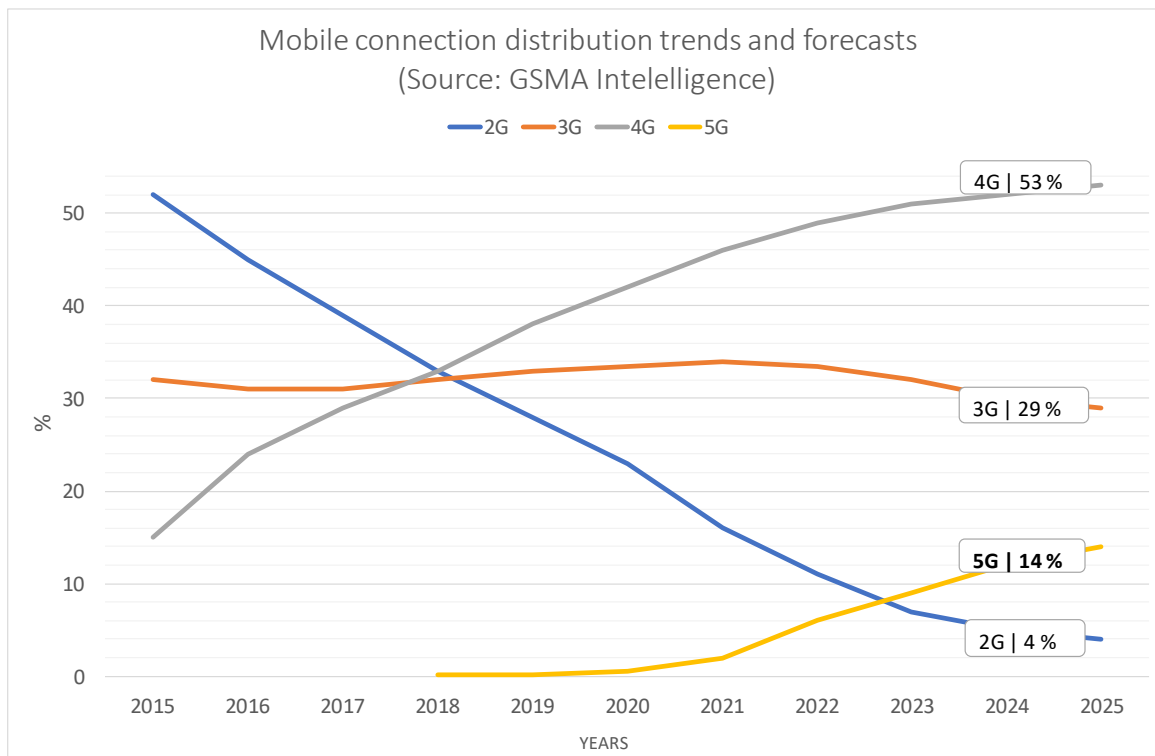


Fig. 2. Forecasts of GSMA Intelligence on breakdown of the number of mobile connections by mobile technology generation 2G, 3G, 4G and 5G until 2025 [16].

Research conducted by GSMA Intelligence on possible developments and scenarios for 5G technology has analysed long-term statistics on the dynamics of mobile connections in the relevant technologies, which resulted in the publication of forecasts of how mobile connections within each generation of mobile technology could be regrouped in the coming years, including providing estimates for the possible amount of 5G technology connections in the mobile network with growth from 2020, reaching 14 % by 2025 (Fig. 2).

Considering the forecasts for broadband Internet access development and research conducted by various companies as well as market research conducted by major operators or operators' associations, the data available to operators is very important given the demand from users for ever increasing connection speeds and data volumes in the Internet environment.

Information about broadband Internet access is provided to the European Commission by the Member States informing about their broadband Internet indicators, which is the subject of a major study of broadband coverage in Europe every year to monitor and continuously update information on progress under the Digital Agenda for Europe, including the digital single market development goals with regard to access to fast and ultra-fast internet – to ensure by 2020 universal broadband Internet coverage with the connection speed **for all users of not less than 30 megabits per second, and broadband Internet coverage with the connection speed of not less than 100 megabits per second to 50 % of households**, and by 2025 **not less than 100 megabits per second, with the possibility to improve the connection rate to 1 gigabit per second** [3]–[7].

## Chapter 2

**The second chapter** of the Doctoral Thesis researches and evaluates the regulatory framework in relation to Internet service and its monitoring in line with the European Digital Single Market Strategy and the connectivity strategy for the European Gigabit Society [3]–[5].

Upon assessment of the existing legal and technical regulatory framework as well as the one planned for implementation along with entry into force of the European Electronic Communications Code, the set of regulatory requirements for access to the open Internet, or “network neutrality”, and the quality of internet service, one should note as essential the diversity of technical regulations and the Internet service quality monitoring and conditions, fragmentation and variety that are often difficult to apply for both supervising institutions and service providers, as well as the scope of application of the requirements is not clear enough [1], [11], [12], [17]–[28].

A new regulatory framework is in force as of December 2018 to replace the existing set of directives in the regulatory framework for the electronic communications sector in determining basic principles for regulation (Fig. 3) by defining the regulation and conditions in the European Electronic Communications Code to be implemented by Member States in their national law within two years [1], [20]–[22].



Fig. 3. The legislative and technical regulation framework for the provision and supervision of Internet services.

The existing topical documents in the area of standardisation of technical aspects on Internet access service quality assessment include the guidelines of the ETSI, recommendations of the ITU [23]–[28], as well as documents of the CEPT ECC on Internet access service, which include a significant part of the research of this Doctoral Thesis [2], [14], [29], [34], [36].

It has been concluded in the due course of research of the regulatory framework that monitoring of the Internet service quality should result in and aim to provide useful, usable, transparently comparable and legally justified information for the purpose of making specific decisions or application of monitoring measures, including about the technical indicators of the Internet access service, such as the speed of Internet service connection or parameters related to data transfer delay and data packet transfer times. At the same time, it is necessary to ensure that obtaining comprehensive information does not impose an excessive burden on service providers and supervisory institutions by assessing the application and mutual harmonisation of different regulations and their levels, selecting from the range of many dozens of parameters the ones most important and representative for the service providers, supervisory institutions and users as well as the most optimal algorithms for measuring or assessing Internet service quality.

## Chapter 3

The third chapter of the Doctoral Thesis provides an outline of the research on service quality measurement methodologies, development of harmonised monitoring models and their implementation scenarios.

Given the growing number of Internet access connections and forecasts from various data sources, over the next few years, with the development of 5G technology networks (Fig. 1 and 2) especially in the mobile Internet sector, especially intended for machine to machine (M2M) services, it is necessary to ensure the availability of high quality services. While service quality indicators may vary across different electronic communications network technologies and across developing generations of technology, mutual comparability in various sections must be ensured between solutions of different technologies, including combinations of technologies and technical solutions, between operators, over time, as well as in other categories, depending on the purpose for which the information is used. This requires a common and harmonised approach to quality monitoring and measurement, while providing differentiated assessment, for example, depending on the type of electronic communications network, whether fixed or mobile, as well as other factors such as the range of services provided or made available in the IP environment.

In order to achieve the objectives and aim proposed for the Doctoral Thesis in terms of service quality assessment indicators it is necessary to do the following:

- to determine key parameters characterising service quality;
- to define measurement methodology and principles – how, when and how much to measure;
- to determine measurement reference points – where to measure.

Experimental measurements were carried out by using ITEST, the Internet access service quality control system of the SPRK, which has been developed by using a multi-module integrated solution of Visualware Inc. software MyConnection Server Broadband Internet Measurement Tool [32], [33]. The measurement system used for the experimental measurements according to the following general structural scheme with a fixed connection point can be seen in Fig. 4 and with a mobile connection point in Fig. 5.

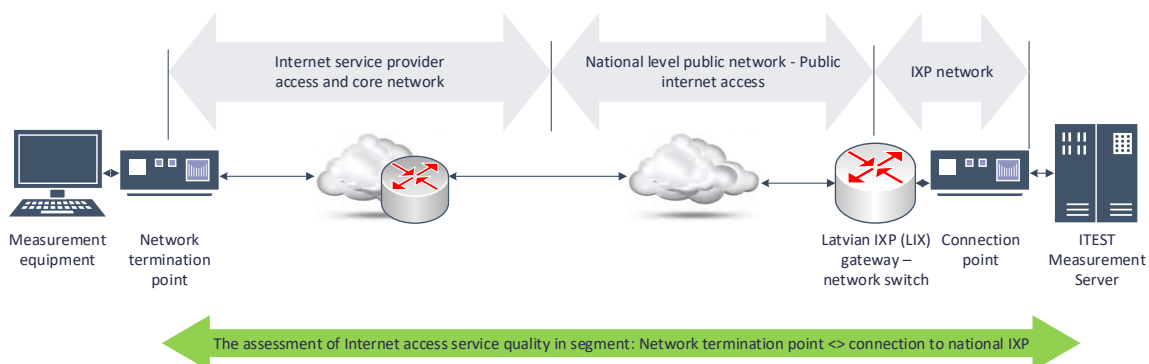


Fig. 4. General architecture for the measurement of service quality indicator connections for measurement from the fixed network connection point to LIX connection point IXP.

Measurements are provided in a network segment from a terminal that provides connection to a network connection or termination point to a measurement server connected to an Internet exchange point connection or termination point [13], [37].

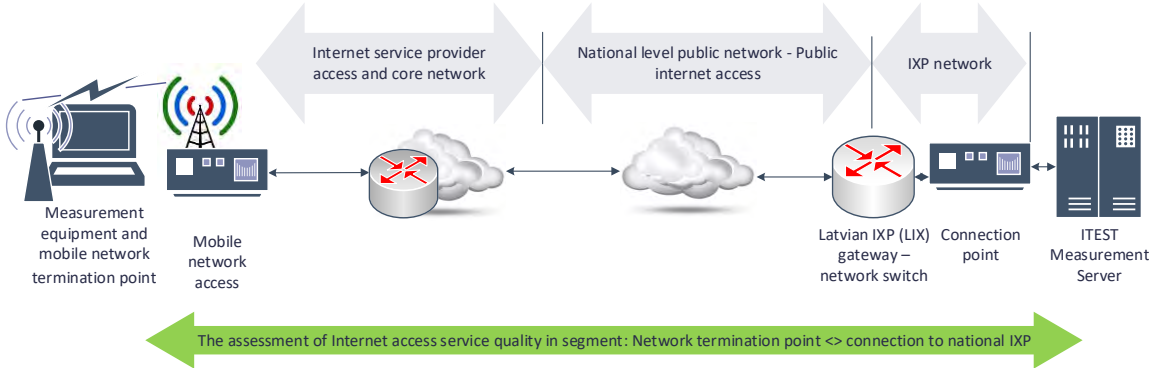


Fig. 5. General architecture for the measurement of service quality indicator connections for measurement from the mobile network connection point to LIX connection point.

Parameters related to the speed of data transmission or Internet connection should be assessed as important considering that they are understandable to the user of the service, they are presented in the offers of the service providers, they affect, to a varying extent, affectively all the services and applications in the Internet environment as well as representing a measurable parameter in the electronic communications network level and, when using appropriate algorithms, are comparable to values at an application level such as specialized software or browser interface.

Research examples of connection speed changes at different times of day on the fixed FTTH (100 Mbps) network and on the mobile 4G network demonstrate significant differences in connection speed dynamics (Fig. 6).



Fig. 6. Example of experimental measurement of changes in download connection speed: a) in fixed FTTH (100 Mbps) network; and b) mobile 4G network.

In the FTTH fixed network, the change in connection speed value can at some points in time reach several dozen percent, whereas in the mobile 4G network shown in the example, the change dynamics are constant or dominant with connection speed values varying over the entire connection speed range possible for the particular technology, reaching a 0 value during individual measuring sessions as well, which indicates a temporary interruption in data transmission. Figure 6 shows changes in connection speed values or fluctuations for a fragment of one measurement session. It means that, despite the requirements set forth in the regulatory framework to limit the full range of connection speeds only to a fixed network service, all types of connection speeds, such as normally available speed and minimum and maximum values can be equally importantly determined for both fixed and mobile network connections.

Upon analysing the changes in the experimental data transmission delay time variation values in relation to the general Internet connection quality indicators, especially regarding the connection speed changes, it is observed that especially in the mobile 3G and 4G technology networks, significantly lower Internet connection speed values have been recorded at higher delay time variation values – when delay time variations exceed 2 milliseconds, connection speed values are reduced by approximately 50 % of the maximum connection speed; within the limit up to 5 milliseconds the connection speed values reach about 30 % of the maximum connection speed, while when the delay time variation values are higher than 10 milliseconds, the connection speed values are recorded within a few percent, not exceeding 10 % of the maximum connection speed value. With the impact of parameters related to data transmission packet delay time (RTT) in the provision of Internet service, the dynamics of changes of indicators and dependence on the type of electronic communications network and other influencing factors, inclusion of indicators characterizing data transmission time and data transmission delay time variations in the range of assessed quality indicators should be assessed as essential.

While parameters related to packet error or loss should be measured at both a network and application level and should be considered mutually comparable considering the principles of accounting and measurement data processing. For the purpose of comparative information, the parameter describing the percentage of packet loss, i.e. packet loss rate, should be assessed as more understandable to the user [29], [34].

The minimum set of technical parameters considered significant for the publication of comparable and comprehensive information, providing at the same time the user of the Internet access service with an understandable and transparent amount of information, includes characteristics of the IP data transmission or connection speed, data transmission delay time or latency, and data transmission delay time variations, and the assessment should be related to the availability of the service, which provides a link between the technical parameters and the administrative parameters of the Internet access service (Fig. 7).

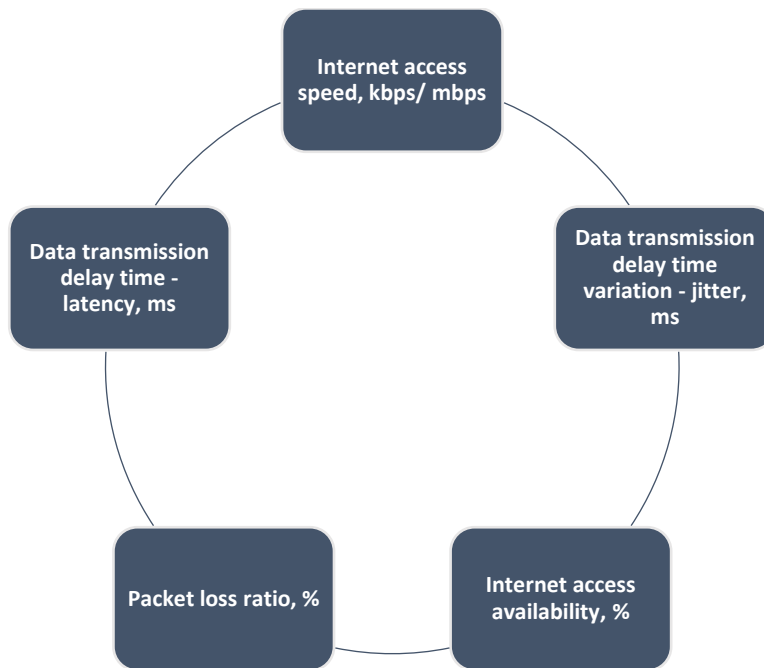


Fig. 7. Minimum set of parameters for assessing the quality of the Internet access service for the publication of comparable information.

A range of criteria was used for the selection of parameters characterising broadband Internet service, which have been evaluated in the course of the study, taking into account the standardisation documentation, information provided by businesses, reports of the European Commission, opinions provided in surveys of CEPT member state administrations, user complaint evaluation as well as the detailed and most significant part of the study – the experimental measurement result analytics, thus identifying a range of technical parameters that are assessed as understandable for the user, having a significant impact on the Internet service with the change of its characteristics, and can be used to obtain comparable information for the above purposes or addressees [15].

The study compares the service quality assessment reference points within the Internet service provider network, for direct and indirect connection of the Internet service provider to a national Internet exchange point, and reference points for Internet service quality assessment when using international Internet exchange points. Figure 8 shows the service quality evaluation segment for the reference points from the network connection point to the national level Internet exchange point for an indirect connection.

In order to ensure objectively comparable assessment of the service quality parameters selected, research has been carried out in determining “where to measure?” in order to choose the optimal assessment stage or reference points for measurement according to the scale of measuring [14].

When evaluating the study of the range of characteristic parameters, evaluating the dynamics of indicators and their understandability for users, it is reasonable to apply similar principles of service quality assessment and perform measuring under specific conditions for a particular technological solution in cases of both fixed and mobile connection points.



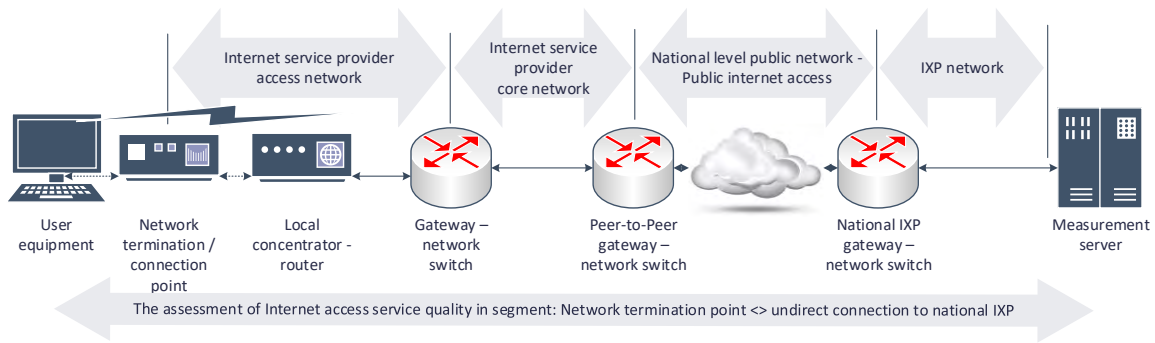


Fig. 8. Service quality evaluation reference points from the network connection point to the national level Internet exchange point for an indirect connection solution.

Reference or measurement reference points have been evaluated.

- Service quality assessment reference points within the Internet service provider's network.
- Service quality evaluation reference points for the direct and indirect connection of the Internet service provider's network to the national level Internet exchange point.
- Service quality evaluation reference points for the assessment of Internet service quality when using international level Internet exchange points.

Under actual conditions, not all operators have developed direct connections to a national or regional internet exchange point switching facility, and, in this case, when evaluating service quality, different operators may have different data paths and number of switching nodes to the measurement reference point. However, as each operator, upon planning and allocating Internet connection capacity to users, plans and forecasts the data flow volume and the load intensity by appropriately purchasing connections at a wholesale level, it has been concluded, including through experimental measurement, that a national or regional level Internet exchange point switching facility provides objective, comprehensive and comparable information on the quality indicators of the user's connection in the event of an indirect connection as well. International level reference points can only be chosen under specific conditions, such as where the electronic communications network is provided through a content delivery network (CDN) or software defined networking (SDN) configuration [38].

According to the assessment in the study, it has been concluded that for the comparison of Internet service quality provided at a national level and evaluation of service performance dynamics, the most optimal solution is choosing the measurement reference points at the stage from the terminal connection point to the national or regional level Internet exchange point.

The types of measurements to be provided by the above interfaces are as follows:

- random measurements dispersed over a geographical area;
- serial measurements at specific geographical locations;
- measurements in motion.

As a result of research, for the optimal coverage of the range of information it is recommended to opt for all three types of measurements, which characterize the broadband

Internet service availability and quality indicators – connection speed and data transmission delay time characteristics, in different sections.

## Chapter 4

**Chapter 4** of the Doctoral Thesis provides the results of the study and proposals for the providing of quality measurement results and the processing of measurement data, which provides for the definition of the principles of information analytics and visualization scenarios that are applicable to the presentation of different types of broadband Internet indicators, such as connection speed in contracts, public spaces or quality declarations.

In order to achieve the goal of providing as wide, comprehensive and useful information as possible for both users and service providers regarding Internet access services in the mobile network, it should be taken into account that, for various reasons, including the ones specified in the Doctoral Thesis in relation to the actual service quality assessment and stability of values in time, for example for parameters related to Internet speed, notes in Regulation 2015/2120 on Open Internet Access with respect to mobile Internet, monitoring of quality and evaluation of Internet access service in a mobile electronic communications network requires a differentiated approach, with appropriate harmonisation of the set of parameters and measurement methods, balancing and maintaining the integrity of the common principles of measurement and data analytics [14].

There is an equal need for clear and comprehensive information on possible limitations, especially in the mobile electronic communications network, for example in terms of volume availability or in relation to connection speeds achievable in reality and their characteristics, such as availability of guaranteed values, provision of maximum values as well as the connection speed advertised by operators or the one commercially offered publicly and in the electronic communications service contract. Along with the Internet service connection speed parameters, important characterising parameters are the data transmission time characteristics – latency or delay time in packet transmission, packet delay variation or unevenness in data transmission speed and packet loss. It is necessary to implement principles for their unified assessment so that the service offered to the user would be based on a set of comparable, reliable and applicable parameters and their values and, where any component is not provided, the rights of the user would be protected, including determining in the contract the values of the parameters, in the event of failure to ensure which one could seek compensation, reduced subscription fees or termination of the contract without penalty or other sanctions.

Although the dynamics of potential values or changes in the value of fixed and mobile Internet speeds are very different, in order to provide end-users with comprehensible information and to provide a unified approach to the Internet service providers for information requests and provision of information to users, for comparability as well as to implement the requirements included in the regulatory framework, it has been concluded that it is possible to use a unified mathematical calculation model for mobile Internet services in

both fixed and mobile electronic communications networks in accordance with the principles defined in Regulation 2015/2120 on Open Internet Access (Fig. 9 and 10).



Fig. 9. Example of broadband Internet download connection speed measurement data concentration in a fixed network (FTTH 100 Mbps).

For the types of connection speed characterising broadband Internet, their actual application has been analysed by using broadband connection speed categories and mathematical processing of measurement results, evaluating the dispersion of the values of measurement results.

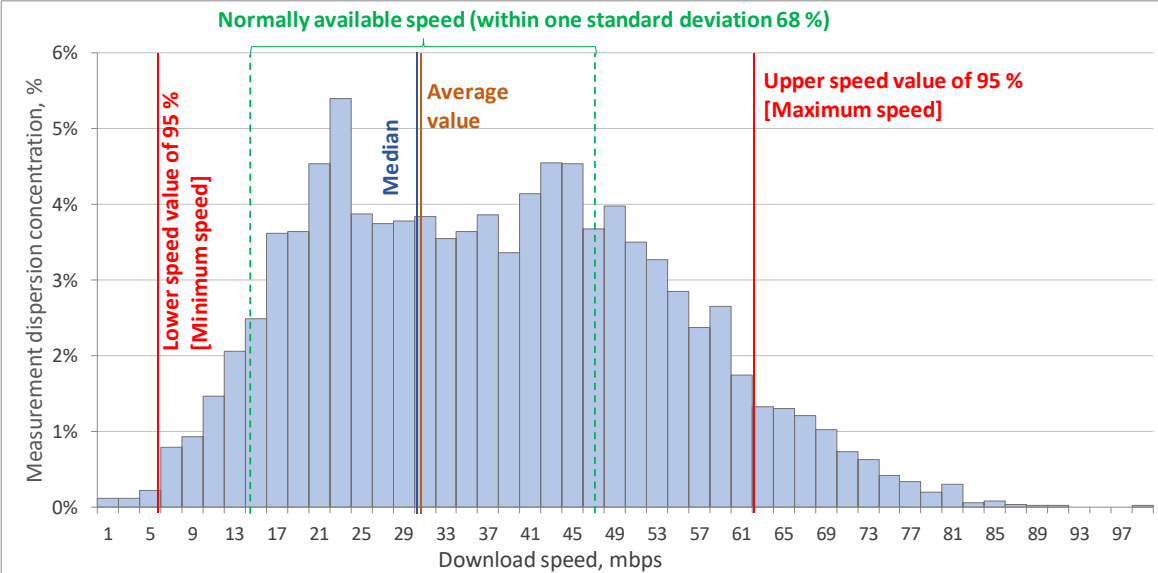


Fig. 10. Example of broadband Internet connection speed measurement data concentration in the mobile network (4G).

Notwithstanding the provisions of Regulation 2015/2120 on Open Internet Access regarding indicating individual numerical values for connection speeds, upon evaluating the measurement results and analysing the probability distribution or dispersion of the measurement data, it is concluded that specifying individual numerical values is not sufficient

to objectively reflect the availability of the Internet access service connection speed. Provision of comprehensive information in both quality declarations and contracts, as well as in measurement result summaries, requires segmentation of connection speeds by indicating value ranges that clearly characterise the Internet connection speed available in reality. For example, the commonly available speeds in both fixed and mobile networks mentioned in Regulation 2015/2120 on Open Internet Access can be successfully specified and described, including in a way clearly understandable for the user, by selecting appropriate speed limits that cover 68 % of the measured data, or actually the connection speed to be provided with such a level of credibility. At the same time, one should take into account the need to ensure comparability between operators or various characteristics of the Internet access services provided by the operator. In order to ensure comparability, it is necessary to define a range of values, and, where the type of speeds of a specific Internet connection service is within such, it is possible to define the minimum, commonly available and maximum connection speed. This means that each operator does not define its own unique connection speed limits, and, by using the connection speed framework, determines or defines in which of the specified frame rate categories it is able to provide the broadband Internet service to the user. In turn, within monitoring, when performing service quality measurements, it is possible to calculate and indicate the actual connection speed in the respective speed categories, which uniformly and clearly show the probability of concentration of Internet connection speeds or distribution by specific categories, as well as by calculating the measurement result dispersion limits and specifying a range of connection speeds, for example 68 % and 95 % of the measurement data [30], [31].

Broadband Internet connection speed categories or a set of speed groups can be successfully applied in both broadband connection metering for theoretical coverage estimation, its service quality declarations, service contracts, comparing the results of measurements and analytical reporting, as well as in the geographic mapping format (Fig. 11) [10], [15].

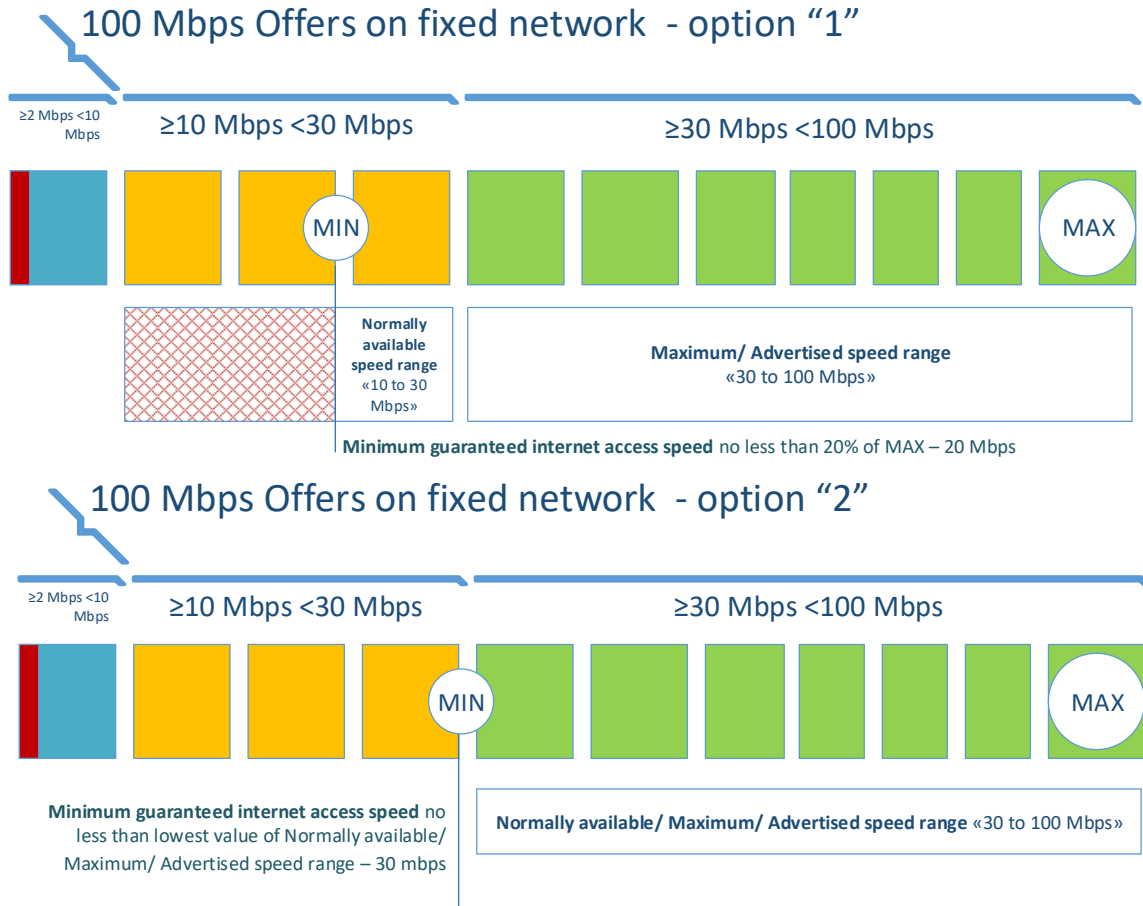


Fig. 11. Example of possibilities to determine the minimum, commonly available and maximum (advertised) connection speed for a broadband Internet service in a fixed network for a 100 Mbps tariff plan.

Data collection, processing and analytics on indicators characterising broadband Internet quality, such as connection speed or data transfer delay time, at the QoS-1 level, which includes a set of theoretical information, which can only be considered useful if such information is provided as an aggregate of information against which the results of systematic and verifiable measurements and quality indicators of services effectively provided to users obtained from measurements at the QoS-2 or QoS-3 level can be compared.

The Doctoral Thesis concludes with a full range of quality assessments on the development of an Internet service quality control concept in the context of 5G mobile technologies. One of the conceptual trends in deploying 5G networks is the developed and planned network segmentation to functionally allocate mobile network resources to different services according to their needs (Fig. 12).

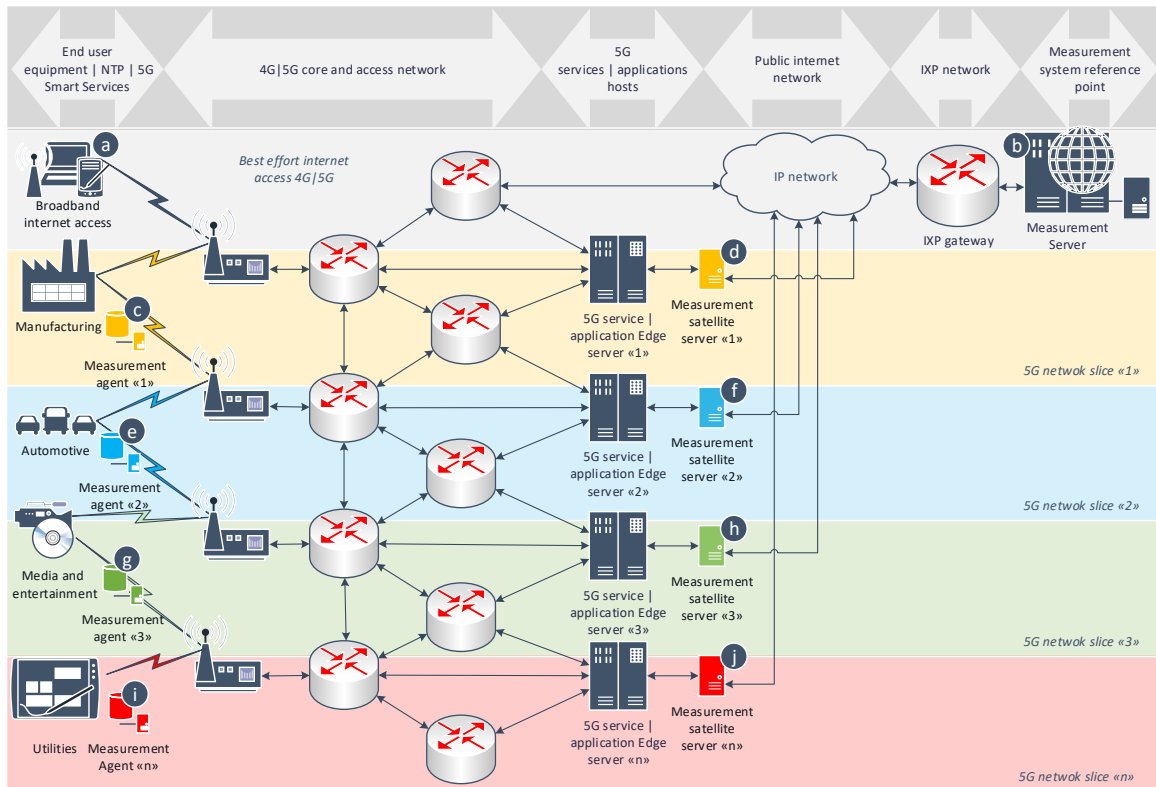


Fig. 12. Conceptual architecture for a combination of service quality assessment stages for overall broadband Internet quality measurement (a–b) and assessment of specialised service quality (c–d; e–f; g–h; i–j).

This technical innovation involves more efficient use of the network, enabling better performance for specific services, with a high priority where they are relevant, such as driving low latency for passing or connected cars, with a latency of 1 millisecond and no more than 5 milliseconds. While for data transmission services that do not require high response rates, such as data exchange for data backups, may have a lower priority on a particular network segment compared to the need for ensuring real-time management.

Upon evaluating the conceptual forecast scenarios for the development of 5G technologies, including regulatory framework and historically standardised metrics, a comprehensive solution for assessing broadband Internet service quality has been developed. The solution combines both a “central” reference point and scattered reference point architecture, providing the possibility to flexibly expand the measurement range across the specific services provided in the fifth-generation (5G) technology platform that cannot be definitively forecasted at this moment [35].

## RESULTS OF THE DOCTORAL THESIS

According to the aims of the Doctoral Thesis to evaluate and provide proposals for a concept of broadband Internet quality measurement methodology for harmonisation of quality monitoring regulations on a long-term perspective, one of the main tasks proposed was to evaluate and determine a set of the most significant parameters characterising the Internet access service and use of such parameters for reflecting comprehensive information about the Internet service quality indicators. This would provide users and consumers with access to friendly, comprehensive and comparable information, both in reality and in the contract, as well as in the public space.

It is equally important that objective, comparable and equivalent section information is available to businesses for benchmarking service contracts with users, quality declarations, broadband Internet indicator surveys, planning investment in electronic communications network development as well as for preparing procurement documentation.

Supervisory authorities also need to monitor the quality of the services provided by electronic communications companies in the context of promoting competition and protecting users' rights as well as to provide knowledge and awareness, by providing objective, comprehensive and comparable information to users, businesses, the European Commission, BEREC and other institutions in the electronic communications sector. Availability of relevant information, including about the quality of broadband Internet speed and coverage indicators, contributes to making fair and informed decisions, for example through market analysis, commitment, complaint and dispute resolution, and evaluating priorities in the strategy of the electronic communications sector.

The Doctoral Thesis provides the outline that according to the research performed and assessment of practical implementation of the solutions, despite the variety and fragmentation of the currently existing Internet service-related laws and regulations, quality assessment and availability of meaningful information related to broadband Internet service indicators makes it possible to implement relevant regulation and conditions as well as to offer effectively functioning evaluation methodologies and concepts for technical solutions. A solution has been provided for the full functionality of the Internet service quality assessment system that ensures effective, non-duplicate monitoring of the Internet service within the existing legal framework and standardisation documentation.

A set of activities identified and harmonised in the Doctoral Thesis is presented in Fig. 13.

The Doctoral Thesis summarises the results of the completed study related to the quality of the broadband Internet service, providing proposals for the implementation of a fully functional complex quality monitoring model, ensuring, as far as possible, implementation of the developed model in the regulatory documentation at an international level and practical implementation in Latvia.

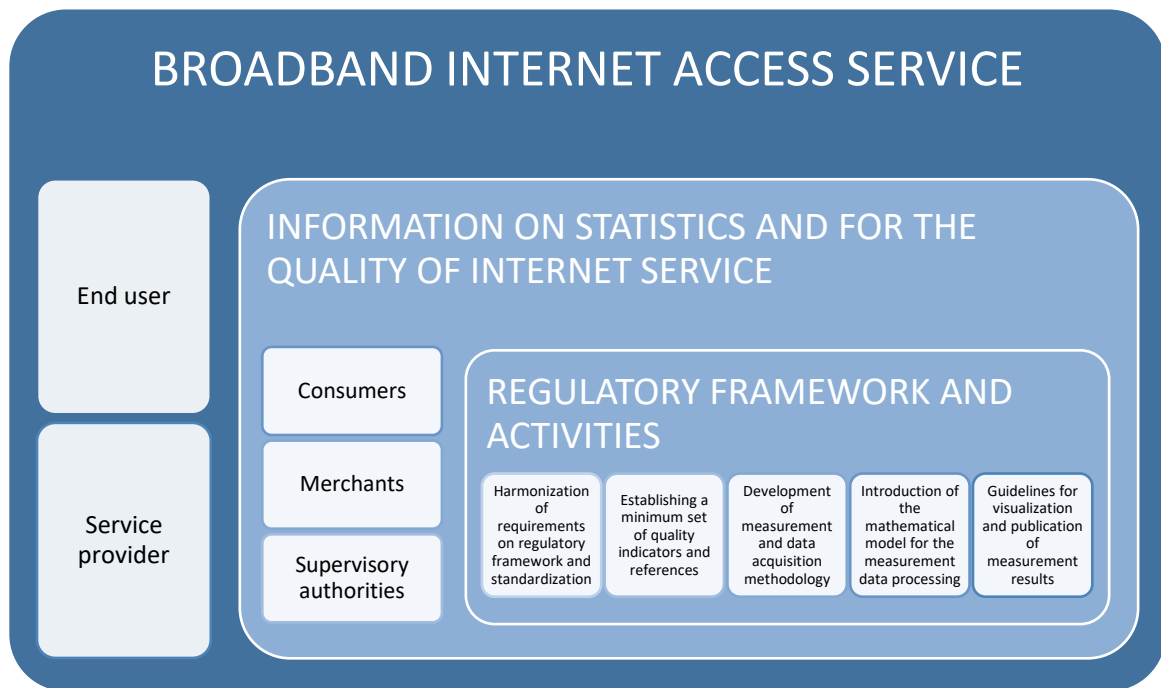


Fig. 13. A set of regulations and activities related to the provision of broadband Internet service information.

Upon assessing any possible **directions for future research**, they could be related to a rapid introduction of new services, including content, for end-users, and the development of technical and the following economical business models for which the definition of quality requirements would be assessed as important.

- Providing quality monitoring of service platforms available on the Internet in the context of technical, consumer rights and contractual regulation through so-called over-the-top or “vertically provided” applications by using designated network segments.
- Upon practical implementation of services provided in the 5G technology environment, in connection with the transposition of the European Electronic Communications Code at the level of national law, a feasibility study must be carried out to determine the distribution of quality monitoring and responsibilities between the businesses involved and the end user and introducing, where necessary, appropriate novelties in regulation and supervisory methodology.



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