RIGA TECHNICAL UNIVERSITY

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MATHEMATICAL MODELS AND ALGORITHMS OF RAILWAY TELEMATICS SYSTEMS

Summary of the Doctoral Thesis

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RIGA TECHNICAL UNIVERSITY
Faculty of Mechanical Engineering, Transport and Aeronautics
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THE 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 21 April 2023 at 13.30 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 6B Ķīpsalas Street, Room 513.

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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 Science (Ph. D.) is my own. I confirm that this Doctoral Thesis had not been submitted to any other university for the promotion to a scientific degree.

Aleksejs Vasiļjevs ……………………………. (signature)

Date: ………………………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction, 3 chapters, Conclusions, 84 figures, 39 tables, 7 appendices; the total number of pages is 131, not including appendices. The Bibliography contains 57 titles.

ABBREVIATIONS

3GPP – 3rd Generation Partnership Project;
AI – Artificial Intelligence;
ATP – Automatic Train Protection;
BTS – Base Transceiver Station;
CCCL – Coaxial Cable Communication Line;
COST – European Cooperation in Science and Technology;
CSV – Comma-Separated Values;
EDGE – Enhanced Data Rates for Global Evolution;
EIRENE – European Integrated Radio Enhanced Network;
EMF – Electromagnetic Field;
EMW – Electromagnetic Wave;
ERA – European Railway Agency;
ERTMS – European Rail Traffic Management System;
ETCS – European Train Control System;
EU – European Union;
FDD – Frequency Division Duplex;
FOCL – Fiber Optic Communication Line;
FRMCS – Future Railway Mobile Communication System;
GSM – Global System for Mobile Communications;
HSPA – High-Speed Packet Access;
HTML – Hypertext Markup Language;
IEEE – Institute of Electrical and Electronics Engineers;
IP – Internet Protocol;
ITU – International Telecommunication Union;
KPI – Key Performance Indicator;
LAC – Local Area Code;
LAN – Local Area Network;
LTE – Long-Term Evolution;
MCC – Mobile Country Code;
MCN – Mobile Communication Network;
MNC – Mobile Network Code;
MS – Mobile Station;
MUX – Multiplexer;
NLOS – Non-Line of Sight;
OTDR – Optical Time Domain Reflectometer;
PC – Personal Computer;
PDH – Plesiochronous Digital Hierarchy;
PIFA – Planar Inverted-F Antenna;
PS – Polystyrol;
PSTN – Public Switched Telephone Network;
SDH – Synchronous Digital Hierarchy;
SHF – Super High Frequency;
SIM – Subscriber Identity Module;
SIP – Session Initiation Protocol;
SCCL – Symmetrical Cable Communication Line;
TCP – Transmission Control Protocol;
TDD – Time Division Duplex;
UDP – User Datagram Protocol;
UE – User Equipment;
UHF – Ultra High Frequency;
UIC – International Union of Railways;
VC – Virtual Container.

TABLE OF CONTENTS

GENERAL DESCRIPTION OF THE THESIS

Topicality of the theme

As technology advances, telematics systems are being used to solve an increasing number of rail transport tasks, such as remote signaling and remote control of railway equipment, train control, transport and freight monitoring, building automation, etc.

Modern trends in facilities management and maintenance are increasing the traffic volumes in telematics systems, e.g., in the collection of data for pre-failure detection, big data, machine learning, IoT and IIoT use cases.

Infrastructure development projects are replacing aging systems with new ones, the development, use, and maintenance of which require a clear understanding of existing and newly developed standards, methods for calculating communication line parameters, mathematical modeling capabilities, design, monitoring, and analysis tools.

Aim and objectives

The aim of the Thesis is development of mathematical models for the calculation of parameters of cable communication lines and mobile communication networks, implementation of the program, evaluation of performance in comparison with experimental results, and provision of recommendations for their practical application in railway transport telematics systems.

Objectives:

1. To analyze the publications on the topic of the Thesis, which will lead to the direction of the research.
2. To summarize methods for calculating the parameters of cable and wireless communication lines.
3. To experimentally investigate the main parameters of communication lines.
4. To create mathematical models of cable lines and mobile networks.
5. To do numerical evaluations of the main parameters of the communication links and comparison with experimental values, based on which the performance and applicability of the mathematical models in practice can be determined.
6. To develop recommendations for the use of the obtained results in the design of telematics systems communication lines in Latvian railways.

Research methodology

The completion of the objectives of the Thesis is divided into three stages:

1. To investigate the theoretical issues, a literature analysis is carried out on the parameters characterizing cable communication lines and mobile communication networks and mathematical models for their determination.

2. For the numerical analysis of communication lines, algorithms have been developed for the calculation of parameters, which are implemented with the Mathcad software.
3. For experimental studies the following equipment, instrumentation, and software was used:
    - for cable communication lines – optical OTDR reflectometers EXFO AXS-100-023B-EI-VFL and EXFO FTB-1-S2-8G, reflectometer IRK-PRO Gamma, digital analyzer Wandel & Goltermann ANT-20E;
    - mobile networks – Samsung M23 and Xiaomi Poco F4 GT mobile stations, Android applications Network Signal Guru, Tower Collector;
    - for the heterogeneous network model – optical multiplexers SURPASS hiT 7020, switches ALOE Systems MVTS Softswitch and Digium Asterisk Softswitch, router HUAWEI B535-232, telephone adapter Cisco ATA 186, VoIP softphones Zoiper and CounterPath X-Lite, software TNMS-M SURPASS hiT 7020 3.2.2 LCT, Wandel & Goltermann ANT-20E digital analyzer, IRK–PRO Gamma reflectometer, EXFO AXS-100-023B-EI-VFL optical reflectometer.

Scientific novelty

In this work, new mathematical models are developed to summarize and systematize the parameters of cable communication lines and mobile communication networks, and new algorithms for automated parameter estimation are developed based on the mathematical models for parameter estimation:

- for calculating the parameters of symmetrical, coaxial, fiber-optic communication lines and determining the maximum length of the cable;
- 2G-5G mobile network parameters and maximum radio coverage area.

Practical value

The mathematical models proposed in the Thesis allow automated parameter calculations of railway telematics systems in the primary design stage of cable communication lines and mobile communication networks.

The numerical parameter estimates are obtained using the Mathcad computer-aided design implementation of the given algorithms and are compared with the standard parameters and experimentally obtained values. The results of the comparison show that the proposed mathematical models reproduce the physical regularities observed in practice and reflect the values of the communication line parameters within acceptable limits.

The developed heterogeneous network combines modern communication technologies and standards used for the transmission of remote control and remote guidance signals, digital information from computer systems, and high-resolution multimedia data and is suitable for the modeling of telematics systems for rail transport.

Publications

The research questions, intermediate and overall results of the Thesis topics have been presented in international scientific publications:

1. Popovs, V., Skudnovs, V., Vasiljevs, A. *Mathematical Models and Algorithms of Radio Wave Propagation in Cellular Networks of Mobile Communication*. Technologijos ir menas, 2016, No. 7, pp. 102–111. ISSN 2029-400X.
2. Popovs, V., Skudnovs, V., Vasiljevs, A., Shevchenko, A. *Problems of Telemedicine in Latvia*. Technologijos ir menas, 2017, No. 8, pp. 101–107. ISSN 2029-400X.
3. Popovs, V., Skudnov, V., Vasilyev, A., Shevchenko, A. *Railway Heterogeneous Communication Network Model Investigations*. In: Procedia Computer Science. Vol. 149: ICTE in Transportation and Logistics 2018 (ICTE 2018), Lithuania, Klaipeda, 2019. Amsterdam: Elsevier, 2018, pp. 223–230. ISSN 1877-0509. Available at: doi: 10.1016/j.procs.2019.01.127 *(SCOPUS)*
4. Kargin, A., Panchenko, S., Vasilev, A., Petrenko, T. *Implementation of Cognitive Perception Functions in Fuzzy Situational Control Model*. In: Procedia Computer Science. Vol. 149: ICTE in Transportation and Logistics 2018 (ICTE 2018), Lithuania, Klaipeda, 2018. Amsterdam: Elsevier B.V., 2019, pp. 231–238. ISSN 1877-0509. Available at: doi: 10.1016/j.procs.2019.01.128 *(SCOPUS)*
5. Mezītis, M., Vasiljevs, A. *Feasibility of IIoT Application in Railway Signalling and Interlocking Systems*. In: Transport Means 2019: Sustainability: Research and Solutions: Proceedings of the 23rd International Scientific Conference. Part 1, Lithuania, Palanga, 2–4 October 2019. Kaunas: Kaunas University of Technology, 2019, pp. 169–175. ISSN 1822-296X. e-ISSN 2351-7034 *(SCOPUS)*
6. Popovs, V., Skudnovs, V., Vasiljevs, A. *Modern Antenna Systems of Mobile Terminals in Cellular Networks of Mobile Communication*. Visnyk Universytetu "Ukraina". Series Informatics, Computing and Cybernetics, 2019, Vol. 1, No. 22, pp.38–48.
7. Popovs, V., Skudnovs, V., Shevchenko, A., Vasilyev, A. *Application of Software Complexes for Monitoring of Cellular Networks of Mobile Communication KPI on Railway Transport*. In: Transport Means 2020: Proceedings of the 24th International Scientific Conference, Lithuania, Palanga, 30 September – 2 October 2020. Kaunas: Kaunas University of Technology, 2020, pp. 748–752. ISSN 1822-296X. e-ISSN 2351-7034 *(SCOPUS)*
8. Popovs, V., Otersone, K., Shevchenko, A., Skudnov, V., Vasiljevs, A. *Experimental Investigations of Radio Coverage Conditions in CNMC 2G-4G along the Railway*. No: Transport Means 2021: Proceedings of 25th International Scientific Conference, Lithuania, Kaunas, October 6–8, 2021. Kaunas: Kaunas University of Technology, 2021, pp. 131–135. ISSN 1822-296X. e-ISSN 2351-7034 *(SCOPUS)*
9. Otersone, K., Vasiljevs, A. *Experimental Investigations of Radio Coverage Conditions in 5G Cellular Mobile Communication Networks for Railway Application*. In: Transport Means 2022: Proceedings of 26th International Scientific Conference, Lithuania,

Kaunas, October 5–8, 2022. Kaunas: Kaunas University of Technology, 2022, pp. 146–150. ISSN 1822-296X. e-ISSN 2351-7034 *(SCOPUS)*
10. Vasiljevs, A. Otersone, K. *Mathematical Models of VHF/UHF Radio Wave Propagation in Cellular Mobile Communication Networks*. In: Transport Means 2022: Proceedings of 26th International Scientific Conference, Lithuania, Kaunas, October 5–8, 2022, pp. 260–266. Kaunas: Kaunas University of Technology, 2022. ISSN 1822-296X. e-ISSN 2351-7034 *(SCOPUS)*

Structure of the Thesis

The Thesis consists of an introduction, three chapters, conclusions, a list of references, and appendices.

Chapter 1 is dedicated to:

- the observation of cable communication lines for railway applications;
- the summary of mathematical models suitable for symmetrical (SCCL), coaxial (CCCL), and fiber-optic (FOCL) communication lines;
- the systematization of formulas for the determination of parameters of cable communication lines and optimal sequence of calculations.

Chapter 2:

- reviews mobile communication systems and standards for the rail sector;
- describes the principles and stages of designing mobile communication networks (MCNs);
- observes mathematical models of radio wave propagation and their use in the design of railway communication networks.

Chapter 3 contains:

- developed algorithms for engineering calculations of symmetrical, coaxial, fiber-optic communication lines and mobile networks parameters;
- implementation of the calculation methodology for determining the parameters of cable communication lines and mobile networks in Mathcad;
- comparisons of calculated standard parameters with experimentally derived values to determine the applicability of mathematical models;
- simulation models of the heterogeneous network model developed.

The appendices include parameter calculation programs for symmetrical, coaxial, fiber-optic communication lines and mobile communication networks in the Mathcad computer-aided design environment.

1. MATHEMATICAL MODELS OF CABLE COMMUNICATION LINES IN RAIL TRANSPORT

Devices designed to transmit electromagnetic energy in a given direction are called guiding systems. In most cases, the surface of the conductors or dielectrics is what makes up the guiding systems, and electromagnetic waves travel along these boundary surfaces, which act as a kind of “rails”.

Telecommunications and radio communications use different types of guiding systems: two-wire lines (overhead, cable), strip lines, coaxial lines, metallic or dielectric waveguides, and optical lines.

Homogeneous and heterogeneous; regular and irregular; isotropic and anisotropic propulsion systems are distinguished. If the parameters of the medium in which the wave propagates are homogeneous, the guiding system is also homogeneous; if the parameters of the medium are heterogeneous, the guiding system is called heterogeneous. Linear homogeneous guiding systems of infinite length are called regular.

In real cases, the guiding systems are heterogeneous, as the parameters in the propagation direction can vary significantly. In communication systems, guidance devices can be used under different conditions and in different frequency ranges.

Depending on the frequency range used and the design of the guiding system through which the electromagnetic waves propagate, one of two calculation methods is applied [50]: using either circuit theory or electrodynamic field equations (Maxwell's equations). The first method is commonly used for the parametric engineering of symmetrical, coaxial, and strip lines. The second method is more general and challenging. It is used to model the propagation of electromagnetic waves (EMW) in the coaxial, waveguide, and optical lines and assumes that the EMW are already excited and do not contain sources of electromagnetic fields (EMF) [49].

Symmetrical cable communication lines (SCSL)

A symmetrical cable is a communication cable consisting of two or more twisted or parallel wires, which are insulated from each other. A symmetrical cable communication line (SCCL) is an electrical circuit with distributed characteristics. The characteristic feature of such circuits is a line of two conductors with identical structural properties. When a voltage is applied to a two-wire line, an electric current of a given frequency flows in the conductors. The current and voltage excite a changing electromagnetic field around the conductors [36], [37].

The primary parameters of a symmetrical cable communication line are the impedance R, the conductance G, the inductance L, and the capacitance C. These parameters are uniformly distributed over the length of the line [10], [38].

Line resistance determines energy losses in the conductors and metallic elements of the cable. Inductance describes the ability of a conductor to store electricity. The capacitance of a symmetrical cable describes the ability of conductors to store charge and it is independent of the frequency of the signal. The conductivity of a communication line reflects the energy losses in the insulation of the cable.

The secondary parameters of the communication line (wave impedance Z_v, attenuation α, phase factor β, signal propagation speed v, velocity factor K_s, signal propagation time T_{iz}) should be calculated according to general formulas taking into account the values of the primary parameters. The total working loss of the line is calculated as the sum of all losses.

The sequence for calculating the primary and secondary parameters of a symmetrical communication line and the corresponding formulas for determining the parameters are summarized in Table 1.1.

Table 1.1

The sequence of calculation of primary and secondary parameters of the SCCL

No.	Parameter	Formula, a unit of measurement	Variables, units of measurement
1.	Resistance	$R = R_0\left[1+F(x)+\dfrac{P_S\cdot G(x)\cdot(d/a)^2}{1-H(x)\cdot(d/a)^2}\right], \dfrac{\Omega}{\text{km}}$	R_0, Ω/km *d*, mm *a*, mm
2.	Inductance	$L=\chi\cdot\left[4\cdot\ln\left(\dfrac{2a-d}{d}\right)+Q(x)\cdot\mu_r\right]\cdot 10^{-4}, \dfrac{\text{H}}{\text{km}}$	*d*, mm *a*, mm
3.	Capacitance	$C=\dfrac{\chi\cdot\varepsilon_r\cdot 10^{-6}}{36\ln\left[\left(2a-d/d\right)\psi\right]}, \dfrac{\text{F}}{\text{km}}$	*d*, mm *a*, mm
4.	Conductivity	$G=2\pi\cdot f\cdot C\cdot \text{tg}\,\delta, \dfrac{\text{S}}{\text{km}}$	*f*, Hz *C*, F/km
5.	Wave resistance	$Z_v=\dfrac{120}{\sqrt{\varepsilon_r}}\cdot\ln\left(\dfrac{2a-d}{d}\right), \Omega$	*d*, mm *a*, mm
6.	Attenuation	$\alpha=8.69\cdot\left(\dfrac{R}{2}\sqrt{\dfrac{C}{L}}+\dfrac{G}{2}\sqrt{\dfrac{L}{C}}\right), \dfrac{\text{dB}}{\text{km}}$	R, Ω/km L, H/km C, F/km G, S/km
7.	Phase coefficient	$\beta=2\pi\cdot f\cdot\sqrt{L\cdot C}, \dfrac{\text{rad}}{\text{km}}$	*f*, Hz *L*, H/km *C*, F/km
8.	Signal propagation speed	$\upsilon=\dfrac{1}{\sqrt{L\cdot C}}, \dfrac{\text{km}}{\text{s}}$	*L*, H/km *C*, F/km
9.	Signal propagation time	$T_{iz}=\dfrac{L_g}{\upsilon}, \text{s}$	L_g, km υ, km/s
10.	Velocity factor	$K_s=\dfrac{c}{\upsilon}$	*c*, km/s υ, km/s
11.	Transmission attenuation	$a_d=\alpha\cdot L+\Delta a_1+\Delta a_2+\Delta a_3, \text{dB}$	α, dB/km Δa_1, Δa_2, Δa_3, dB

Coaxial cable communication lines (CCCL)

A coaxial cable communication line (CCCL) consists of two metallic conductors: one in the form of a tube (screen), the other inserted into the tube. An insulating material is placed between the screen and the central conductor. The coaxial cable communication line is a closed-loop guiding system. Coaxial cables are mainly used for frequencies from 50 kHz. The high-frequency signal produces a strong proximity effect and a skin effect when the operating current flows only in a thin layer on the outer side of the inner conductor and the inner side of the screen [36], [37].

The main characteristics of a coaxial line, like a SCCL, are four transmission parameters: active impedance, conductivity, inductance, and capacitance [38]. They represent the influence of the cable materials' physical properties on the signal transmission quality.

The secondary parameters (wave impedance, length coefficient, phase coefficient, signal propagation speed, velocity factor, and signal propagation time) of a communication line shall be calculated using the values of the primary parameters. The sequence for calculating the primary and secondary parameters of a coaxial communication line and the corresponding formulas for determining the parameters are summarized in Table 1.2.

Table 1.2

The sequence of calculation of primary and secondary parameters of the CCSL

No.	Parameter	Formula, a unit of measurement	Variables, units of measurement
1.	Length resistance	$R = \frac{\sqrt{f \cdot \mu}}{\sqrt{\pi}} \cdot \left(\frac{1}{\sigma_a \cdot d} + \frac{1}{\sigma_b \cdot D} \right) \cdot 10^6, \frac{\Omega}{\text{km}}$	R_0, Ω/km d, mm a, mm
2.	Length inductance	$L = \frac{101}{\sqrt{f}} \cdot \left(\frac{1}{\sqrt{\sigma_a} \cdot d} + \frac{1}{\sqrt{\sigma_b} \cdot D} \right) + 2\ln\left(\frac{D}{d}\right) \cdot 10^{-4}, \frac{\text{H}}{\text{km}}$	d, mm a, mm
3.	Length capacity	$C = \frac{\varepsilon_r \cdot 10^{-6}}{18\ln(D/d)}, \frac{\text{F}}{\text{km}}$	d, mm a, mm
4.	Conductivity of length	$G = 2\pi \cdot f \cdot C \cdot \text{tg}\,\delta, \frac{\text{S}}{\text{km}}$	f, Hz C, F/km
5.	Wave resistance	$Z_v = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right), \Omega$	d, mm a, mm
6.	Coefficient of length reduction	$\alpha = 8.69 \cdot \left(\frac{R}{2}\sqrt{\frac{C}{L}} + \frac{G}{2}\sqrt{\frac{L}{C}} \right), \frac{\text{dB}}{\text{km}}$	R, Ω/km L, H/km C, F/km G, S/km
7.	Phase coefficient	$\beta = 2\pi \cdot f \cdot \sqrt{L \cdot C}, \frac{\text{rad}}{\text{km}}$	f, Hz L, H/km C, F/km
8.	Signal propagation speed	$\upsilon = \frac{1}{\sqrt{L \cdot C}}, \frac{\text{km}}{\text{s}}$	L, H/km C, F/km
9.	Velocity factor	$K_s = \frac{c}{\upsilon}$	c, km/s υ, km/s
10.	Signal propagation time	$T_{iz} = \frac{L_g}{\upsilon}, \text{s}$	L_g, km υ, km/s

Fiber optic communication lines (FOCL)

Optical fiber is the main element of a fiber-optic communication line (FOCL) that carries the signal. It can be structurally considered as a circular dielectric waveguide with a core and cladding, operating in the optical frequency range. The core of the optical fiber is made of transparent glass and is designed to transmit optical energy, while the cladding is made of glass of lower transparency, which prevents energy from passing through the core and ensures a condition of total internal reflection [36], [37].

The most important parameters of the FOCL [39] are the numerical aperture *NA*, the relative difference in refraction index Δ, the normalized frequency *V*, the critical wavelength of the modes λ_{kr}, and the critical frequency f_{kr}. The magnitude of the optical signal power loss is evaluated by the attenuation *α*, which depends on the losses in the optical waveguide and cable. The broadening of the signal pulses in the optical fiber is called dispersion *τ*, which affects the bandwidth Δ*F*. The sequence and formulas for calculating the parameters of the FOCL are summarized in Table 1.3.

Table 1.3

The sequence for calculating the parameters of the FOCL

No.	Parameter	Formula, a unit of measurement	Variables, units of measurement
1.	Coating refraction index	$n_2 = n_1 \cdot \sqrt{1-2\Delta}$	–
2.	Numerical aperture	$NA = \sqrt{n_1^2 - n_2^2} = n_1\sqrt{2\Delta}$	–
3.	Representative frequency	$V = \frac{\pi \cdot d \cdot NA}{\lambda}$	*d*, μm *λ*, μm
4.	Critical wavelength	$\lambda_{kr} = \frac{\pi \cdot d \cdot NA}{2.405}$, μm	*d*, μm
5.	Critical frequency	$f_{kr} = \frac{c}{n_1 \cdot \lambda_{kr}} \cdot 10^3$, MHz	λ_{kr}, μm
6.	Phase velocity	$v_\varphi \le \frac{c}{n_1} \cdot 10^3, \frac{\text{m}}{\text{s}}$	*c*, km/s
7.	Attenuation	$\alpha = \frac{n_1 \cdot \pi \cdot \text{tg}\,\delta}{\lambda} \cdot 8.69 \cdot 10^8 + \frac{K_R}{\lambda^4}, \frac{\text{dB}}{\text{km}}$	*λ*, μm K_R, μm^4·dB/km
8.	Total dispersion	$\tau = \Delta\lambda \cdot \left(M(\lambda) + \frac{2 \cdot n_1^2 \cdot \Delta}{c \cdot \lambda} \cdot 10^9 \right), \frac{\text{ps}}{\text{km}}$	Δ*λ*, nm *M*(*λ*), ps/(nm·km) *c*, km/s *λ*, μm
9.	Channel bandwidth	$\Delta F = \frac{k_f}{\tau} \cdot 10^{12}$, Hz	τ, ps
10.	Length of the regeneration section	$L_m = \frac{P_r - P_u - \delta - \alpha_r - \alpha_s \cdot n_s - \alpha_{ns} \cdot n - \alpha_{saz} \cdot n_{saz}}{\alpha + (a_{ns}/L_b)}$, dB	P_r, P_u, dBm α_r, α_s, α_{ns}, α_{saz}, dB *α*, dB/km

2. MATHEMATICAL MODELS OF MOBILE COMMUNICATION NETWORKS (MCN) IN RAIL TRANSPORT

A mobile or cellular network is a wireless communications network based on the division of a coverage area into cells. Each cell contains one or more fixed base transceiver stations (BTS), which provide communications between subscribers' mobile stations (MS). GSM for Railways or GSM-R (GSM-Railway) is the international second-generation (2G) wireless communications standard for railway voice, signaling, and interlocking. GSM-R is a subsystem of the European Rail Traffic Management System (ERTMS).

ERTMS has two main elements: the first is the European Train Control System (ETCS), which replaces the existing train protection systems (ATP – Automatic Train Protection) and is designed to replace the many incompatible safety systems currently used on European railways. It consists of onboard equipment and field equipment elements that form a system that monitors train traffic. The second element of ERTMS is GSM-R, which is a mobile communication network optimized for railways, used for rail-specific voice and data services. GSM-R provides wireless communication in ETCS levels 2 and 3.

The development of GSM-R was based on the public mobile standard GSM and was completed in the year 2000. The cost of the development was considerably lower, as only the functional requirements of the existing standard had to be added [6] and the whole system did not have to be designed from scratch. GSM-R requires a high–speed and reliable MCN infrastructure for rail communications. The standard uses the frequency range 876–880 MHz for the uplink and 921–925 MHz for the downlink [27], [52]. These bands are reserved for railways throughout the European Union (EU).

GSM-R is a critical part of the railway infrastructure, for which safety, security, and operational efficiency are the most important parameters. Therefore, the reliability of the GSM-R wireless network as a whole and the individual hardware must be many times higher than in public GSM networks [9], [27]. But today, GSM-R systems are considered obsolete [42]: they no longer meet the functional requirements of railway operators, and hardware manufacturers stop producing new equipment and spare parts, which has a negative impact on the maintenance of the system and increases costs.

The FRMCS (Future Railway Mobile Communication System) project, launched in 2012 by the International Union of Railways (UIC), aims to develop a new railway communication standard to fully replace GSM-R in the future. The FRMCS radio subsystem is adaptable to several modern mobile communication standards (LTE, LTE-A, 5G NR, etc.) [20], but recent decisions by the European Railway Agency (ERA) and the UIC, as well as the EU strategy for 5G deployment in Europe, clearly indicate that the new standard will be based on 5G.

The Commission Implementing Decision (EU) 2021/1730 of 28 September 2021 on the harmonized use of the paired frequency bands indicates, that in Europe FRMCS systems will use 874.4–880.0 MHz frequency bands for uplink (MS to BTS), 919.4–925.0 MHz bands for downlink (BTS to MS) in frequency division duplex (FDD) mode, and 1900–1910 MHz bands in time division duplex (TDD) mode.

MCN design principles

The first principle of mobile network design is the use of cellular topology. Interconnected cells in a single network can provide communications over an area of any size where it is practical and cost-effective to do so. The second principle is to ensure the uniformity of the MCN coverage area, i.e., when mobile stations (subscribers) move between base station service areas, communications must be stable and stay uninterrupted.

The third principle of mobile network design is scalability. The mobile network operator must be able to extend the MCN coverage area, change network infrastructure, and introduce new standards to support the latest generations of mobile communication technology.

The successful operation of today's mobile networks depends to a large extent not only on the design of the access network infrastructure in the initial stages but also on adaptive measures to adjust the network to changing factors and conditions in the future. Thus, in the MCN, the process of designing the territorial radio coverage should include not only the calculation of the cell dimensions, cluster structure, and other parameters of the service area but also periods of testing and adaptation of the entire network and its equipment.

Propagation characteristics of MCN radio waves

Modern mobile networks use both ultra-high frequency (UHF) and super-high frequency (SHF) electromagnetic waves, which are virtually immune to reflection and scattering from the ionized layers of the atmosphere. Waves in these frequency ranges propagate over short distances mainly as ground waves (diffraction of such waves is weak) and over longer distances due to scattering by the troposphere and the guiding effect of tropospheric waveguides.

In the real world, any radio signal is inevitably affected by fading – the effect of attenuation and signal strength level fluctuation that occur due to multipath propagation, obstruction, or environmental and weather conditions [23]. Fading has two components: fast and slow (Fig. 2.1).

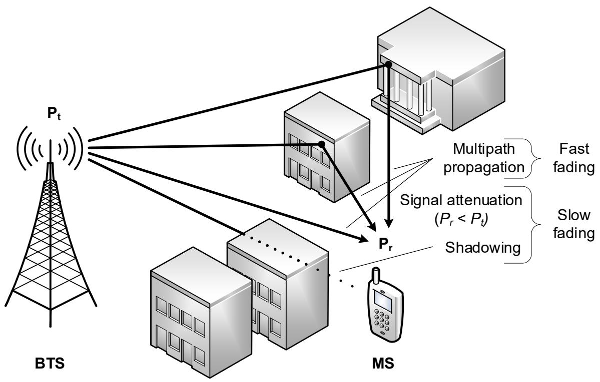


Fig. 2.1. Fading components and their sources.

Slow fading occurs when a mobile station moves over a large distance, which leads to changes in the propagation environment conditions, resulting in radio signal attenuation [26], [35], the magnitude of which depends on the distance between the BTS and the MS.

Fast fading occurs when the local position of a mobile station changes, or when radio waves propagate in multipath mode (multipath fading). This causes the time broadening of the signal and changes the characteristics of the channel [47].

Principles for calculating the MCN service area

The statistical method of designing mobile network service area [27], [31] is based on the determination of the cell area and the calculation of the distances between base transceiver stations using statistical data on the radio propagation environment, channel parameters, and electrical characteristics of the equipment used.

In the determined method [27], [31], base stations are deployed in a way, which minimizes the average radio channel usage interval (number of cells per cluster) and at the same time achieves a satisfactory level of service within the service area of the entire mobile communication system. Optimal siting of base stations requires knowledge of the average level of the radio signal radiated from possible base station locations and received by mobile stations at any location, even beyond the boundaries of the designed cells. Information on signal levels can be obtained by calculations, measurements, or prediction.

Mathematical models of radio wave propagation

Radio coverage planning is an important stage in the design of mobile communication systems. One of the main objectives of mobile network planning is to achieve homogeneous radio coverage while maintaining a high quality of communications services and minimizing overall costs.

For the development of the optimal radio coverage map, the MCN design phase should use condition-dependent mathematical models of radio wave propagation [4], [44], which describe electromagnetic wave propagation, determine the presence or probability of various sources of obstruction, reflection, scattering, diffraction, and calculates the electromagnetic energy losses in the radio tract [45]. The theoretical models can be improved by experimental measurements and drive tests to achieve high accuracy. Simplified mathematical models used in engineering calculations are a compromise between accuracy and complexity. Simulating radio transmission is computationally intensive, time-consuming, and not always practical.

Mathematical models, which can be utilized to determine the power of electromagnetic waves, transmitted from a base station and received by a mobile station, are summarized in Table 2.1 [31]. The following parameters are used: P_t – BTS antenna transmitter power, dBm; f – operating band center frequency, MHz; λ – operating wavelength, m; G_t, G_r – BTS, MS antenna gain factors; h_t, h_r – BTS, MS antenna heights, m; r – the distance between the BTS transmitter and MS receiver, km; f_0 – normalizing frequency, f_0 = 1 MHz; λ_0 – normalizing wavelength, λ_0 = 1 m; h_0 – normalizing height, h_0 = 1 m; r_0 – normalizing distance between BTS and MS, r_0 = 1 km.

Table 2.1

Mathematical models of MCN radio wave propagation

No.	Model	Key characteristic formulas
1.	Free space [16]	$P_{r\,LOS} = P_t + 10\lg G_t + 10\lg G_r - 20\lg(4\pi) + 20\lg\left(\frac{\lambda}{\lambda_0}\right) - 20\lg\left(\frac{r \cdot 10^3}{r_0}\right) < 0,$ where $P_{r\,LOS}$ – average power level at the signal reception point in line of sight conditions, dBm.
2.	Two-ray [15]	$P_r \approx P_t + 10\lg G_t + 10\lg G_r + 20\lg\left(\frac{h_t}{h_0}\right) + 20\lg\left(\frac{h_r}{h_0}\right) - 40\lg\left(\frac{r \cdot 10^3}{r_0}\right),$ where P_r – average power level at the signal reception point, dBm.
3.	Log-distance path loss [14], [15]	$P_r = P_{r\,LOS} - 10 \cdot n \cdot \lg\left(\frac{r}{r_0}\right) - X_g,$ where n – attenuation exponent; X_g – random value for normal (Gaussian) distribution with a zero mean, representing signal attenuation condition, which was caused by its fading.
4.	Lee [18], [19]	$P_r = P_{r0} - 10\gamma \cdot \lg\left(\frac{r}{r_{n0}}\right) - 10n \cdot \lg\left(\frac{f}{f_{n0}}\right) + 10\lg(\alpha_0),$ where α_0 – adjustment factor, dB; P_{tmW} – BTS transmitter power, mW; P_{r0} – power at the r_{n0} point, dBm; γ – path loss correction due to distance; n – frequency correction factor, $2 \le n \le 3$; v – MS antenna height correction factor; f_{n0} – nominal frequency, f_{n0} = 900 MHz; P_{tn0} – nominal BTS transmitter power, P_{tn0} = 10 W; h_{tn0} – nominal BTS antenna height, h_{tn0} = 30.48 m; h_{rn0} – nominal MS antenna height, h_{rn0} = 3 m; r_{n0} – nominal distance between BTS and MS, r_{n0} = 1.6 km.
5.	Okumura [45]	$P_r = P_{r\,LOS} - A_{mu}(f, r) + H(h_t) + H(h_r) + G_{area},$ where $A_{mu}(f, r)$ – median attenuation relative to free space, dB; $H(h_t)$ – BTS antenna gain factor, dB; G_{area} – gain correction factor depending on the environment, dB.
6.	Okumura–Hata [11]	$P_{r\,Hata} = P_t - 69.55 - 26.16\lg\left(\frac{f}{f_0}\right) - \left(44.9 - 6.55\lg\left(\frac{h_t}{h_0}\right)\right)\lg\left(\frac{r}{r_0}\right) +$ $+13.82\lg\left(\frac{h_t}{h_0}\right) + a(f, h_r) + K(f),$ where $a(f,h_r)$ – correction factor for MS antenna height, dB; K – correction factor that depends upon the environment, dB.
7.	COST231 Hata [5]	$P_r = P_t - A - B\lg\left(\frac{f}{f_0}\right) + 13.82\lg\left(\frac{h_t}{h_0}\right) + a(f, h_r) - \left[44.9 - 6.55\lg\left(\frac{h_t}{h_0}\right)\right]\lg\left(\frac{r}{r_0}\right) - C,$ where A – attenuation component, dB; B – frequency correction factor; $a(f,h_r)$ – correction factor for MS antenna height, dB; C – attenuation correction factor, depending on the environment, dB.
8.	COST231 Walfish–Ikegami (WI) [5], [13]	$P_{r\,LOS} = P_t + L_{LOS} = P_t - 42.6 - 26\lg\left(\frac{r}{r_0}\right) - 20\lg\left(\frac{f}{f_0}\right),$ $P_{r\,NLOS} = P_t + L_{rt},$ where L_{LOS} – path loss for free space (LOS) environment, dB; L_{rt} – path loss, dB.
9.	Hata–Davidson [45]	$P_r = P_{r\,Hata} - A(h_t, r) + S_1(r) + S_2(h_t, r) + S_3(f) + S_4(f, r),$ where $P_{r\,Hata}$ – received signal strength for Okumura–Hata model, dBm; $A(h_t,r)$, $S_1(r)$ – distance correction factor, dB; $S_2(h_t,r)$ – BTS antenna height correction factor, dB; $S_3(f)$ – frequency correction factor, dB; $S_4(f,r)$ – frequency and distance correction factor, dB.
10.	Propagation of radio	$P_r \approx P_{t\,LOS} - \alpha_{mF} \cdot r + 10\lg\left[\varsigma(r)\right],$

Table 2.1 continued

No.	Model	Key characteristic formulas
	waves in forests [53]	where α_{mF} – path attenuation factor, dB/km; $\varsigma(r)$ – correction factor.
11.	Propagation of radio waves in free space with the reflection from the forest [53]	$$P_{rW} = \frac{P_t \cdot G_t \cdot G_r \cdot \lambda^2}{(4\pi)^2} \int_{V_F} \frac{F_t(\theta)^2 \cdot \sigma(\phi)}{r_1^2 \cdot r_2^2 \cdot V_0} dV,$$ where P_{rW} – received signal power, W; $F_t(\theta)$ – BTS antenna radiation pattern, $F_t(\theta) = 1$ for omnidirectional antennas; V_F – volume of the forest, m^3; V_0 – norming volume, $V_0 = 1$ m^3; φ – angle between the direction of the main wave and its reflection from the forest, °; $\sigma(\varphi)$ – effective scattering area of a volume unit, m^2; r_1 – distance between BTS and forest, km; r_2 – distance between the forest and the MS, km.

3. ENGINEERING ALGORITHMS AND RESEARCH OF COMMUNICATION LINES FOR TELEMATICS SYSTEMS

The organization of the interoperability of railway infrastructure elements is one of the main design challenges for telematics systems. A typical telematics system consists of hardware that is connected to each other via various communication channels (Fig. 3.1).

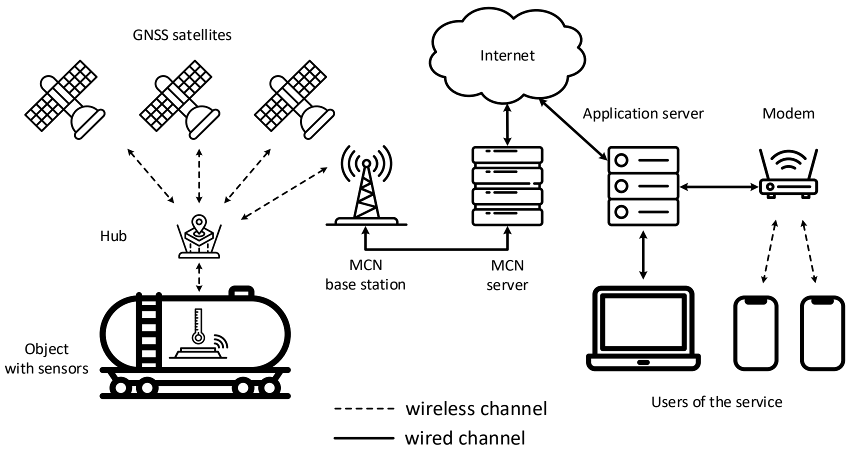


Fig. 3.1. Example of a telematics system and its equipment.

The construction of a heterogeneous telecommunication network, consisting of various elements of telematics systems, requires communication between different sites using both wired and wireless standards. Consequently, in modern railway telematics systems, the design of the communication network should be based on engineering solutions for calculating the parameters of cable communication lines (mainly symmetrical and optical) and mobile communication systems.

Algorithm for automated engineering calculations of cable communication lines

Designing a cable communication link requires a clear understanding of the magnitudes of signal transmission parameters over a wide operating frequency spectrum. These characteristics help to assess the suitability of a particular cable for the requirements of the design.

The formulas for calculating the parameters of cable communication lines described in Chapter 1 of the Thesis were originally designed for manual calculation and were not suitable for the automation of this process. For the development of mathematical models suitable for the computer-aided design of symmetrical, coaxial, and fiber optic communication lines it is necessary to:

1) express parameters and variables in SI units;
2) use the same prefixes of SI units for the same variables in all formulas and expressions;
3) order the sequence of parameter determinations so that, for successive calculations, the values of the unknowns are calculated before they appear in the formulas and expressions;
4) express all coefficients given in graphs and tables as functions;
5) introduce new coefficients that determine the values of variables depending on the physical characteristics of the communication line;
6) create an algorithm for calculating the parameters.

The first three conditions were met in the review, analysis, and compilation stages of the SCCL, CCCL, and FOCL in Chapter 1.

The exact values of the parameters given in the graphs were obtained by the process of digitization. In the case of material and waveguide dispersion, the functions $M(\lambda)$ and $B(\lambda)$ are expressed using the numerical data arrays and the interpolation method (Fig. 3.2).

$$\lambda_t := (0.7\ \ 0.8\ \ 0.9\ \ 1\ \ 1.1\ \ 1.2\ \ 1.3\ \ 1.4\ \ 1.5\ \ 1.6\ \ 1.7\ \ 1.8\ \ 1.9\ \ 2\ \ 2.1\ \ 2.2)^T\ \mu m$$

$$M_t := (189.6\ \ 114.9\ \ 73.9\ \ 46.6\ \ 26.7\ \ 12.2\ \ 0.46\ \ -9\ \ -16.7\ \ -23\ \ -29\ \ -35\ \ -39.5\ \ -45\ \ -49\ \ -54)^T\ \frac{ps}{nm \cdot km}$$

$$B_t := (3.46\ \ 3.97\ \ 4.58\ \ 5.18\ \ 5.75\ \ 6.32\ \ 7.01\ \ 7.5\ \ 8.2\ \ 8.78\ \ 9.79\ \ 11.62\ \ 14.15\ \ 17.43\ \ 21.56\ \ 26.55)^T\ \frac{ps}{nm \cdot km}$$

$$M(\lambda_f) := \mathrm{interp}(\mathrm{pspline}(\lambda_t, M_t), \lambda_t, M_t, \lambda_f) \qquad ps \cdot (nm \cdot km)^{-1}$$

$$B(\lambda_f) := \mathrm{interp}(\mathrm{pspline}(\lambda_t, B_t), \lambda_t, B_t, \lambda_f) \qquad ps \cdot (nm \cdot km)^{-1}$$

Fig. 3.2. Expression of specific material and waveguide dispersion as functions in Mathcad.

Parameters, whose values are given in tables or depend on the design of the communication line, were also expressed as functions by introducing new coefficients $k_{st.}$ (type of twist), $k_{vm.}$ (conductor material), $k_{im.}$ (insulation material): a, D, ψ – $a(k_{st.})$, $D(k_{st.})$, $\psi(k_{st.})$; ρ, σ– $\rho(k_{vm.})$, $\sigma(k_{vm.})$; $F(x)$, $G(x)$, $H(x)$, $Q(x)$ – $F(\sigma, d, f)$, $G(\sigma, d, f)$, $H(\sigma, d, f)$, $Q(\sigma, d, f)$; P_S – $P_S\ (k_{st.})$; ε_r , tgδ – $\varepsilon_r\ (k_{im.}\ , f)$, tg$\delta(k_{im.}\ , f)$.

To automate the process of parameter calculation for symmetrical, coaxial, and fiber optic cables (based on the developed algorithms), programs in the Mathcad engineering environment were proposed. These programs allow seeing the values of primary and secondary parameters immediately after entering the information about the specified communication line and its structure. The final report shows the frequency dispersion plots in the case of SCCL, CCCL and the dependence of the values on the length of the line. This simplifies the task of designing the cable line, as the initial need to experimentally determine the cable parameters and plotting characteristic curves by hand disappear.

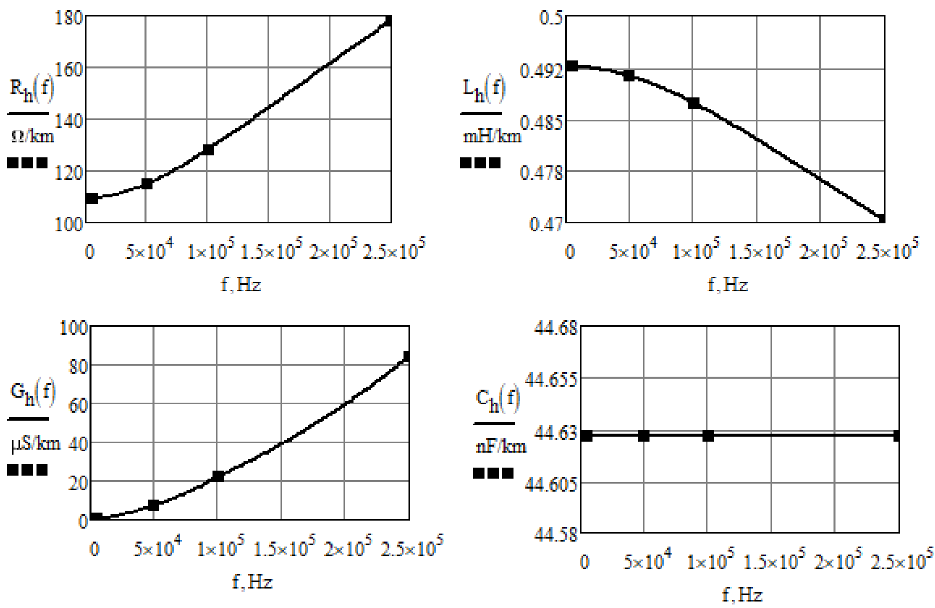
All line parameter values and graphs in Mathcad are calculated and constructed automatically. The result of the mathematical modeling of the cable communication line are summarized in the report (Fig. 3.3) at the end of the corresponding program.

Report

Cable type = "symmetrical" Conductor material = "copper" d = 0.64·mm Δ = 0·mm

Insulation = "pentaethylene glycol (PEEG)" Type of twist = "pair" δ = 0.265·mm h = 65·mm

Primary parameters:



f (Hz) =	R (Ω/km) =	L (mH/km) =	G (μS/km) =	C (nF/km) =
$1\cdot10^3$	109.408	0.493	0.084	44.627
$5\cdot10^3$	109.426	0.493	0.421	44.627
$50\cdot10^3$	114.924	0.491	7.321	44.627
$100\cdot10^3$	128.272	0.487	22.432	44.627
$250\cdot10^3$	178.23	0.47	84.119	44.627

Fig. 3.3. Excerpt from the SCCL mathematical modeling Mathcad report.

Algorithm for calculating SCCL parameters

Development of a program in Mathcad for the calculation of symmetrical communication line parameters based on the calculation sequence (Table 1.1) requires the algorithm. In the provided algorithm (Fig. 3.4), the calculations of the primary and secondary SCCL parameters are given in the form of subroutines.

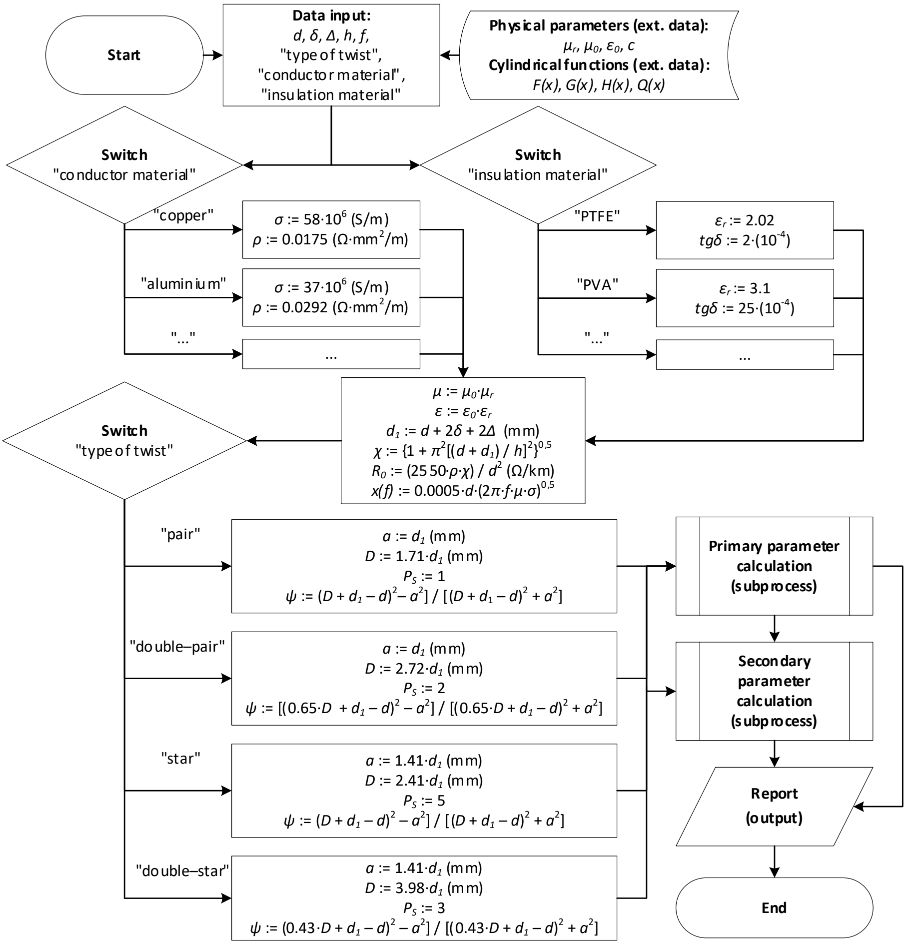


Fig. 3.4. The algorithm for calculating the parameters of SCCL in Mathcad.

To determine the calculation accuracy of the proposed SCCL mathematical model, a Belden 7701 NH symmetrical cable with known primary and secondary parameters was used. In the technical description of the cable, apart from information on the construction and mechanical properties, the manufacturer indicates the electrical parameters of the cable, experimentally obtained during the cable certification process.

The calculated parameters of the communication line and the parameters from the cable data sheet are compared in Table 3.1. As can be seen, the calculated values of wave impedance, impedance, capacitance, and ripple factor do not exceed the standard values of these parameters.

Overall, the calculated and standard parameters of the Belden 7701 NH cable differed from each other by no more than 5 %, indicating the suitability of the mathematical models for use in engineering practice for the design of symmetrical communication cable lines.

Table 3.1

Comparison of calculated and standard parameters of the SCCL

Parameter	Frequency, MHz	Calculated value	Standard value	Unit
Wave resistance	–	99.793	100	Ω
Length resistance to DC	–	54.67	55	Ω/km
Length capacity	–	44.627	46	pF/m
Coefficient of length reduction	0.772	1.331	1.3	dB/100 m
	1	1.511	1.5	
	4	3.047	3.1	
	10	4.886	4.9	
	16	6.251	6.3	
	20	7.034	6.9	

Algorithm for calculating CCSL parameters

The procedure for calculating the parameters of a CCCL is not significantly different from the engineering calculations for a symmetrical cable line. Accordingly, based on the SCCL calculation algorithm (Fig. 3.4) and the sequence of the determination of the parameters of the CCCL (Table 1.2), an algorithm for the calculation of the primary and secondary parameters of the CCCL was implemented for the development of a Mathcad program:

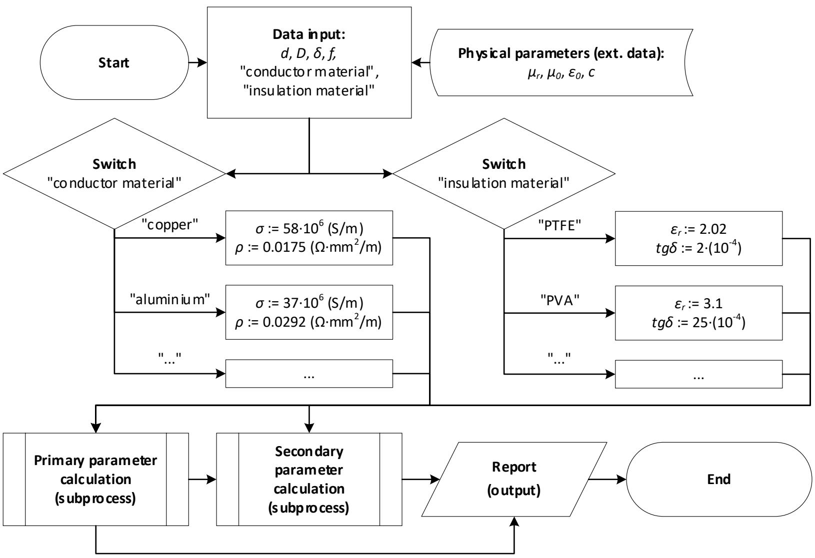


Fig. 3.5. Algorithm for calculating the CCCL parameters in Mathcad.

The Belden CX3C1 coaxial cable, designed for use in high-frequency (up to 2.15 GHz) signal transmission systems, was selected to determine the accuracy of the CCCL engineering calculations. The calculated parameters of the Belden CX3C1 cable are summarized in Table 3.2, where they are compared with the parameters from the datasheet for this cable.

Table 3.2

Comparison of calculated and standard parameters of the CCCL

Parameter	Frequency, MHz	Calculated value	Standard value	Unit
Wave resistance	–	74.959	75	Ω
Capacitance	–	52.8	54	pF/m
Attenuation	5	0.394	0.4	dB/100m
	50	1.283	1.3	
	100	1.845	1.8	
	200	2.674	2.6	
	400	3.928	3.9	
	600	4.968	4.8	
	800	5.909	5.7	
	1000	6.795	6.5	

As can be seen, the calculated parameters of the wave impedance and the attenuation differed from the standard parameters of the Belden CX3C1 cable by no more than 5 %, allowing the models to be used in engineering practice for the design of coaxial cable lines.

Algorithm for calculating FOCL parameters

According to the sequence of calculation of the FOCL parameters, an algorithm was developed for the determination of the fiber optic link attenuation, dispersion, and the length of the regeneration section (Fig. 3.6). Based on the proposed algorithm, a program for the automated calculation of the FOCL parameters was developed in the Mathcad environment.

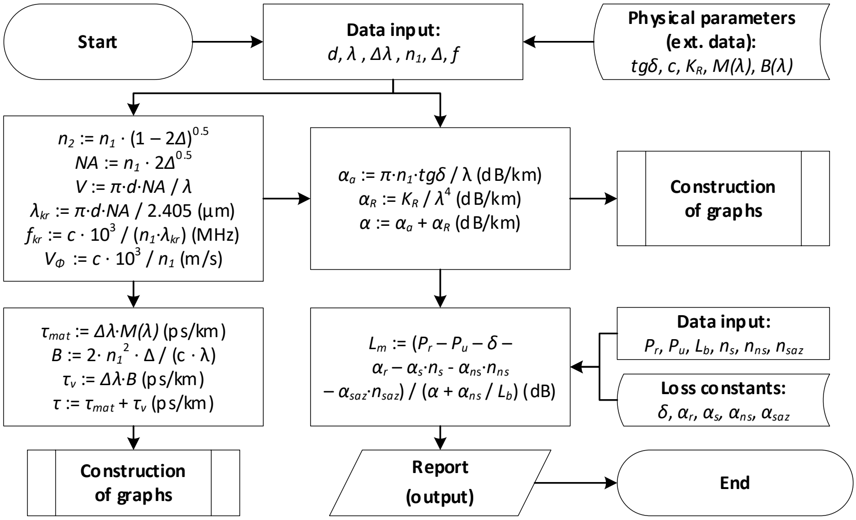


Fig. 3.6. Algorithm for calculating the parameters of the FOCL in Mathcad.

Belden LT096FM single-mode fiber optic cable was used for the analysis of the parameters of the fiber optic communication link. The cable contains 96 optical fibers, each fiber having a diameter of 8.6 µm. The Belden LT096FM cable is designed for signal transmission at 1310 or 1550 nm. The maximum permissible values of the cable, as indicated in the manufacturer's datasheet, and the parameters calculated in Mathcad are summarized below:

Table 3.3

Comparison of calculated and reference parameters for the present FOCL

Parameter	Calculated value	Standard value	Unit
Critical wavelength	1.232	1.26	µm
Longitudinal refractive index, λ = 1310 nm	0.357	0.35	dB/km
Longitudinal refractive index, λ = 1550 nm	0.234	0.25	dB/km
Optical fiber dispersion	15.305	18	ps/km

Table 3.3 shows that the calculated values of the parameters do not exceed the values set by the manufacturer by more than 15 %. Taking into account all the calculations, it can be concluded that the described fiber optic cable line models and parameter estimation algorithms give reliable results and can be applied in the design of telematics systems for rail transport.

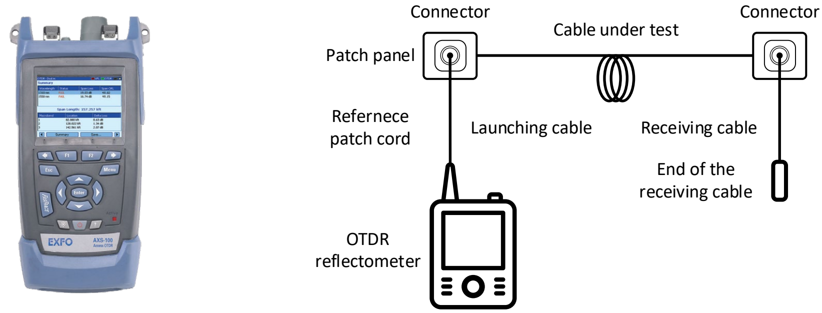
Experimental measurements of FOCL

Optical communication lines are the backbone of modern railway telematics systems. In Latvian railways, optical fibers are regularly tested in order to identify problematic sections of the FOCL, where there are fluctuations in parameters or an increase in losses, to eliminate deficiencies and to guarantee stable communications.

Measurement of fiber loss using an optical time-domain reflectometer (OTDR) is one of the most important tests in the FOCL. The OTDR is an optoelectrical measurement instrument designed to characterize optical fiber parameters. The reflectometer introduces a series of optical pulses into the fiber from one end and receives them at the other end of the line. The signal at the output of the fiber may be attenuated, scattered, or repeatedly reflected by inhomogeneities in the cable material, and the analysis of these phenomena provides detailed information on the condition of the optical cable and the parameters of the line as a whole.

To check the accuracy of the proposed calculation method of the FOCL parameters, fiber measurements of the backbone optical cable in the Riga–Salaspils section were carried out. In this section, the optical cable OKSTM-10-01-0.22-96 consisting of 96 individual optical strands is used. The measurements were carried out using portable OTDR reflectometers from EXFO: AXS-100-023B-EI-VFL (Fig. 3.7 a)) and FTB-1-S2-8G.

Loss measurements in the fiber optic cable were carried out under the supervision of the responsible staff of the Electrical Engineering Department of SJSC "Latvijas dzelzceļš", without affecting the safety of train movements and the operation of critical communication equipment. The OTDR reflectometer connection diagram, which was used for the measurements, is shown in Fig. 3.7 b).



a) b)

Fig. 3.7. EXFO AXS-100 OTDR reflectometer external appearance (a) and connection diagram (b).

The measurements results are provided as individual fiber loss values for each of the 4 sub-routes: Riga–Skirotava, Skirotava–Dole, Skirotava–Salaspils, Dole–Salaspils. The measurements were compiled, supplemented with information from technical documentation on the number of fiber welding points and other joints in the lines that affect losses, and analyzed. The variation of the total loss magnitude was expressed as minimum, maximum, and average values.

Theoretical loss calculations were performed for each sub-route, taking into account cable parameters, line length, number of welds and splices, and other factors which affect signal power. The parameters were determined using the FOCL calculation program in Mathcad. A summary of the processed measurements, compared with the theoretical loss values obtained from engineering calculations, is given in Table 3.4.

Table 3.4

Comparison of experimental measurements and engineering calculations of FOCL

Start point	**End point**	**Line length, km**	**Wave-length, nm**	**Experimentally obtained loss values, dB**			**Calculated value, dB**
				Min.	**Max.**	**Average**	
Riga-pas.	Skirotava, park A	8.726	1310	3.21	3.91	3.48	3.41
			1550	1.94	2.44	2.15	2.18
Skirotava, park A	Dole	9.649	1310	3.69	4.07	3.87	3.75
			1550	2.22	2.51	2.36	2.39
Skirotava, park A	Salaspils	11.799	1310	4.55	4.93	4.64	4.49
			1550	2.67	3.11	2.82	2.83
Dole	Salaspils	2.233	1310	1.04	1.67	1.41	1.35
			1550	0.68	1.16	0.96	0.92

The calculated total losses in the fiber-optic line, using known cable parameters and connection diagrams of the network elements, differed from the experimental average by no more than 5 %. It can be concluded that the tested 5-year-old fiber optic cables show no degradation, all transmission parameters are within normal limits, and the mathematical models of the FOCL discussed in Chapter 1 provide a fairly accurate prediction of the parameters at 1310 and 1550 nm wavelengths.

MCN cell radio coverage area calculation algorithm

The challenge of determining the radio coverage area of an MCN cell is not only a problem of designing new mobile networks but also of maintaining existing networks, as the propagation conditions of radio signals change due to environmental factors. In railway telematics systems, mobile wireless networks play an important role in the organization of communications and, ensuring radio coverage uniformity, its continuous monitoring are mandatory tasks.

The minimal requirements for determining the radio coverage area of a cell: to be aware of the base station radio power ratio dependence, which determines the received signal power at the mobile station (MS) location; to know the value of the mobile station receiver sensitivity parameter $P_{r\,min}$.

Changes in the power of the signal received by MS are theoretically described by mathematical models of radio waves, but in practice the sensitivity is determined by the modem parameters of the mobile equipment. An algorithm was developed to determine the power of the radio signal at the MS receiving point and the radius of the cell radio coverage, which is shown in Fig. 3.8.

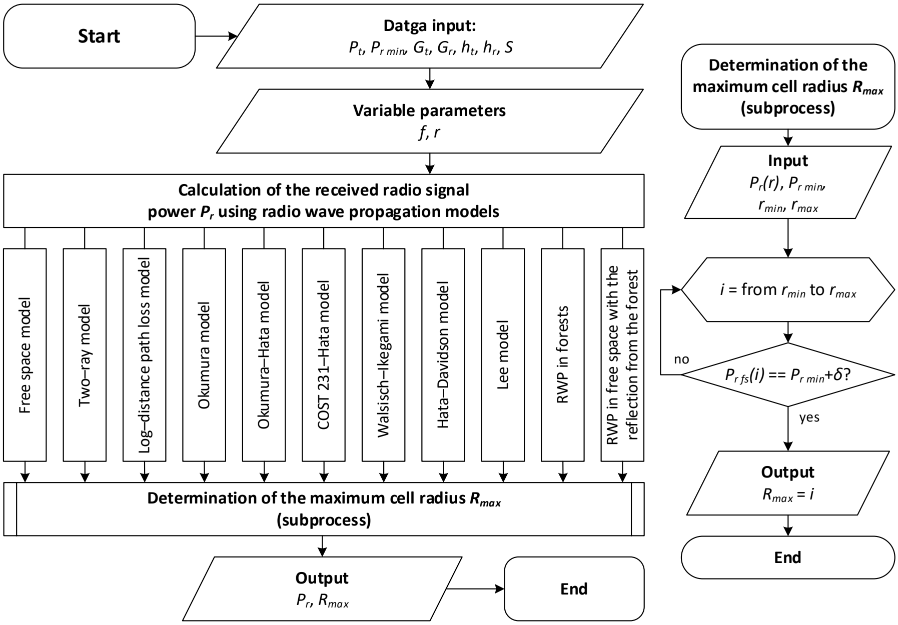


Fig. 3.8. Algorithm for calculating the maximum radius of an MCN cell.

The flowchart (Fig. 3.8) shows, that depending on the sensitivity value $P_{r\,min}$ of the MS receiver of the mobile station and the use of corresponding mathematical model defining the function $P_r(r)$, the algorithm allows to calculate the maximum radius $\boldsymbol{R_{max}}$ of the mobile cell.

The logic of the described algorithm can also be represented graphically. For example, by constructing a power level curve $P_r(r)$ (Fig. 3.9) and marking the MS receiver sensitivity as a horizontal line, the intersection of this line and the curve on the horizontal axis will be the value of the R_{max} for the downlink mode.

For the assessment of environmental factors on the propagation of radio waves, as well as the results obtained using mathematical models (described in Chapter 2) and algorithm (Fig. 3.8), the numerical calculation of the received radio signal power P_r were implemented in the Mathcad software. The received signal power is defined as a function $P_r(r)$ (Fig. 3.9) of the distance between the transmitter (BTS) and the receiver (MS) in the downlink mode, using the following parameters: BTS transmitter output power: $P_t = 50$ W (47 dBm); operating frequency: $f = 900$ MHz ($\lambda = 0.33$ m); BTS and MS antenna gain factors: $G_t = 10$, $G_r = 1$.

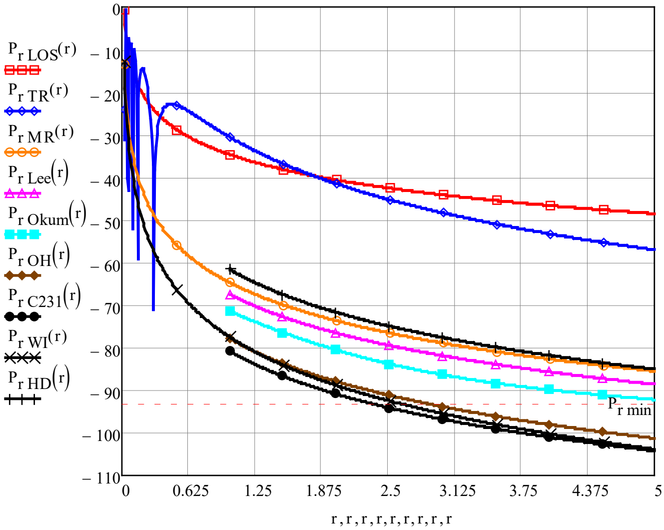


Fig. 3.9. Comparison of the radio signal power at the reception point P_r (dBm) as a function of the distance between the BTS and the MS (in downlink mode) for the mathematical models.

As can be seen from the graph (Fig. 3.9), as the distance between the BTS transmitter and the MS receiver increases, the power of the signal at its receiving point decreases according to the radio wave propagation conditions. For example, at a distance $r = 3$ km, the received signal power under dense building conditions (*Walfisch-Ikegami* model) would be $P_r = –95$ dBm.

Models (Fig. 3.9) are presented for comparison with experimentally obtained dependences of radio signal propagation in Philadelphia, New York and Tokyo [40].

The graph (Fig. 3.10) shows that the dependence of $P_r(r)$ for the city of Philadelphia is approximately described by Lee's model, while for Tokyo it is similar to the COST 231-Hata model. The differences in the curves are due to the choice of the model's parameters: BTS and MS antenna lift heights, antenna gain coefficients, average building heights, etc.

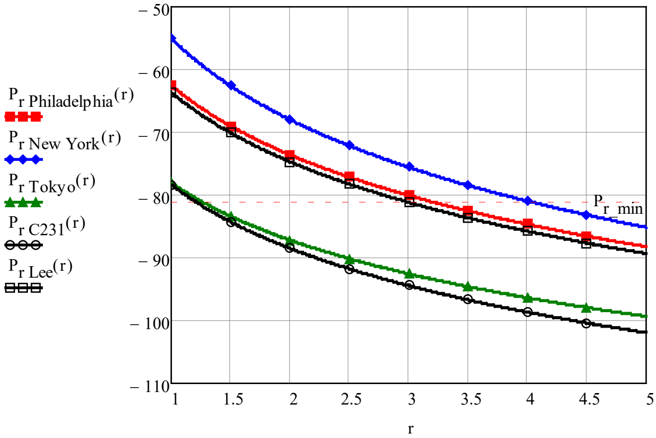


Fig. 3.10. Theoretical and experimental values of MS received signal power.

Experimental measurements of MCN radio coverage

In order to guarantee the high quality of the communication services provided by mobile operators, it is necessary to continuously measure and monitor several MCN parameters following the requirements specified in the standards [1], [2].

Monitoring the condition of mobile networks allows MCN bottlenecks to be identified early and potential failures to be addressed before they occur. Ignoring the importance of MCN monitoring sometimes leads to catastrophic consequences, such as taking a section of the network out of service, which is unacceptable in rail transport telematics systems.

Measuring mobile network parameters requires specialized equipment capable of receiving and processing radio signals. There are two main measurement methods for MCN: passive and active (Fig. 3.11). Passive measurements are made using a scanning receiver (scanner) which does not require an active connection to the service provider. Active measurements are performed using mobile equipment (user equipment, UE), and the connection to the mobile operator must be active during testing.

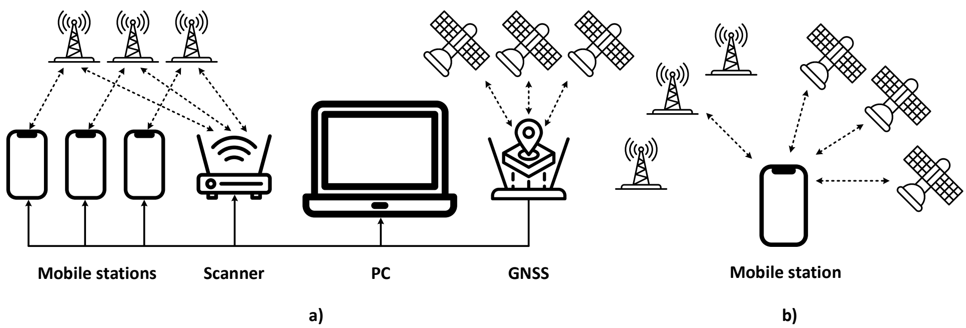


Fig. 3.11. MCN parameter measurement methods: a) active; b) passive.

Methodology for measuring and processing MCN parameters

The active measurement method was chosen for the experimental studies [22], [25] due to its affordability and the minimal amount of hardware required.

The measurement kit consisted of 2 smartphones with Qualcomm chipsets running the Android operating system (Samsung M23 equipped with Snapdragon SM7225 and Xiaomi Poco F4 GT equipped with Snapdragon SM8450) and corresponding applications for network testing installed on the phones (Network Signal Guru, Tower Collector).

To avoid potential problems with dual SIM mode, smartphones were set up to use only one SIM card. The SIM cards of the mobile operator were installed in both devices at the same time. For measurements near the railway, MS were secured in a backpack in a vertical position so that they were 1 m above the ground on the tester's back.

The Android applications [28] were configured to save all measurement data in log files for later analysis. Data from the log files were merged, converted to CSV format and processed using a Python script. The script reduced the number of data points by averaging measurements for the same cell towers at the same location in an attempt to rule out inconsistencies due to random factors and MS measurement errors. The resulting log file was used for data display and final analysis of the MCN parameters using the developed web application (HTML and JavaScript).

MCN radio coverage measurement results

Mobile communication services for employees of the SJSC "Latvijas dzelzceļš" group are provided by the telecommunications operator Tele2, whose 2G mobile network was selected for the radio coverage experimental studies. The measurements were carried out in Riga, at the reception and dispatch parks of Skirotava railway station. The results of the measurements of the received radio signal power are plotted on the map (Fig. 3.12).

Each mapped circle corresponds to one measurement at a given geographical location, and the color of the circle represents the signal power in decibels per milliwatt (dBm). The color coding is given in the bottom left corner of the figure.

The review of the measurement results identified the Tele2 2G base stations providing mobile communications in the Skirotava station area and their approximate (triangulated) locations. For one BTS (MCC247, MNC 2, LAC 421, ID 820-822) the specific installation location (56.90580, 24.21051) was found in the vicinity of the Skirotava station building.

Based on the MCN measurements for the specified BTS and knowing the MS geographical coordinates at each measurement point, the experimentally obtained data points were plotted as on the graph (Fig. 3.13, $P_{r\ eksp}$), where the signal power values were plotted on the vertical axis and the distance between the BTS and the MS measurement locations – on the horizontal axis.

The analysis of the resulting plot showed that the signal power values fluctuate within a small range, which can be described by the propagation of radio signals in multipath mode under NLOS conditions. In order to obtain an approximated curve of the signal power variation, a curve fitting method was applied, resulting in a distance-dependent function $P_r(r)$ of the received signal power.

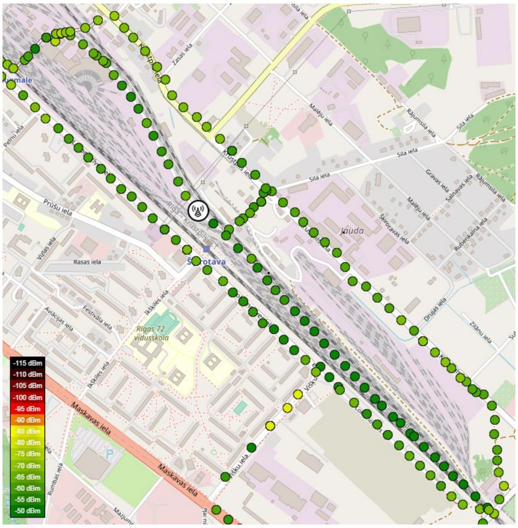


Fig. 3.12. Tele2 2G MCN radio coverage measurements at Skirotava station.

The resulting regularity of signal power variations at the mobile station reception point was compared with Okumura, Lee, Okumura-Hata mathematical models of radio wave propagation, using following parameters: $P_t = 40$ W *(46* dBm*)*; operating band frequency: $f = 900$ MHz ($\lambda = 0.33$ m*)*; gain coefficients of BTS and MS antennas: $G_t = 10$, $G_r = 1$; BTS and MS antenna height: $h_t = 30$ m, $h_r = 1$ m; signal propagation environment – urban.

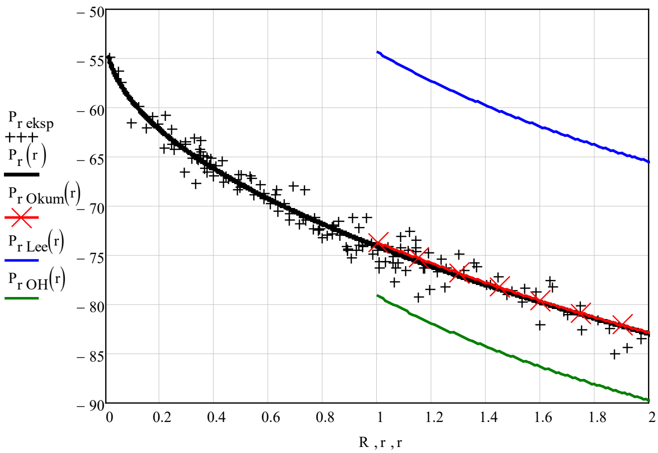


Fig. 3.13. Experimentally obtained MS power curve $P_r(r)$, compared with mathematical models of radio wave propagation (Okumura, Lee, Okumura-Hata).

As can be seen from the comparison (Fig. 3.13), the curve of the Okumura model ($P_{r\,Okum}(r)$) is almost identical to the experimental data at $r = [1; 2]$ km. It is worth mentioning that Okumura, as well as several other mathematical models, has a defined constraint: the minimum distance between the BTS and the MS is 1 km. Therefore, for the $r = [0; 1]$ km, the calculations of the Okumura, Lee, and other models could not be shown.

Heterogeneous network simulation models

In the primary design phase of heterogeneous networks, the need for network models with advanced, forward-looking technologies usually arises. In this context, a task was formulated to design an experimental heterogeneous network model with the following parameters: network edges – fiber optic and symmetric cable communication lines; network nodes – electrical and optical multiplexers, switches, modems; network terminals – digital telephones, personal computers, mobile devices; information technologies – SDH, TCP/IP, VoIP.

Organized heterogeneous network (Fig. 3.14) [29], [34] is as similar as possible in its design to real networks used by leading Latvian companies, such as Latvian railways, LMT, Tele2, Tet, etc.

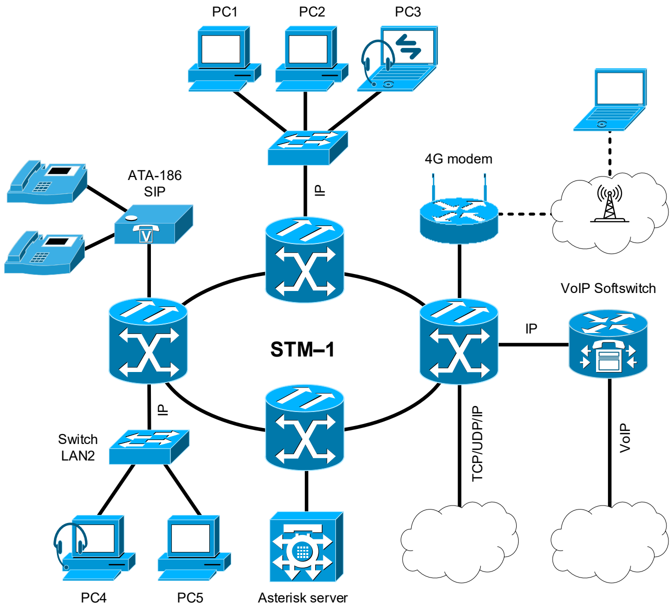


Fig. 3.14. Heterogeneous network diagram.

Elements of the heterogeneous core network [30], [34]:

- network ribs: single-mode fiber optic cables ($\lambda = 1310$ nm, $\alpha = 0.22$ dB/km), copper coaxial cables ($Z_v = 70\ \Omega$), copper symmetric cables ($Z_v = 120\ \Omega$);
- network nodes: optical multiplexers SURPASS hiT 7020, switches ALOE Systems MVTS Softswitch and Digium Asterisk Softswitch, router HUAWEI B535-232 with built-in 4G modem;
- network terminal equipment: analog telephone adapter Cisco ATA 186, VoIP softphones Zoiper and CounterPath X-Lite, personal computers for network monitoring with software TNMS-M SURPASS hiT 7020 3.2.2 LCT, digital

analyzer Wandel & Goltermann ANT-20E, reflectometer IRK-PRO Gamma, optical reflectometer EXFO AXS-100;

- network interfaces: LC connectors for SFP module connection of optical multiplexers, FC connectors for connection to SDH analyzer and tester, BNC connectors for coaxial cables, 8P8C and 6P6C connectors for twisted pair cable.

The STM–1 network has a double–ring topology, and each SURPASS hiT 7020 multiplexer is connected to two adjacent multiplexers. The multiplexers are equipped with optical transceivers – STM-1 SFP modules Fiberxon FTM-3101C-L15-A with LC connector.

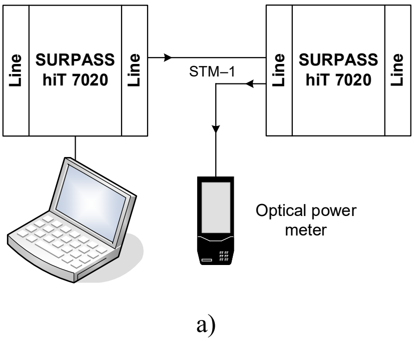
Asterisk and MVTS servers are used to provide Voice-over-IP (VoIP) technology. VoIP is a digital voice communication system capable of transmitting sound information without significant loss and is based on the principle of IP packet switching.

Voice signals are transmitted from the VoIP phone over the STM-1 network, where the traffic goes to the Asterisk Softswitch server. Asterisk is an open-source PBX software. It supports all standard PBX features and a large number of VoIP protocols. Asterisk performs the basic PBX functions and sends the call over the SDH network to the MVTS Softswitch server, where the routing and call transfer takes place on the public switched telephone network (PSTN). Data transmission from the PC is done via the local and STM-1 network, where the traffic is delivered to the global Internet via the router. The PCs are pooled in the local networks and connected to the SDH network via an Ethernet interface.

Monitoring and measurement methods for heterogeneous networks

TNMS-M SURPASS hiT 7020 3.2.2 LCT, the vendor's software, was used to plant the SURPASS hiT 7020 optical multiplexers and monitor the network, providing information on data multiplexing in virtual containers (VC-4, VC-12, etc.).

The power level of the optical transmitter determines the maximum length of the cable line. This parameter is of considerable importance and can be measured using an optical power meter (Fig. 3.15 a)). The Wandel & Goltermann ANT-20E analyzer was used to determine the overall network performance. The connection diagram of the analyzer is shown in Fig. 3.15 b).



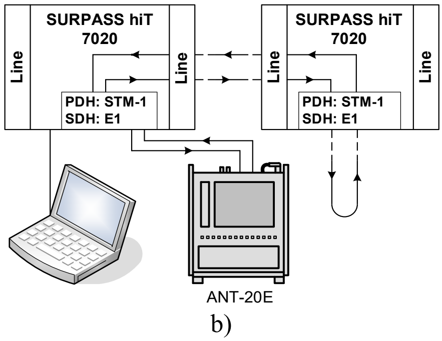


Fig. 3.15. Connection schemes: a) for optical power measurement; b) for PDH/SDH analysis.

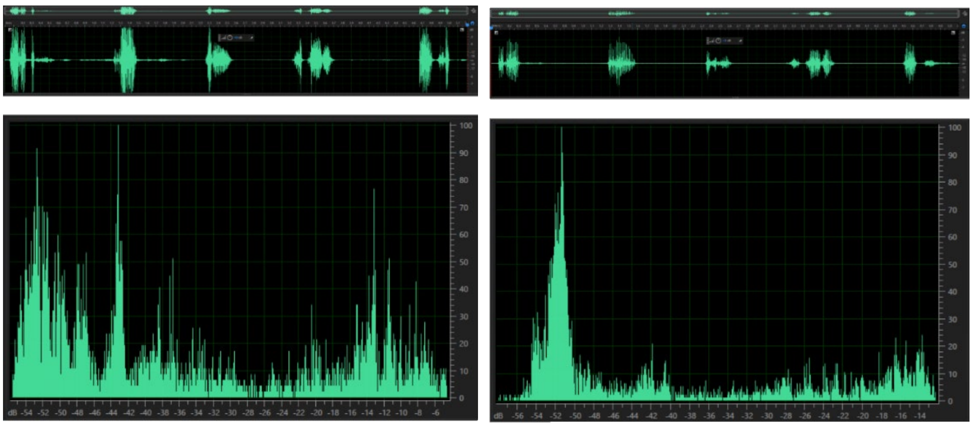
This type of network tester allows one to generate and analyze traffic, view the structure and content of PDH and SDH frames, measure loss, dispersion, and signal delay in the transmission line.

Two operational scenarios were described and implemented for the heterogeneous network model: speech and data. Additionally, Zoiper VoIP softphone was utilized for VoIP calls, and Adobe Audition software was used for spectral analysis of the voice signals [34].

For the analysis of speech signal pass-through, part of the heterogeneous network hardware (Fig. 3.14) was used. Voice signals were transmitted from VoIP phones over the STM-1 network, processed, and routed in the Asterisk Softswitch server, where the connection can be implemented by the following routes:

1) VoIP Softphone (PC3) → LAN1 → MUX1 → MUX4 → LAN2 → VoIP Softphone (PC4);
2) PH1 → ATA-186 SIP → MUX4 → MUX3 → Asterisk Softswitch → MUX3 → MUX2 → VoIP Softswitch → PSTN;
3) PH1 → ATA-186 SIP → MUX4 → MUX3 → Asterisk Softswitch → MUX3 → MUX2 → 4G modems → MCN.

In the first route, the analogue signal is transmitted from the microphone to the PC3 audio input. Several processes take place on the PC itself: sampling, coding and compression of the analogue signal using G.711, ilbc, GSM, G.729 codecs, and spectral analysis. The signal then is transmitted to the PBX Asterisk via the STM-1 primary network and, after switching in the PBX server, is sent to another Zoiper VoIP softphone. After digital-to-analogue conversion, the analogue output signal is fed to the handset and to the PC4 audio input, where the spectral analysis of the output voice signal is realized. The spectrum of the output voice signal after passing through the PC3-LAN1-MUX1-MUX4-LAN2-PC4 path is shown Fig. 3.16.



a) b)

Fig. 3.16. Speech test signal spectrum: a) input; b) output.

For the data transmission analysis, PC1-PC3 on the local LAN1 network were connected to the mobile operator network using STM-1 multiplexers and a 4G radio modem, following the route PC1/PC2/PC3 → LAN1 → MUX1 → MUX2 → 4G modem → MCN.

A test digital signal was generated on PC1 LAN1 and received on PC4 LAN2. All test data for transmission over the STM-1 network was subjected to standard multiplexing, structuring into virtual containers and demultiplexing. The transmission rate on LAN1, LAN2 and on their switch interfaces is 100 Mbit/s, on the STM-1 network it is 155 Mbit/s.

TNMS-M SURPASS hiT7020 3.2.2 LCT software was installed on PC2 LAN1 to monitor the data transmission on the STM-1 network, while the flows on the optical channels were monitored using a Wandel & Goltermann ANT-20E analyzer. PingPlotter software was used to measure the time delay of the test data transmission.

Two experiments were defined to test the data transmission, the results of which are shown in Fig. 3.17. The first experiment aims to transmit multimedia test information over a heterogeneous network, using an STM-1 environment, from PC1 to PC5. The second experiment aims to transmit a high–resolution test video stream in H.264/AVC format from a media server (PC1) over a heterogeneous core network (Fig. 3.14) to a remote media client (PC6) over a 2G-4G mobile network.

The results of the time delay measurements for the first experiment are shown in Figs. 3.17–3.18. During signal transmission from test transmitter PC1 to receiver PC5 (Fig. 3.17), the maximum delay (*max*) was 3 ms, the average delay (*cur*) – 1 ms and the jitter (*jttr*) – 0,07 ms, corresponding to near-ideal transmission conditions.

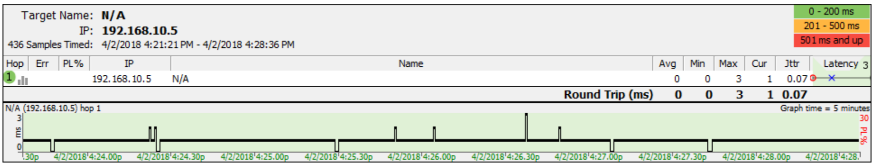


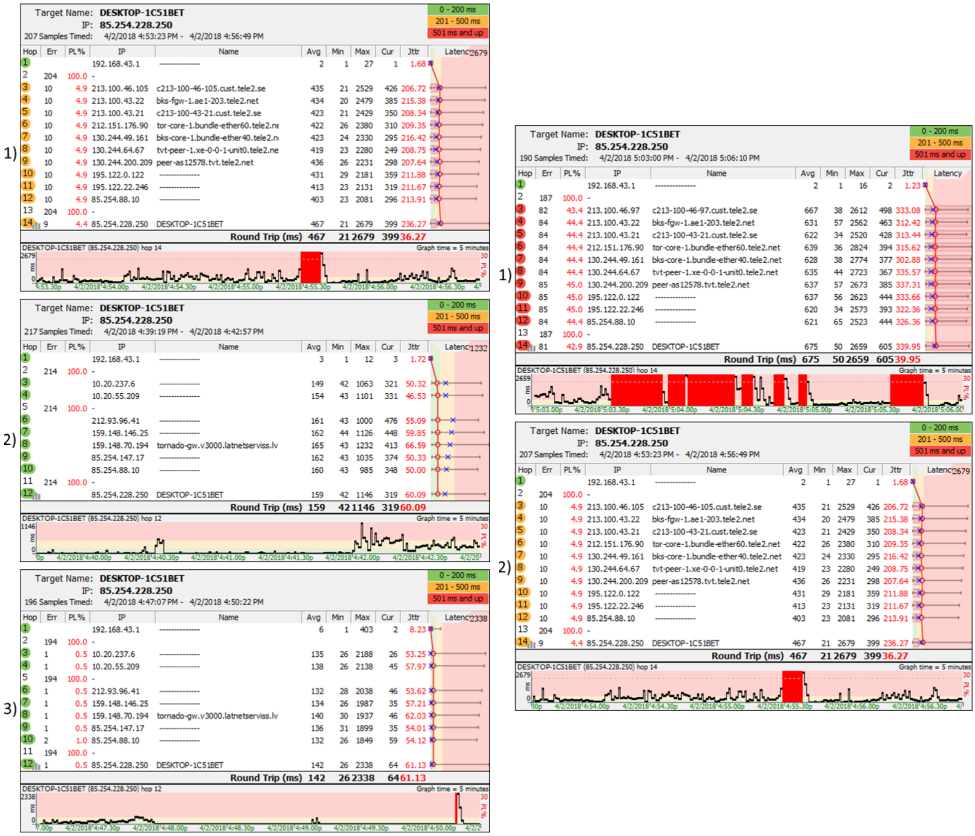
Fig. 3.17. Data transmission time delay measurement results for the first experiment.

The results of time delay measurements when a test signal is transmitted from a media server to a media client are shown Fig. 3.18. The maximum delay (*max*) ranges from 402 ms to 2800 ms. The average delay value (*cur*) ranges from 2 ms to 444 ms and the jitter ranges from 8.23 ms to 340 ms.

The results of the second experiment show that when transmitting test data over MCN and using a 2G connection, it is still possible to transmit and receive video streams and audio test signals in high definition (H.264/AVC) even if the base station signal reception is sufficiently poor or if the remote computer (media client) is several kilometers away from the base station. In this case, the initial buffering usually requires a long period of time, approximately 60–70 seconds, to ensure that the received video and audio test material does not lose its quality.

PingPlotter measurement software shows, that IP packet loss for 2G connections (EDGE) on LMT (Fig. 3.18 a)) and Tele2 (Fig. 3.18 b)) are around 35–45 %, and the presence of jitter indicates a large packet transit time dispersion (up to 400 ms). It should be noted that the experimental results were predictable, as they are related to the narrow bandwidth of the MCN 2G radio channel.

Similar experiments were carried out with multimedia test data over the 3G and 4G mobile networks of public operators LMT, and Tele2. It was found that the initial buffering delay of the stream decreases to 2–3 seconds when transmitting high–definition video format (H.264/AVC) in real time, compared to 2G MCN. Video and audio test streams are transmitted with virtually no loss of quality, but jitter is observed in the testing of both operators: in the LMT network jitter did not exceed 60 ms, which is acceptable for multimedia information transmission, while in the Tele2 network jitter reached 200 ms, which in practice can cause failures, especially in protocols such as VoIP.



a) b)

Fig. 3.18. Time delay measurement results for the second experiment on LMT (a) and Tele2 (b) MCN: 1) 2G (EDGE); 2) 3G (HSPA); 3) 4G (LTE-A).

Heterogeneous network modelling results

The main advantages of the heterogeneous network under study can be formulated as follows:

- transparent implementation of PDH, SDH multiplexing technology;
- easy access to different signals, data packets, and streams by multiplexing at high data rates in PDH, SDH standards;
- flexible access to network elements, the ability to extend the network, change its configuration;

- performance monitoring is carried out in accordance with the ITU-T Y.1731 standard using a network management system (OAM&P);
- standard interfaces allow network equipment and services to be interconnected to explore different application scenarios:
    - switched transmission of traffic flows (E1/E3) between PBX and PSTN;
    - high–speed traffic over TCP/UDP/IP protocols;
    - connecting the STM-1 network to other SDH networks;
- connection to external MCN via radio modem;
- use of VoIP protocol (H.323/SIP) in heterogeneous network equipment, allowing the connection of fixed and mobile telephone networks via the Internet;
- the network configuration is suitable for the transmission of high-resolution multimedia data [33], digital information from computer systems, remote control and remote control signals in the field of railway telematics for the following functions: communication of train control systems; remote monitoring and control of railway objects; video surveillance; computer-assisted vision (for visual inspection of railway objects and equipment, wagon monitoring and tracking systems, road traffic monitoring solutions); train driving automation and driving assistance (using machine learning and artificial intelligence (AI) technologies).

The proposed heterogeneous network reflects the capabilities of modern telecommunication technologies and can be used as a simulation model for the study of rail transport telematics systems [34].

CONCLUSIONS

The use of cable communication lines remains a constant, despite the proliferation of wireless information transmission technologies. In railway telematics, twisted pair cables are used in signaling, interlocking and locking systems, computer networks, video surveillance, etc. Coaxial cables are hardly used in modern communication networks, but fiber-optic cables are increasingly used, not only in trunk lines but also on the termination side.

Mobile technologies for transport are also increasingly in demand. Many rail telematics systems rely partly or entirely on wireless data transmission. In ERTMS subsystem ETCS levels 2 and 3, both voice communication and signaling (interlocking) data is transmitted using the mobile communication standard for rail GSM-R. A replacement for this standard, the future FRMCS, is currently under development.

Railway telematics systems consist of elements based on different communication technologies and form heterogeneous telecommunication networks. The construction, maintenance and renewal of such networks requires an in-depth knowledge about the applicable standards, the design of communication links, and the tools available to address the design challenges.

In accordance with the objectives of the Thesis, the following results were achieved:

1. Mathematical models of cable lines were reviewed, allowing to realize engineering calculations of parameters of symmetrical, coaxial, fiber-optic communication lines.

2. 11 mathematical models of radio wave propagation were investigated, which are designed to calculate the radio signal power of a base station in a mobile communication network at the receiving point of a mobile station and allow to determine the limits of the radio coverage area of the base station.
3. Algorithms for calculating parameters of symmetric, coaxial, fiber-optic communication lines and mobile communication networks were developed.
4. Based on the developed calculation algorithms, the numerical estimation of symmetrical, coaxial, fiber-optic communication lines and mobile communication networks parameters has been implemented using the developed automated calculation programs in Mathcad environment.
5. The main parameters of symmetrical and coaxial communication lines were determined: attenuation and velocity factor. The attenuation indicates the losses in the line and determines its maximum theoretical length. The velocity factor shows the number of times the propagation speed of the pulse in the line is less than the speed of light. Its exact value is essential to know, for example, to determine fault locations in a cable line using a reflectometer.
6. As part of the numerical calculations, a frequency dispersion analysis of the primary and secondary parameters of symmetrical and coaxial communication lines was performed. For the symmetrical cables used in the example calculations, as the signal frequency increases in the range 1–250 kHz, the attenuation increases from 4.53 to 7.58 dB/km and the velocity factor decreases from 1.407 to 1.375. If the maximum allowable line attenuation is assumed to be 20 dB, the maximum theoretical line length is between 4.41 and 2.64 km, excluding losses in connectors and hardware.
7. The main parameters characterizing fiber-optic communication lines were determined: the attenuation and the total dispersion. Dispersion describes the spread of the spectral or mode components of an optical signal over time, which affects the pulse shape and width. Inter-mode dispersion in multimode cables dominates among other sources of dispersion.
8. The problem of determining the maximum length of a fiber-optic communication line was addressed, and an example of the numerical calculation of a regeneration section is given. For the fiber optic cable, used in the example calculations, at the given parameters of 1550 nm wavelength, the ripple factor was 0.234 dB/km, the total dispersion was 15.3 ps/km, the regeneration circuit length was 54.53 km.
9. An algorithm for determining the cell coverage area boundaries of mobile networks has been developed, based on which the automated calculation of the maximum cell radius in Mathcad were implemented. Depending on the propagation environment conditions and the mathematical model used, for the base station and cellular parameters given in the example, the maximum radio coverage radius of the base station at $P_{r\,min}$ = –81 dBm ranges from 1.026 to 3.794 km.
10. A comparative analysis of numerical and standard parameters of symmetric, coaxial, and fiber-optic lines was carried out. The analysis shows that the values of the parameters of the communication lines determined by engineering calculations do not

exceed more than 5 % of the symmetric or coaxial and 15 % of the fiber optic cable standard values.

11. Measurements of power losses of the fiber-optic communication line (Riga–Salaspils) were experimentally obtained at 1310 and 1550 nm wavelengths. For individual fibers of the trunk, cable measurements were expressed as average values for each of the 4 sections: Riga–Park A, Park A–Dole, Park A–Salaspils, Dole–Salaspils. On the 8.726 km long Riga–Park A section, the average total losses were 3.48 dB (1310 nm) and 2.15 dB (1550 nm). Numerical calculations for this section, taking into account information on welding points and connectors, showed values that were not significantly different from the experimental results – 3.41 dB (1310 nm) and 2.18 dB (1550 nm).
12. Experimental measurements of the radio coverage of a mobile communication network have been carried out, using the proposed methodology for determining the power loss of the signal at the receiving point. Experimental measurements of the parameters of the 2G mobile network of the public operator Tele2 were performed at the Skirotava station along the railway lines. The obtained results were plotted on a map and shown in the form of a graph.
13. The experimentally obtained Tele2 2G base station power variation curve, depending on the distance between the base station transmitter and the mobile station receiver, was compared with mathematical models of radio wave propagation based on the following BTS and MS parameters: $P_t = 40$ W, $f = 900$ MHz, $G_t = 10$, $G_r = 1$, $h_t = 30$ m, $h_r = 1$ m. It was found that over a distance range of 1 to 2 km, for the given parameters, the signal power variation is perfectly described by the Okumura model.
14. A modern heterogeneous network model is implemented, and its experimental analysis is carried out. The proposed network combines symmetric, coaxial, fiber-optic communication lines, and mobile communication technologies and is suitable for the study of modern railway telematics systems.
15. The developed experimental heterogeneous network allows to implement the following main functions: to transparently transfer data through the SDH network and to view the multiplexing processes in it; to implement telephone communication using VoIP technology; to transmit high-resolution multimedia data, digital information of computer systems, and remote control signals for the analysis of the operation of communication channels of railway telematics systems.

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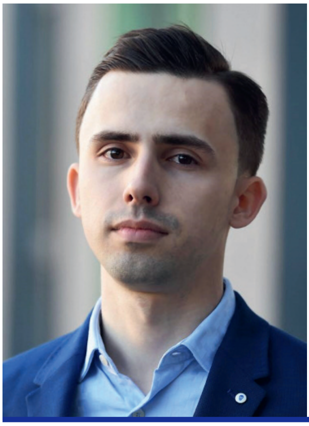

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