TECHNICAL UNIVERSITY - GABROVO

Faculty of Electrical Engineering and Electronics

eng. Michail Georgios Angelakis

METHODS AND MEANS
FOR THE INTELLIGENT MONITORING AND CONTROL
OF RADIO CHANNELS IN WIRELESS COMMUNICATION NETWORKS

A U T H O R's S U M M A R Y

of a dissertation

for acquiring the educational and scientific degree "Doctor"

Field of higher education: 5. Technical Sciences

Professional field: 5.3 Communication and Computer Engineering

Doctoral program: "Communication Networks and Systems"

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Scientific supervisor: Prof. Krasen Kirov Abgelov, PhD

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Gabrovo, 2026

The dissertation work was discussed and directed for official defense at a session of the Extended Department Council of the Department of Communication Engineering and Technologies at the Faculty of Electrical Engineering and Electronics of the Technical University – Gabrovo, held on 03.07.2026.

The dissertation work contains 126 pages. The scientific content is presented in an introduction, four chapters and a conclusion, and includes 64 figures, 21 tables and 14 equations. 95 literary sources are cited. The numbering of the figures, tables and equations in the Author's abstract is consistent with that in the dissertation work.

The development of the dissertation work was carried out in the Department of Communication Engineering and Technologies at the Faculty of Electrical Engineering and Electronics of the Technical University – Gabrovo.

The official defense of the dissertation will take place on September 10, 2026 at 1:00 p.m. in Room 2215, University campus No. 2 "Bazhdar" of the Technical University – Gabrovo.

The materials related to the defense are available to those who are interested in Room 3209, University campus No. 3 "Rectorate" of the Technical University – Gabrovo.

The reviews and opinions of the members of the scientific jury and the Author's abstract are published on the university's website: www.tugab.bg.

Author: © Michail Georgios Angelakis
Title "Methods and Means for the Intelligent Monitoring and Control of Radio Channels in Wireless Communication Networks
Circulation: 3 pcs. (English language)
Place of printing: University Publishing House "Vasil Aprilov" at TU – Gabrovo

I. GENERAL CHARACTERISTICS OF THE DISSERTATION

Relevance of the problem

The relevance of the topic is determined by several key factors defining the development of communication technologies in recent years:

- frequency spectrum congestion – the use of unlicensed frequency bands (2.4 GHz, 5 GHz and the newly opened 6 GHz) leads to serious interference (mutual interference) between devices;
- network heterogeneity: dozens of different technologies operate simultaneously in the same physical space, competing for airwave resources;
- strict latency and throughput requirements – a number of modern critical applications require latency below 1 millisecond and connection reliability above 99.999%;
- environment dynamics – physical obstacles, multipath propagation of signals, attenuation and the Doppler effect in mobile objects constantly change the characteristics of the radio channel in real time.

This dissertation work analyzes the main methods and proposes a synthesis of models, application of intelligent mechanisms and practically oriented tools and approaches for monitoring, control and solving optimization problems in radio channel management and QoS provision in wireless communication networks.

Purpose and objectives of the dissertation work

The aim of the dissertation work is to develop and research appropriate methods and tools for intelligent monitoring and real-time control of processes for reliable and efficient transmission and reception of wireless radio signals, as well as integrated intelligent processing for interference suppression by monitoring the dynamic state of the wireless connection channel in wireless communication networks.

To achieve the formulated goal, it is necessary to solve the following *generalized tasks*:

1. Creation and description of a methodology for modeling and researching the processing, reliable and efficient transmission and reception of wireless radio signals and response to the influence of the dynamic state of the wireless connection channel in wireless communication networks.
2. Synthesis and development of simulation models of a wireless communication channel with an integrated intelligent algorithm for suppressing interference and for studying its impact on the efficiency of wireless communication networks.
3. Conducting research on the parameters of wireless communication networks and the possibilities for improving the quality of transmitted information, reliability, efficiency and range of the network through intelligent monitoring and control.

4. Development and research of a practical experimental model of an innovative universal system for intelligent monitoring and control of radio channels in wireless communication networks.

The research methods are mainly differentiated in the individual chapters, such as analytical, simulation and practical, and cover the dependencies of the parameters characterizing the implementation of individual models.

Scientific novelty

The scientific novelty of the dissertation work can be reduced to the following more significant contributions:

1. Synthesis of a complex methodology for multi-criteria analysis and assessment of the state of wireless radio channels and an architectural model for proactive monitoring of wireless networks, based on the effective combination of standard telemetry protocols with algorithms for dynamic monitoring of parameters in a heterogeneous hardware infrastructure.
2. Development and research of an innovative wireless channel model with an integrated intelligent algorithm for noise and interference suppression by applying a specialized training module for filtration and precise reconstruction of CSI during channel prediction.
3. Development, implementation and experimental verification in a real environment of a specialized platform for intelligent monitoring, providing reliable collection and processing of real-time data on the status of the wireless infrastructure and proactive response through automation of signaling processes, event management and localization of problems in the radio channel of wireless communication networks.

Applicability

The applicability of the dissertation work is related to the creation of methodologies of procedures related to correct approaches in modeling, selection and implementation of architecture, necessary equipment and correct configuration and implementation of intelligent monitoring, control and evaluation of signal parameters in wireless communication channels, which will ensure improvement of the reliability, efficiency and quality of services in wireless communication networks.

Approbation of the dissertation work

The main stages of the development of the dissertation work are presented in eight publications at international conferences and scientific journals, fully covering the minimum requirements for the criterion under consideration. Two of the papers were presented at the International scientific conference UNITECH (2022 and 2025), four of the papers were presented at the National conference TechCo (2024 and 2025) and two of the papers - at the Student Scientific Session of the Technical University of Gabrovo (2024). Two of the publications are single-authored. The publications were published in collections with scientific review during the 2022-2025 study period, actually representing nearly 2/3 of the content of the dissertation. The publications present a large part of the research carried out and the main conclusions of the dissertation are presented.

Structure and volume of the dissertation work

The dissertation work includes an introduction, four chapters, a conclusion, a list of abbreviations used, a list of publications on the dissertation and a list of references. The total volume is 126 pages and includes 64 figures, 21 tables and 14 equations. 95 literary sources are cited.

II. CONTENTS OF THE DISSERTATION

CHAPTER 1. CURRENT STATE AND PROBLEMS IN PROVIDING MONITORING AND CONTROL IN WIRELESS COMMUNICATION NETWORKS

Unlike wired transmission media, the radio environment is highly dynamic, unpredictable and shared in nature. This requires the development and implementation of modern methods and tools for constant monitoring of radio channels in wireless communication systems to ensure stability, security and the required quality of service (QoS).

The design and operation of these systems face unprecedented challenges caused by the exponential growth in the number of connected devices, the heterogeneous nature of traffic and the critical requirements for ultra-low latency and high reliability.

The main problems in providing monitoring and control in modern wireless computer networks are related to:

- the technical specifications of the IEEE 802.11 wireless computer network standards;
- ensuring security in wireless computer networks;
- regulatory restrictions and standards related to the frequencies used and the transmitted power in wireless communications;
- interference and disturbance in the radio frequency spectrum used by wireless computer networks;
- challenges in designing wide-area wireless point-to-multipoint (P2MP) networks.

1.6. Analysis and conclusions to Chapter 1

Modern digital infrastructure relies heavily on wireless computer communication networks. With the advent of standards such as Wi-Fi 7 (802.11be), the fifth and sixth generation mobile networks (5G/6G), as well as large-scale architectures of the Internet of Things (IoT and Industrial IoT), the radio channel is becoming a critical and at the same time the most vulnerable point in the communication environment.

Unlike wired transmission environments, the radio environment is highly dynamic, unpredictable and shared. It is necessary to develop and implement modern methods and tools for constant monitoring of radio channels to ensure sustainability, security and the required quality of service (QoS). This will provide a response and countermeasure to the main limiting factors in wireless communication technologies: frequency spectrum congestion, network heterogeneity, strict requirements for latency and throughput, as well as environmental dynamics.

Radio channel monitoring is not an auxiliary function, but a fundamental part of the management of modern wireless networks in three main areas: optimization of network resources and spectrum management, proactive detection of failures and countermeasures against malicious actions. It can be defined in three main directions:

1) Network resource optimization and spectrum management

Without detailed information about the state of the radio frequency spectrum, effective dynamic frequency channel allocation (Dynamic Frequency Selection - DFS) and transmitted power management are impossible. Monitoring allows the detection of "dead zones" and areas with high interference, which helps in the correct positioning of access points (APs).

2) Proactive fault detection

By constantly analyzing signal parameters, network administrators and automated systems can predict connection degradation before it leads to interruption of user sessions.

3) Cybersecurity and countermeasures

The radio channel is an open environment, which makes it an easy target for malicious actions. Monitoring is key to identifying:

- Jamming: intentionally generating noise to disrupt communication.
- Rogue APs: attackers who impersonate a legitimate network to steal data (Man-in-the-Middle attacks).

Intelligent monitoring methods can rely on software-information approaches and be:

- passive – based on monitoring and analysis of the radio frequency spectrum and evaluation of quality indicators such as RSSI and SNR
- active – based on generating test traffic and measuring and evaluating quality indicators such as RTT, BER, throughput, etc.

With passive methods (Passive Monitoring), no additional traffic is generated in the network. Monitoring devices ("scanners" or network controllers themselves) operate in "listening" mode (promiscuous mode or monitor mode) and perform:

- measurement of energy parameters – monitoring of RSSI (Received Signal Strength Indicator) and Noise Floor (noise level);
- calculation of quality metrics – mathematical determination of the signal/noise ratio;
- analysis of CSI (Channel State Information) – a modern method that provides information about how the signal propagates along each individual subcarrier frequency in MIMO (Multiple-Input Multiple-Output) systems.

In Active Monitoring methods, controlled test traffic is injected into the radio channel to assess the actual behavior of the network by:

- Latency & Jitter measurement – sending ICMP packets or specialized UDP streams to estimate the round-trip time (RTT);

- Loss assessment – monitoring the percentage of lost packets (Packet Loss Rate) and the bit error rate (BER - Bit Error Rate).

Intelligent monitoring methods should be based on hybrid hardware and software-information approaches and can be passive or active: specialized spectrum analyzers; software-defined radio (SDR) with digital signal processing and software configuration of the frequency range; specialized hardware sensors; packet analyzers (Sniffers) that intercept radio frames (802.11 frames) and allow detailed parsing of the headers (RadioTap headers) to extract the physical parameters of the connection; Wi-Fi planning and analysis systems for visualization of coverage and interference levels in three-dimensional space; centralized management systems that integrate built-in monitoring based on cloud technologies that automatically adjust network parameters when the radio channel deteriorates.

The integration of software-defined radio with artificial intelligence algorithms outlines the direction of development in this area - moving from reactive monitoring (removing problems that have already occurred) to proactive, self-learning and adaptive management of the wireless resource.

1.7. Purpose and objectives of the dissertation

The essence of a wireless communication network is to provide the necessary broadband connectivity to end devices through reliable and secure transmission of radio signals in the wireless communication channel, which can be achieved through effective signal processing (coding and encryption of the source and the channel), optimal balancing of quality indicators and effective evaluation of the communication channel.

Given the state and problems in wireless communication networks analyzed in Chapter 1, the present dissertation work aims to develop and research appropriate methods and tools for intelligent monitoring and real-time control of the processes for reliable and efficient transmission and reception of wireless radio signals, as well as integrated intelligent processing for interference suppression by monitoring the dynamic state of the wireless communication channel in wireless communication networks.

To achieve the formulated goal, it is necessary to solve the following generalized tasks:

1. Creation and description of a methodology for modeling and researching the processing, reliable and efficient transmission and reception of wireless radio signals and response to the influence of the dynamic state of the wireless connection channel in wireless communication networks.
2. Synthesis and development of simulation models of a wireless communication channel with an integrated intelligent algorithm for suppressing interference and for studying its impact on the efficiency of wireless communication networks.

3. Conducting research on the parameters of wireless communication networks and the possibilities for improving the quality of transmitted information, reliability, efficiency and range of the network through intelligent monitoring and control.
4. Development and research of a practical experimental model of an innovative universal system for intelligent monitoring and control of radio channels in wireless communication networks.

CHAPTER 2. RESEARCH AND ANALYSIS OF APPROACHES FOR MODELING, ANALYSIS AND CONTROL OF WIRELESS RADIO CHANNELS

2.1. Analysis of signal attenuation and interference in wireless radio channels

Propagation losses primarily depend on the signal losses in free space.

In an urban environment with tall buildings, the signal emitted by the transmitting antenna will propagate mainly through the canyon effect, and not over the buildings. As a result of this type of propagation, the so-called corner effect occurs, which is an increase in signal attenuation by about 20 dB when the receiving station is located in shadow (for example, around a street corner) relative to the transmitting antenna.

As a result of these effects, a change in the shape of the coverage area occurs, because the signal power in cross streets is determined mainly by diffraction (corner effect), while in longitudinal streets – the longitudinal reflection of the street canyon.

Corner effect models are based on either the Geometrical theory of diffraction (GTD) or the Uniform theory of diffraction (UTD).

The main cause of short-term fading is multipath propagation of signals, in which signals arrive at the receiving location via paths of different lengths (and therefore with different phases). For this reason, short-term fading is often called multipath fading. As a result of multipath propagation of signals, time dispersion (scattering) occurs, which manifests itself as a stretching of the signal in time. Time dispersion practically manifests itself in the time domain as a signal extension due to delay (time dilation), and in the frequency domain as a coherent bandwidth.

2.2. Development and research of a wireless communication channel model with an integrated intelligent interference suppression algorithm

The fulfillment of a number of requirements regarding reliability, delay and throughput in modern wireless networks depends largely on the availability of accurate knowledge of the state of the wireless communication channel. Obtaining channel state information (CSI – Channel State Information) may require the exchange of a large amount of service information in future networks due to the use of multiple antennas, wider frequency bands and high mobility of user devices.

To address the above-mentioned challenges, the implementation and study of a wireless channel model architecture with built-in Noise & Interference (NI) suppression is considered. In the presented design, coarse channel estimates are first obtained using classical algorithms, such as the least squares (LS) method, and then two projection modules are applied to extract the NI components in the channel subspace and its orthogonal subspace, respectively. Then, a NI estimation network is used, which will be further extracted from the received signals. Finally, a channel refinement and augmentation network is used to form a cleaner version of the channel estimate, which is fed into a channel parameter extractor to obtain the channel representation. The NI suppression module can be trained independently or in conjunction with the backbone parameter extractor. In both cases, the output channel representations are able to reflect the characteristics of the wireless channels more accurately. The wireless channel model with the used NI suppression structure achieves improved performance compared to the channel prediction task.

2.2.1. Structure of the wireless channel system model with integrated noise and interference suppression algorithm

As shown in Fig. 2.3, a wireless network model is considered, which consists of an NI suppression module, a CSI correction and position coding module, and several transform encoder blocks. The NI suppression module is used to obtain a pure value of the estimated CSI from the pilot signals and their corresponding received signals. The transmission of the pilot signals can be subject to strong interference and noise in the channel, which leads to distortion of the received signal. The CSI correction and position coding module encodes the CSI samples into chunks, which are further processed by transform encoder blocks. It detects the inherent correlations and contextual patterns in the data and outputs a universal channel representation that is suitable for various tasks in the downlink channel.

A MIMO-OFDM communication system with N transmit antennas and M receive antennas is considered. Each slot consists of L OFDM symbols, each of which contains K subcarrier frequencies.

Based on the known pilot signals and their associated derived equivalents, the LS algorithm is first applied to form an initial CSI estimate on the pilot signals. Then, a CSI refinement network is built to generate CSI in all signals. With supervised learning, the CSI refinement network is able to offer implicit NI suppression capability, thus benefiting the post-processing.

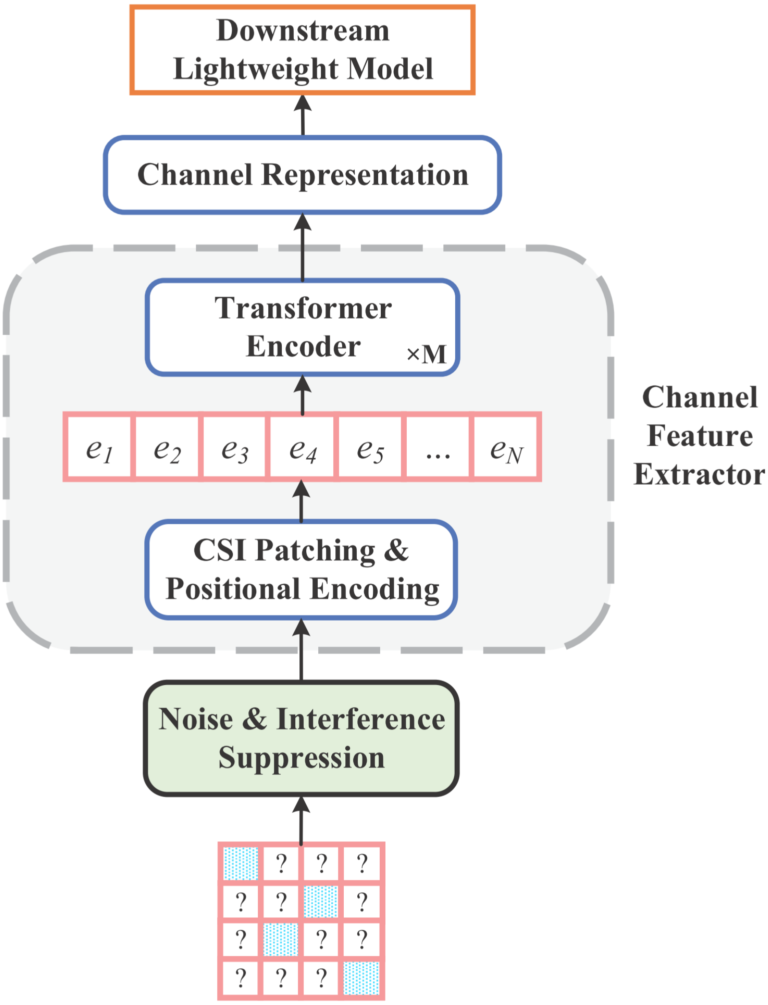


Fig. 2.3. Wireless channel model with noise and interference suppression structure

In order to recover the NI more accurately, an NI estimation network is introduced. This network uses the system value of SINR and NI as input parameters.

In the NI suppression model, the CSI refinement network, the NI estimation network, and the SINR computation module are trainable modules. The CSI refinement network and the SINR computation module are trained using standard supervised methods with normalized mean square error (NMSE). The NI estimation network is trained in two stages. In the first step, the NI estimation network is trained using a labeled NI, following a supervised training method to minimize the NMSE. After the NI estimation network has been trained for several rounds, this module will be trained together with the CSI network to minimize the CSI reconstruction error over all REs.

2.2.2. Configuring a simulation model of a wireless communication channel with an integrated intelligent interference suppression algorithm

The open-source wireless channel generator DeepMIMO was used to create the CSI dataset for both training and evaluation. Data collected from hypothetical coverage area scenarios are used to train and evaluate the model.

Fig. 2.5 shows a scenario where the “BS” is the base station and the user devices are distributed in the “UE network” area (i.e., a network of user devices).

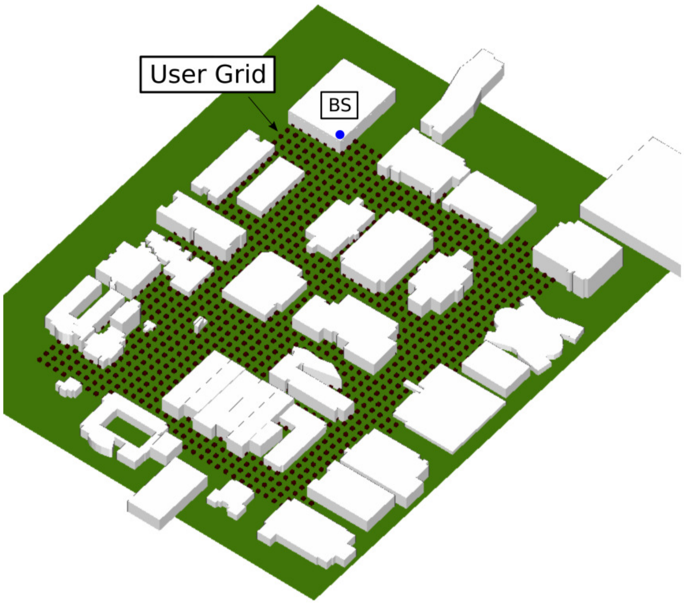


Fig. 2.5. Assessment scenario in a hypothetical coverage area

To specifically assess the contribution of the NI suppression module, the channel feature extractor is not trained. Instead, the parameters from a pre-trained LWM (Large Wireless Model) are used directly. This ensures that the performance improvement comes from the NI suppression module and not from overtraining effects.

A channel prediction task is considered, which aims to predict the CSI on adjacent subcarriers based on the existing CSI. For comparison, a simulation study is implemented with four competing solutions chosen as benchmarks:

1) LS plus linear interpolation (LI) (LS+LI): In this approach, LS channel estimation is first applied to estimate CSI on pilot RE, and then a linear interpolation algorithm is used to obtain the full CSI for all RE.
2) LMMSE: used to recover the CSI of all REs. This is a widely adopted approach in 5G BS and UE.
3) Transform-based method: In this method, LS algorithm is first used to estimate the channel to obtain CSI for pilot RE, and then a transform-based network is deployed to recover the full CSI for all RE.
4) Perfect CSI: This corresponds to an ideal case where the CSI for pilot REs is completely known. This case is used to demonstrate the upper bound of the performance.

For all the above-mentioned comparative studies and the proposed scheme, the input data is the same, and the output data is the recovered CSI for all REs for each slot. These outputs are fed to the channel feature extractor to obtain a universal CSI representation, which is further processed by a lightweight ResNet model to obtain the final channel prediction results.

2.2.3. Research and analysis of a wireless communication channel model with an integrated intelligent interference suppression algorithm

A performance evaluation of the downlink channel prediction method comparing the considered method with other solutions is presented in Fig. 2.6, where the training sample rate is 50%.

Traditional model-based methods (i.e. LS+LI, LMMSE) perform worse over the entire range of SINR variation, as the predefined model fails to accurately match the different channel conditions. In contrast, the transform-based method is able to achieve a significant improvement in performance compared to model-based methods, which is achieved by effectively extracting the time-frequency-spatial correlations that are critical for completing the CSI estimation. Nevertheless, a significant performance gap remains between the transform-based method and the case of perfect CSI. By integrating the noise-interference (NI) mechanism into the channel estimation, the considered method is able to generate channel predictions that well reflect the true channels, thus outperforming all other solutions in the downlink channel problem.

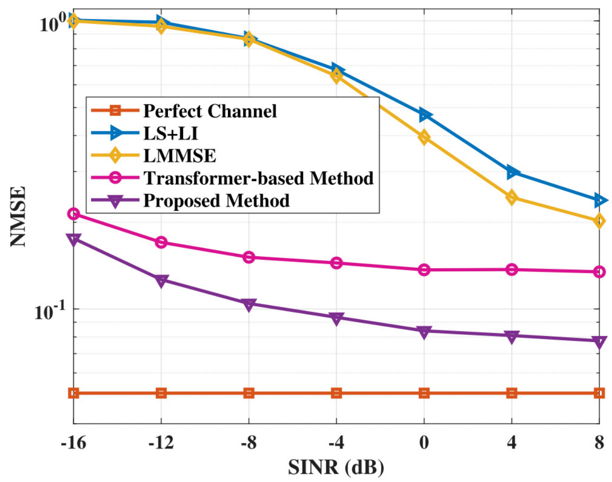


Fig. 2.6. Determining the normalized mean square error (NMSE) depending on SINR

Fig. 2.7 and Fig. 2.8 present the determination of NMSE for different methods with respect to the number of predicted subcarriers and the number of training samples for the downlink channel, respectively, for a SINR value of 8dB. As shown in both figures, the considered method consistently achieves the lowest NMSE error in channel prediction, demonstrating its adaptability. The channel predictions obtained by the proposed method contain richer and more discriminative channel features, which facilitates easier and more data-efficient training, thus minimizing the risk of overfitting with limited labeled samples.

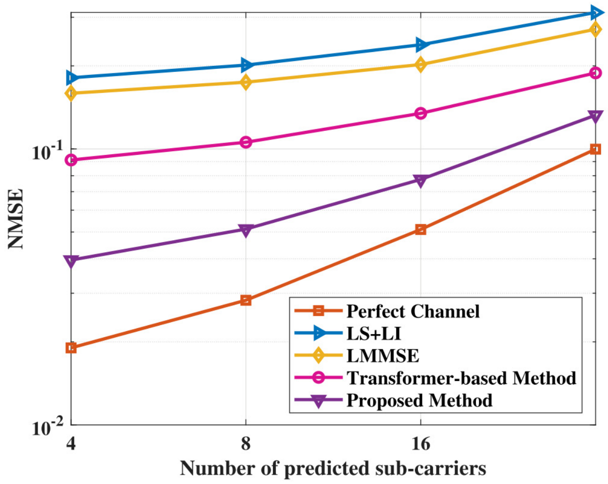


Fig. 2.7. Determining the normalized mean square error (NMSE) depending on the number of predicted subcarriers

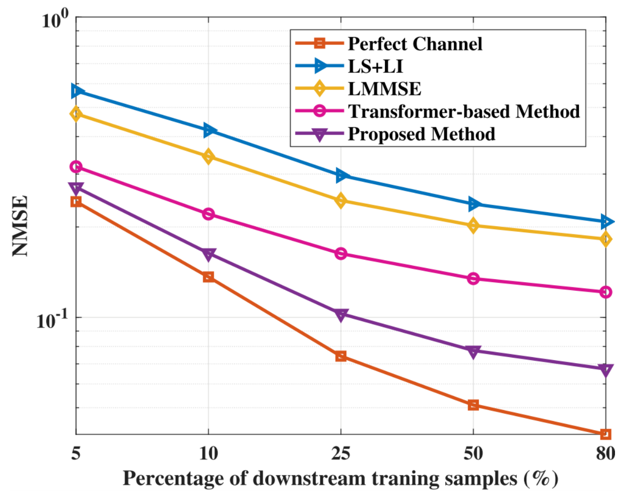


Fig. 2.8. Determining the normalized mean square error (NMSE) depending on the percentage of training samples

In addition to the above, the considered method shows greater performance improvements under favorable conditions, such as when there are fewer subcarriers to predict or when more training samples are available. These results underline the strong potential of the considered method for high-precision communication scenarios in future wireless systems, such as ultra-reliable low-latency communication (URLLC) and massive MIMO transmission, where accurate channel knowledge is of vital importance.

2.3. Planning a wireless connection channel for a real object for a wireless P2MP communication network

The main goal is to plan, build, configure, test and analyze a wireless connection channel for a real object for a wireless P2MP communication network.

This object will be used to conduct a study of the quality indicators in a real working environment in the built P2MP wireless communication network and to study the possibilities of ensuring the quality of the transmitted information, the reliability, efficiency and range of the network through intelligent monitoring and control.

In addition, the designed and built P2MP wireless communication network will be used to develop and study a practical experimental model of an innovative universal system for intelligent monitoring and control of radio channels in wireless communication networks.

2.3.1. Description of the research object

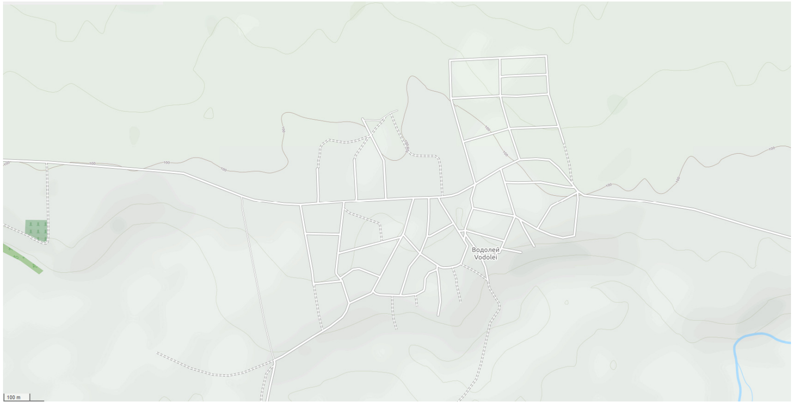


Fig. 2.9. Topographic map with scale of the village of Vodoley

The village of Vodoley, located in Northern Bulgaria, Veliko Tarnovo Municipality, Veliko Tarnovo District, was chosen as the real object of research.

2.3.2. Analytical calculation of radio coverage

Analytical planning of radio coverage proceeds in three steps:

- calculation of the coverage distance and free space losses;
- calculation of the power budget of the line
- calculation of the parameters of the transceiver equipment.

2.4. Analysis and conclusions to Chapter 2

1. An analysis and assessment of the degree of influence of the angular effect, the canyon effect, random interference attenuation, fading, time dispersion and Doppler shifting on the propagation and power distribution of signals in the radio channel was carried out in order to determine the key parameters and their interaction in real-time monitoring.
2. A wireless communication channel model with an integrated intelligent interference suppression algorithm has been developed and researched.
3. It has been found that traditional mathematical models for channel state information (CSI) have limitations. Classical model-based methods (such as LS+LI and LMMSE) rely on strict and fixed a priori assumptions about the environment, making them highly sensitive to mismatches and ineffective in real dynamic conditions.
4. It has been proven that large wireless and language models (LLM/LWM), trained only with ideal channel state information (perfect CSI), produce distorted performance in reality, since practical transmission is always accompanied by inevitable noise and interference.
5. Important advantages of noise and interference (NI) suppression architectures have been identified. The incorporation of a specialized training module for noise and interference (NI) filtering, combined with SINR calculation, allows

for more accurate CSI reconstruction and achieves the lowest normalized mean square error (NMSE) in downlink channel prediction.

CHAPTER 3. CONSTRUCTION, RESEARCH, MONITORING AND CONTROL OF WIRELESS RADIO COVERAGE OF A P2MP COMMUNICATION NETWORK

3.1. Planning and construction of a wireless P2MP communication network for conducting experimental research

3.1.1. Selection of equipment for building a wireless P2MP communication network for conducting experimental research

3.1.1.1. Selection of equipment for the base station

Fig 3.1. Selecting equipment for the base station (Mikrotik RBGrooveA-52HPnr2)

Equipment from the manufacturer Mikrotik, specifically the GrooveA-52HPn model, was selected. It meets all the requirements to ensure coverage in the selected location.

3.1.1.2. Selection of power supply unit with UPS function

Monitoring of the built system should also include monitoring of the supply voltage.

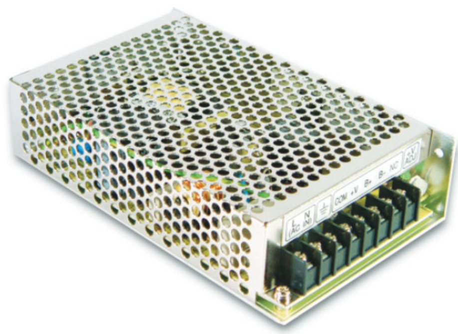


Fig. 3.2. Selecting a power supply unit (Meanwell AD-55A)

The selected equipment for the base station can operate with a wide range of input voltage from 9V to 30V. This will allow direct connection of a power supply unit with UPS function without an inverter, the voltage will be about 13.6V when the main power supply is available, and when it fails, the voltage will come directly from a connected battery and will be 12.6V, gradually decreasing. This additional feature will be used as a data input to the monitoring system, which will determine from this value whether it is working with main or backup power supply.

3.1.1.3. Selection of transmitting antenna

The calculated coefficient of the transmitting antenna is 11.18dBm.

Fig. 3.3. Selecting a transceiver antenna (TP-Link TL-ANT2412D)

An example of an antenna is the TL-ANT2412D model, which operates in the 2.4Ghz~2.5Ghz frequency range, has a transmission coefficient of 12dBi, which is slightly above the required. It also has 360° coverage in the horizontal plane.

The antenna has an N-connector and can be connected to the base station without connecting cables.

3.1.1.4. Selection of user equipment

The Ubiquiti Loco M2 model was selected – it meets all the requirements to be able to work at any point in the village of Vodoley.

Fig. 3.4. User equipment selection (Ubiquiti Loco M2)

3.1.2. Software planning of the radio frequency channel and radio coverage of a wireless P2MP communication network

Ligowave's LinkCalc software is used for planning and simulation of wireless coverage.

As can be seen from Fig. 3.8, the planned coverage meets the necessary requirements. At the top of the figure, there is a color scale that indicates what the model plans for the received signal level.

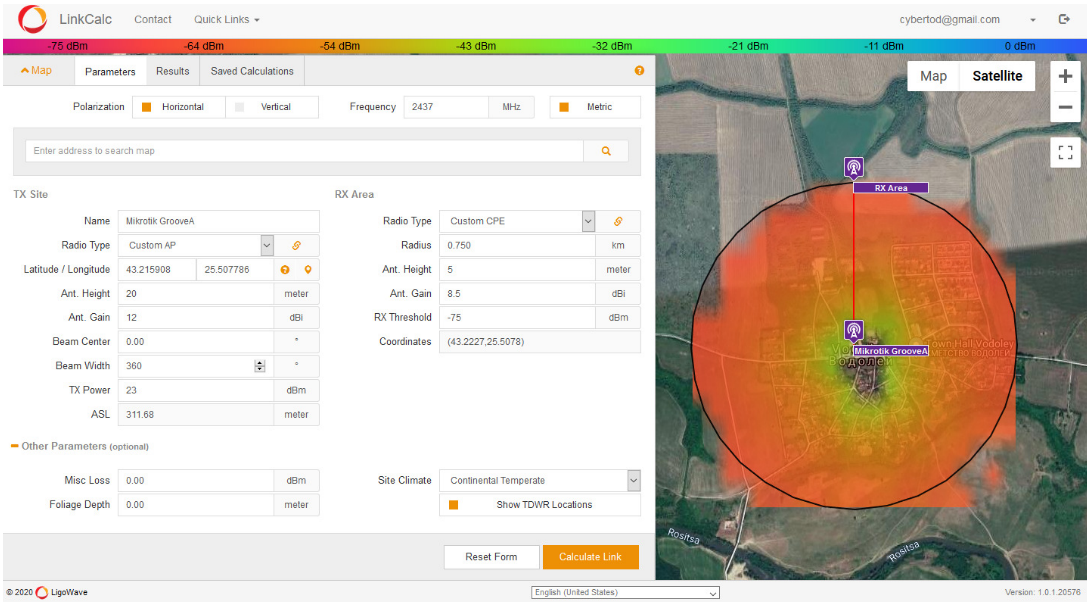


Fig. 3.8. Output of results from the simulation planning of P2MP radio coverage in a wireless communication network using the LinkCalc software tool for the village of Vodoley

3.1.3. Building and configuring a wireless P2MP communication network

3.1.3.1. Configuring Mikrotik GrooveA in base station mode

Fig. 3.9 shows the screen where the basic parameters of the wireless interface are configured.

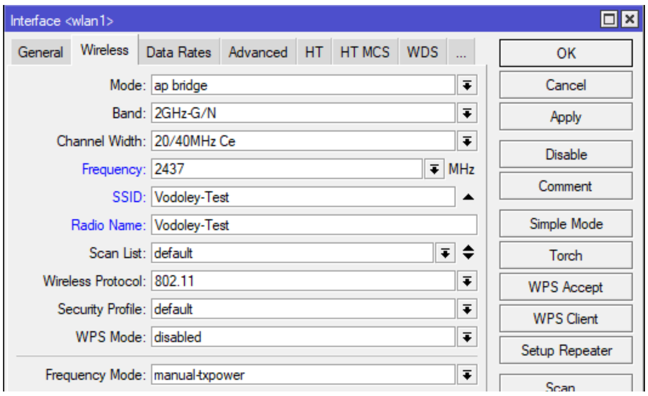


Fig. 3.9. Configuring the wireless interface of the base station

3.1.3.2. Configuring Ubiquiti Loco M2 in client mode

Ubiquiti devices are configured via a web browser. Again, only the configuration of the wireless interface parameters is considered.

The main parameters in airOS are configured on the screen shown in Fig. 3.11. Another menu that contains important settings for the wireless interface, and especially in the case of outdoor wireless connection, is the *Advanced* menu – Fig. 3.12.

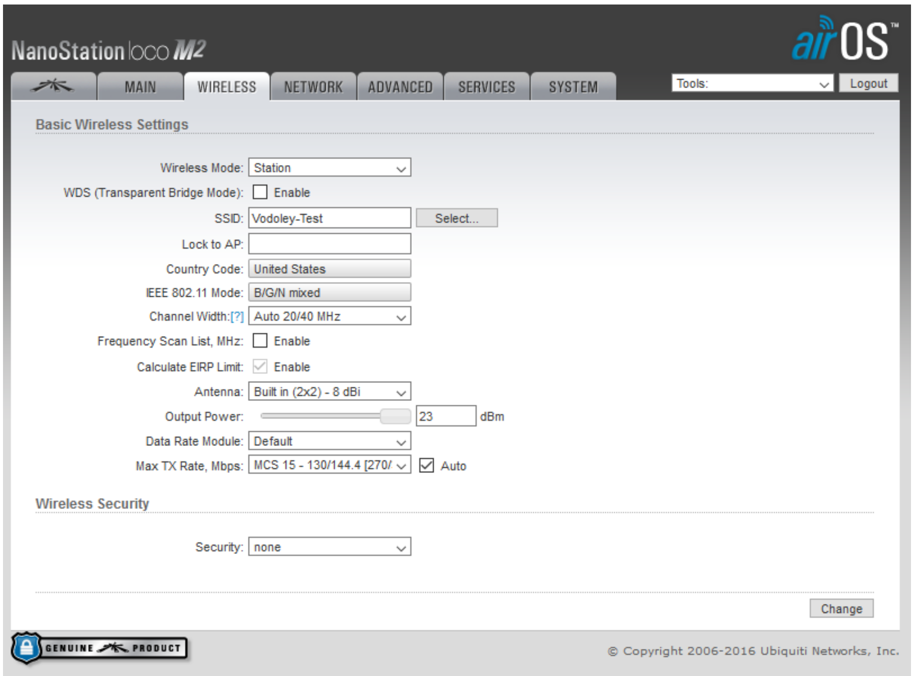


Fig. 3.11. Configuring the wireless interface on a client device

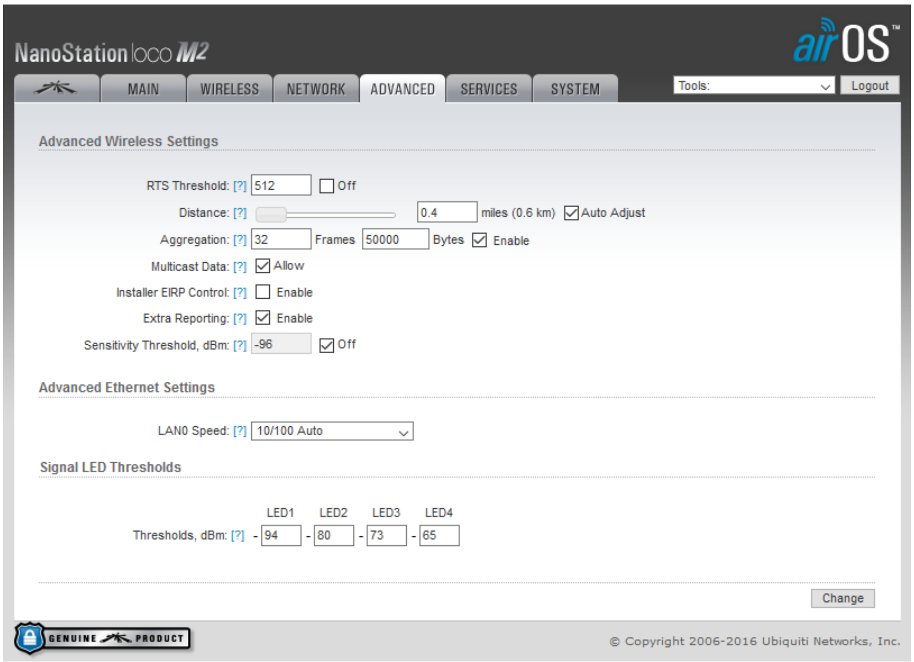


Fig. 3.12. Configuring advanced parameters on a client device

3.2. Experimental study and analysis of monitoring and control of wireless radio coverage of a P2MP communication network

3.2.2. Experimental study of wireless radio coverage of P2MP communication network

The terrain of the settlement is flat. The control points for the purposes of the experimental study were selected in different locations of the settlement and at different distances from the base station.

Measurements are made at 12 control points. In most points, there is direct visibility between the client device and the base station, but in some of them there is vegetation between the antennas and there is no complete direct visibility.

The results of the measured values of the radio signal level at the corresponding monitoring control points are presented in Table 3.1. The measured levels are from the perspective of the client device. The measured RX level is what is received at the client, and the TX level is what the base station receives from the client.

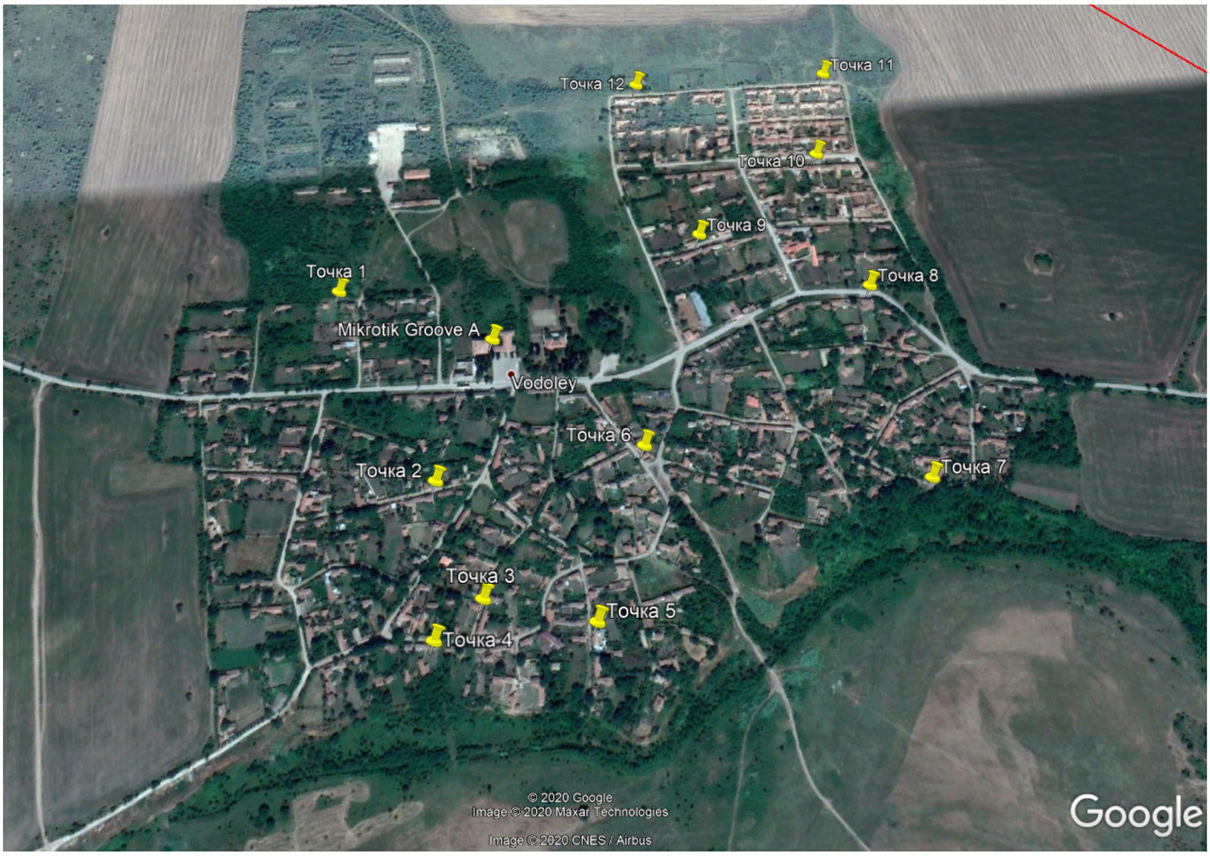


Fig. 3.15. Control points for monitoring and researching wireless radio coverage

Table 3.1. Experimentally measured radio signal levels at selected control points

Control point (CP)	Distance	Measured RX level, dBm	Measured TX level, dBm
CP 1	233м	-54	-53
CP 2	227м	-57	-59
CP 3	375м	-61	-59
CP 4	438м	-75	-73
CP 5	432м	-61	-61
CP 6	260м	-71	-70
CP 7	620м	-70	-61
CP 8	538м	-68	-67

CP 9	340м	-56	-54
CP 10	570м	-63	-60
CP 11	685м	-62	-60
CP 12	500м	-57	-54

Fig. 3.16 shows the monitoring of the client equipment, which shows the status and parameters: the device model, its operating mode, SSID of the base station, software version, time since startup, channel, channel width, transmission power, network port mode, processor load, occupied memory, MAC address of the base station, received signal strength, signal strength for both polarizations, noise level, transmission quality factor.

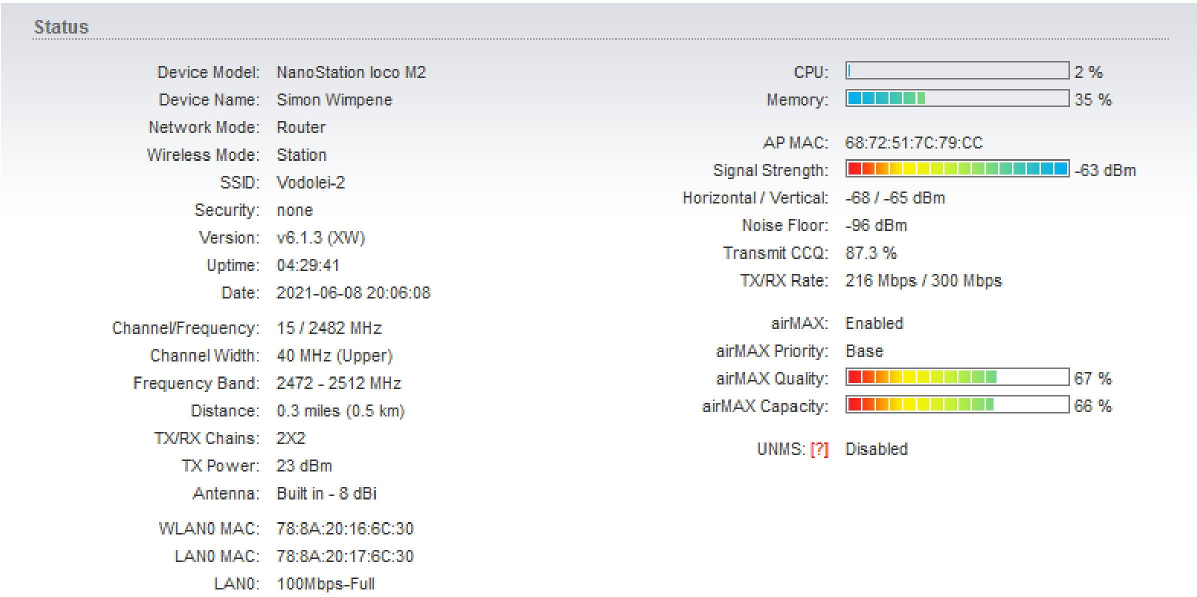


Fig. 3.16. Main screen of the client device monitoring system (Ubiquiti Loco M2)

The main screen does not have complete information about the base station, as well as the measured TX signal level. Fig. 3.17 displays the monitoring of additional parameters, e.g. data via CDP protocol, such as the base station model, its software version, both the received and the sent signal level are visible, the distance as detected by the base station is visible, and also the transmission power of the base station. The right part shows the measured signal for different modulations. In this case, with a sufficiently good signal, only MCS14 and MCS15 work stably.

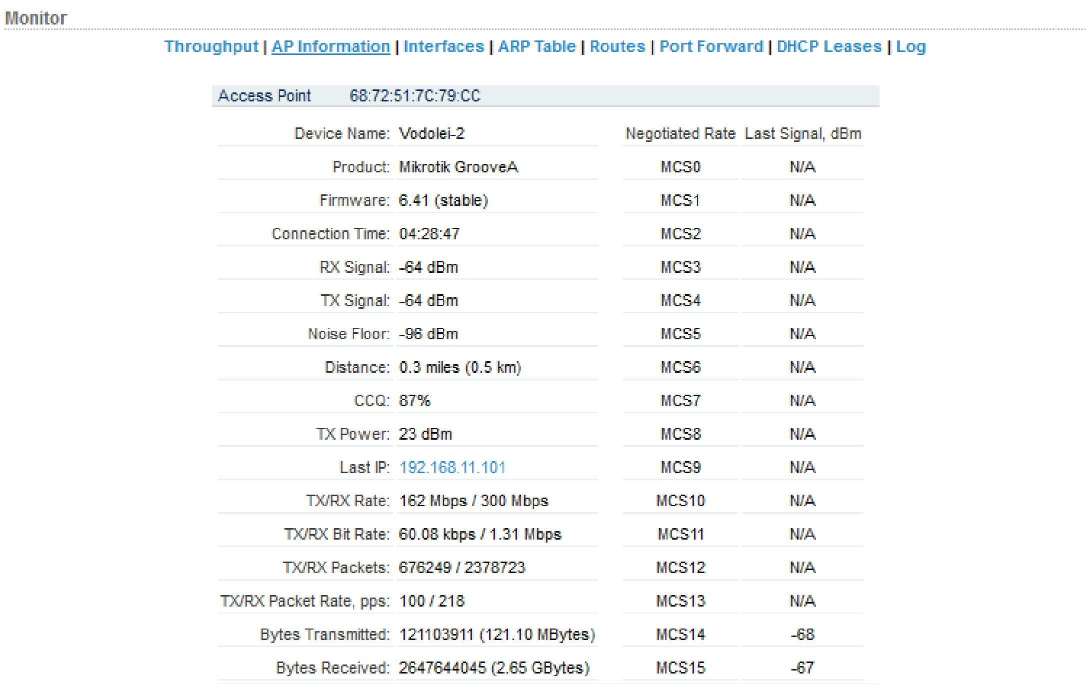


Fig. 3.17. Results of the monitoring of a network-connected client wireless device

To examine how stable the signal is, several measurements are performed at certain time intervals. These tests are performed for CP 11, since it is the farthest from the base station. The results are presented in Table 3.2. The signal remains stable and almost without any changes.

Table 3.2. Reported data for CP 11 within a few days

Measurement	Date and time	Measured RX level, dBm	Measured TX level, dBm
1	08.06.2025 18:50 h	-61	-62
2	08.06.2025 21:01 h	-62	-63
3	09.06.2025 07:27 h	-61	-60
4	09.06.2025 11:22 h	-61	-62
5	09.06.2025 16:05 h	-62	-63

For CP 6, several additional measurements are also performed because there is vegetation between the base station and the client device and it needs to be established whether the signal will be stable at all times and in different weather conditions. The results of these measurements are described in Table 3.3.

Table 3.3. Reported data for CP 6 under different weather conditions

Date and time	Weather data	Measured RX level, dBm	Measured TX level, dBm
08.06.2025 18:52 h	light rain	-75	-73

08.06.2025 21:02 h	cloudy	-74	-71
09.06.2025 07:26 h	cloudy	-74	-71
09.06.2025 11:22 h	sunny	-73	-71
09.06.2025 16:05 h	sunny	-71	-70

3.2.3. Analysis of the results obtained

As can be seen from the result in Fig. 3.8, obtained in the software planning and the results in Table 3.1, obtained in the actual study of wireless coverage, the results are good and when compared approximately coincide. This is largely helped by the flat relief of the settlement and the lack of obstacles. However, in some points there is a low signal level, which is mainly due to vegetation that blocks part of the first Fresnel zone.

From the additional measurements in CP 11 described in Table 3.2 it is seen that the signal almost does not change and remains constant. This is due to the stationarity of the devices and direct visibility. The quality of the connection in such a case is completely predictable.

The result in CP 6 is interesting, where the low measured is partly due to obstacles between the antennas. From the additional measurements made, which are presented in Table 3.3, it is evident that the signal level changes within certain limits, but remains stable enough to work normally. In addition, the low signal level can also be attributed to the fact that in order to obtain a large transmission coefficient in the horizontal plane, the radiation angle in the vertical plane is relatively small. Here the distance is small, the transmitting antenna is mounted high, and the measurement with the client equipment is made from a relatively lower height. With these good signal levels obtained, it is possible that the client equipment of some of the sites is not on the roofs of the houses, but is in a lower place, such as a terrace or behind a window.

3.3. Analysis and conclusions to Chapter 3

1. A high degree of correspondence has been achieved between the theoretical model considered and the methodology applied in practice. The actually measured radio signal levels at the control points largely coincide with the preliminary results of the software simulation in LinkCalc tool
2. Optimal planning and design are key factors for the effective operation and quality of wireless radio coverage. The developed P2MP test network in a real environment and the conducted experimental studies establish the degree of single and complex influence of factors such as terrain, direct visibility, the presence of obstacles in the first Fresnel zone, the stationarity of the devices and weather conditions.
3. Software optimizations of the communication equipment are essential for its optimal configuration. Enabling the RTS/CTS mechanism (via RTS Threshold) and automatic setting of the ACK timeout are critical to

eliminating the "hidden point" problem and maintaining a stable connection over long distances.
4. Given the dynamically changing degree of influence of various factors, the monitoring system aims to proactively monitor and respond in order to ensure adaptability, continuous high efficiency of the network and the quality of the services provided.

CHAPTER 4. IMPLEMENTATION OF AN EXPERIMENTAL MODEL OF A UNIVERSAL SYSTEM FOR INTELLIGENT MONITORING AND CONTROL OF WIRELESS COMMUNICATION NETWORKS

The stages of development of the system for intelligent monitoring and control of wireless communication networks are as follows:

1) Defining the structure of a network operations center for monitoring telecommunication networks.
2) Selecting a software platform for implementing a system for intelligent monitoring and management of wireless communication networks.
3) Adding additional modules to expand the functionality of the system for intelligent monitoring and management of wireless communication networks.
4) Adding templates for easy and flexible configuration of the system.
5) Adding data sources and graphs for visualization of monitoring parameters in real time.
6) Creating an interactive map for data visualization in the control and monitoring center.
7) Simulation of events for experimental testing of the system for intelligent monitoring and management of wireless communication networks.

The main functional characteristics of the designed monitoring and control system are the following:

1) The system for monitoring and managing the radio channels in real time of the built wireless network is based on open-source software – Cacti.
2) Additional software modules WeatherMap and Thold were used to expand the functionality of the system, to provide interactive visualization in real time of data and graphs in the control and monitoring center and for signaling in case of emergency events.
3) Specialized templates have been added for easier configuration of different types of network devices and for configuring the toolkit for visualization of the wide range of data on the status of wireless connectivity and the network as a whole.
4) The system monitors and visualizes real-time data on the status of all

network devices: access point status; information on connected client devices; information on active connections and network performance for resource optimization; management of wireless radio channels; management, forecasting and signaling in emergency conditions.

4.4. Adding templates for easy and flexible system configuration

Templates for monitoring network devices have been developed to facilitate the entry of information for different types of devices.

Fig. 4.10 shows the screen from which templates are added.

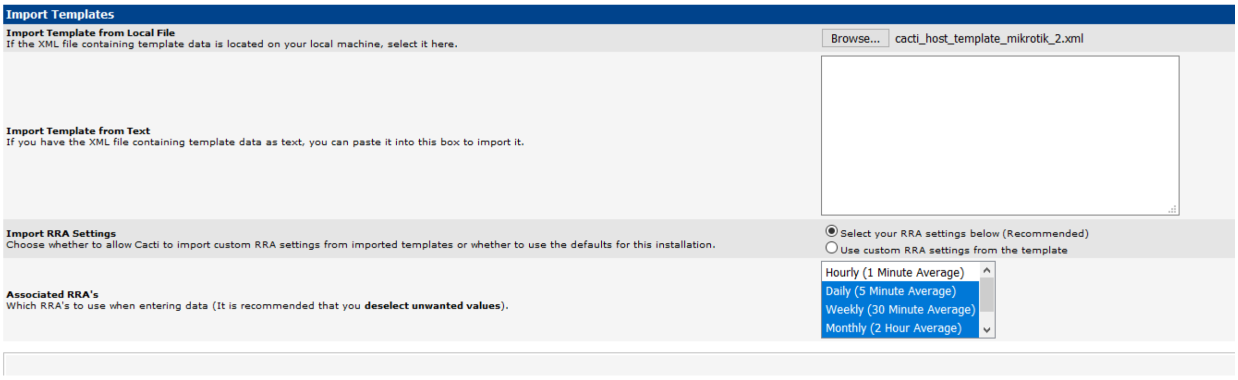


Fig. 4.10. Adding a template to the monitoring system

4.5. Adding data sources and graphs for visualizing real-time monitoring parameters

4.5.1. Add visualization for base station parameters

In order to add graphs, the device itself must first be added, as described in the Cacti documentation.

Fig. 4.12 shows the screen for adding a new device.

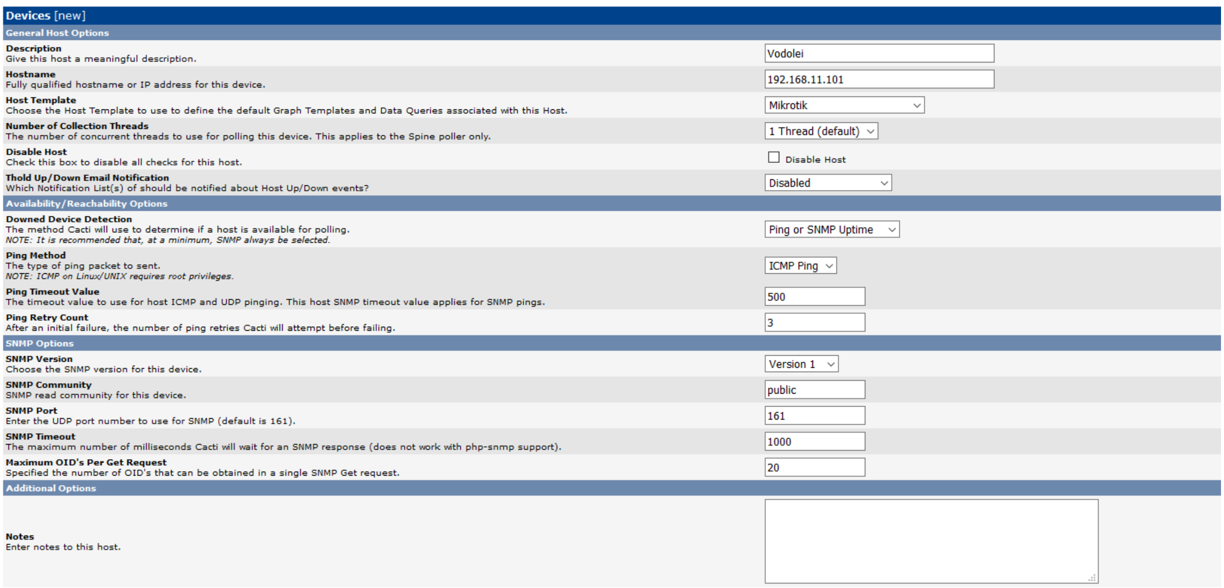


Fig. 4.12. Screen for adding a network device

Fig. 4.15. shows the result of adding a network device to the monitoring system.

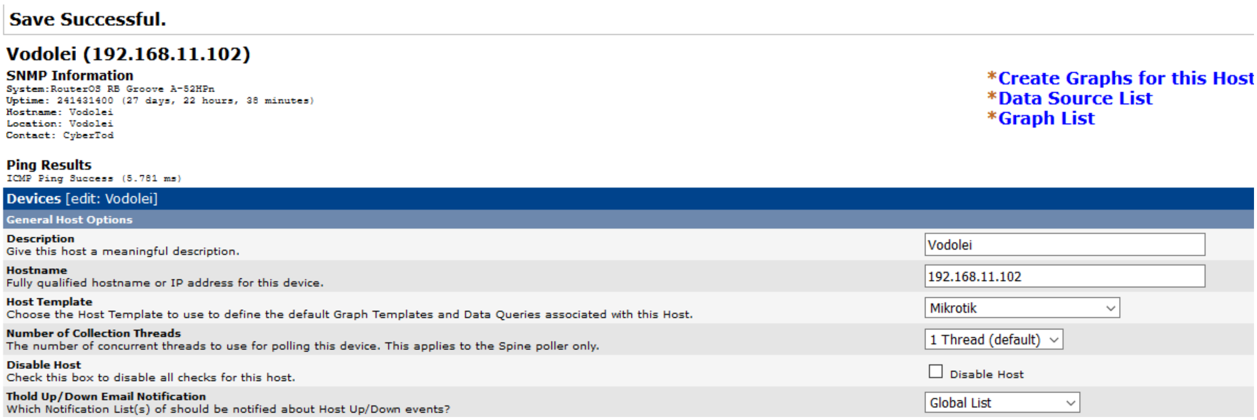


Fig. 4.15. Added network device in the monitoring system

Next is the addition of graphs. Fig. 4.16 shows the screen for adding graphs for visualizing the various parameters for monitoring and controlling the wireless network and radio signals.

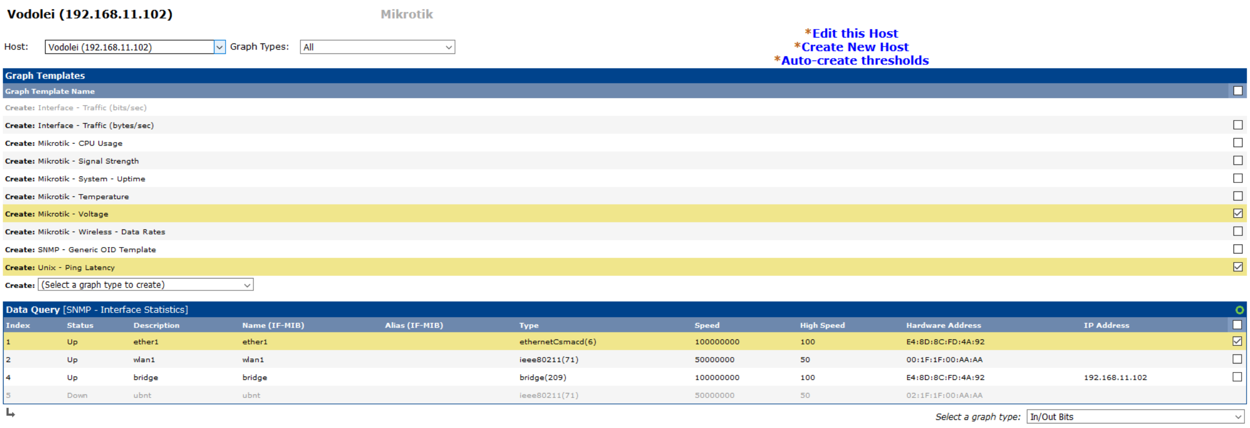


Fig. 4.16. Screen for adding graphics

The monitoring and control system has configured visualizations with information about the change in supply voltages, the time delay of the signal from the monitoring center to the base station, the traffic load on all network interfaces, etc.

Fig. 4.18 shows a visualization of the total traffic from the base station to the client equipment. This graph uses two data sources and shows the traffic in both directions – downlink and uplink.

Fig. 4.19 shows a visualization of the change in the supply voltage of the base station. The supply voltage is stable with a maximum value of 13.6V and an average value of 13.59V. The value coincides with that measured with a multimeter at the output of the power supply unit. It is possible to adjust it with a potentiometer, but this value is chosen so as not to overcharge the connected battery.

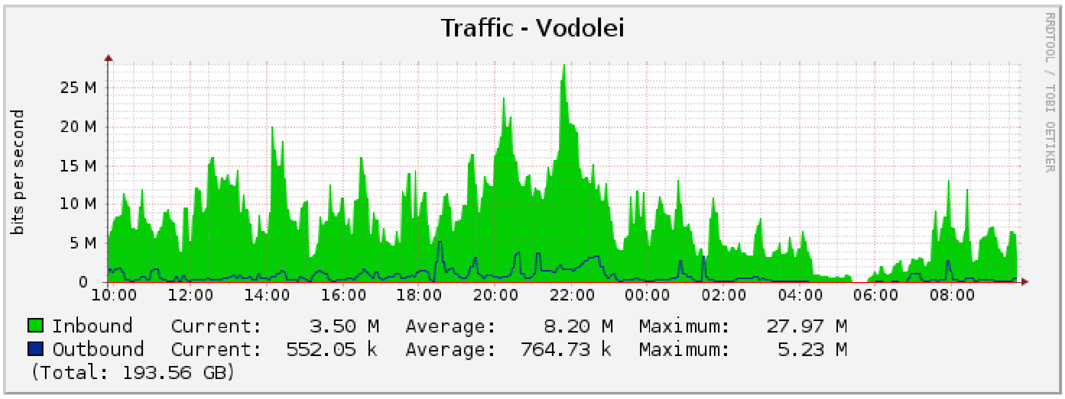


Fig. 4.18. Visualization of the traffic load on the wireless interface of the access point

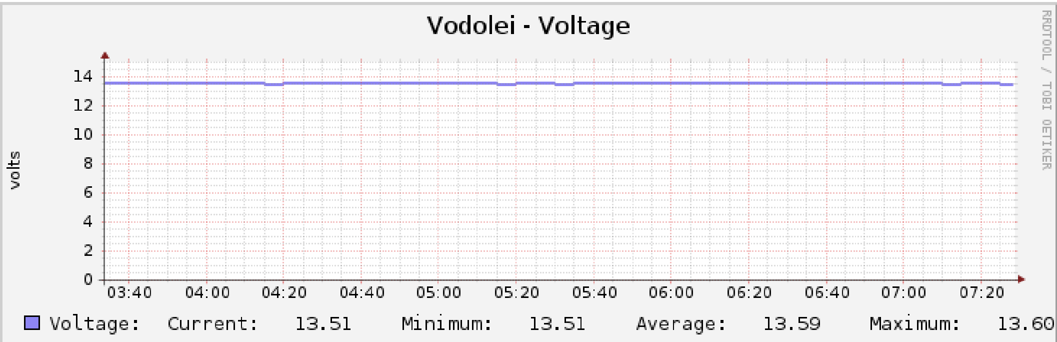


Fig. 4.19. Visualization of the supply voltage variations of the access point

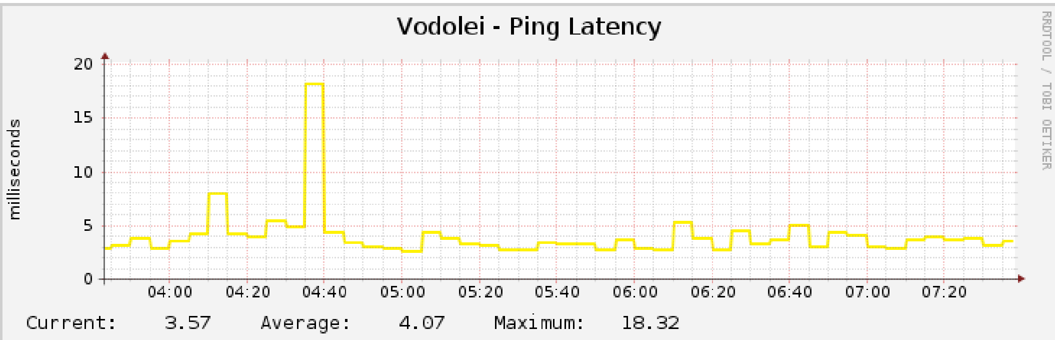


Fig. 4.20. Visualization of the time delay of the signal to the access point

The last visualization, shown in Fig. 4.20, displays the change in the signal delay between the server with the monitoring system and the base station. The average delay is 4.07 ms, which is a good value considering that the Cacti server is not located in the same settlement, and the Internet connectivity is also obtained via a wireless radio connection.

4.5.2. Add visualization for client equipment parameters

Monitoring of client devices will allow to monitor the power of the radio signal received by them. Graphs will also be added for visualization of traffic load, as well as for time delay.

Fig. 4.22 presents the mechanism for adding visualization of client device parameters.

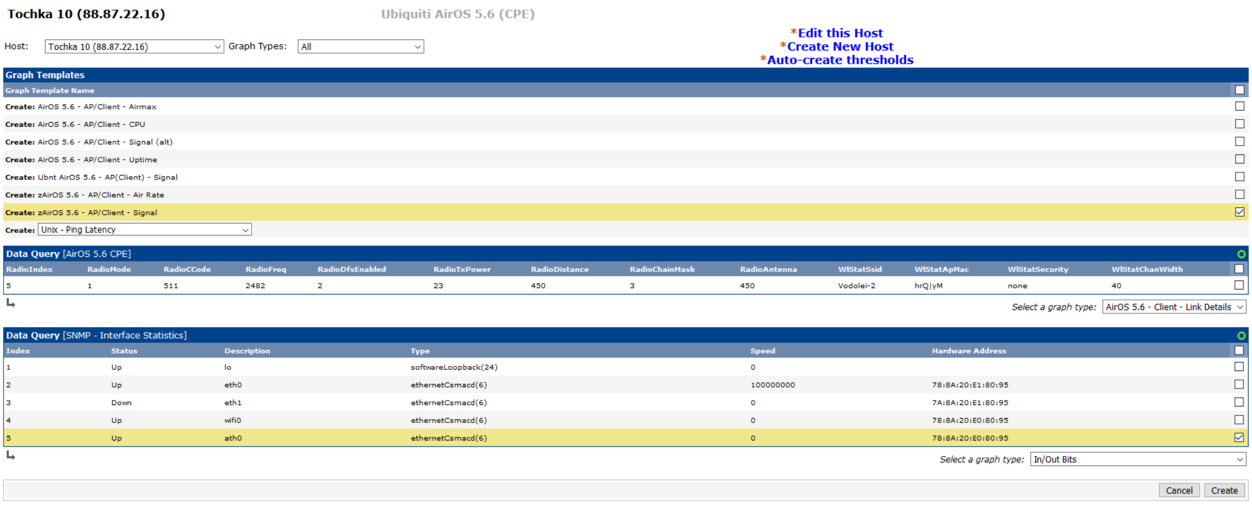


Fig. 4.22. Adding visualization for client device parameters

Fig. 4.23 presents the result of monitoring and visualization of the signal level received by the wireless interface of client equipment for Control Point 10. In addition to the level of the received signal, the noise level is also taken into account, and in the legend of the graph, the signal-to-noise ratio SNR is calculated from their difference.

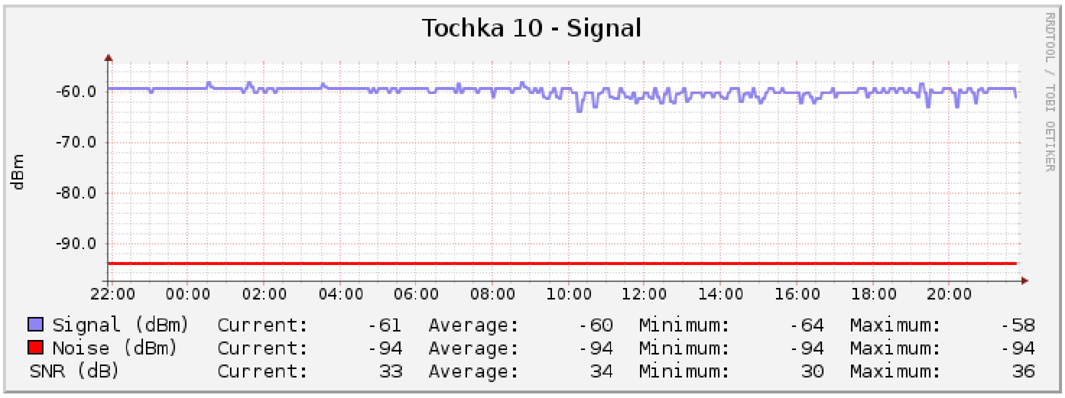


Fig. 4.23. Visualization of the signal level in the wireless interface of client equipment

The added graph for measuring ping delay can now also be used here

To assess the quality of the wireless connection, a visualization of the time delay of the signal to the client equipment has been added. As an example of this, the graph for the wireless interface of the client equipment for Control Point 6 shown in Fig. 4.24 is shown. As a disadvantage, it can be noted that this graph template shows the delays, but not the losses in percentage terms.

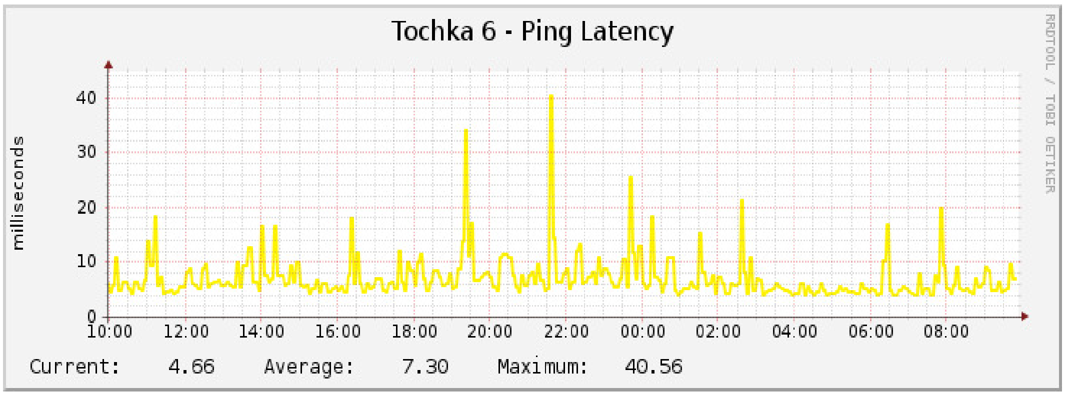


Fig. 4.24. Visualization of the time delay of the signal to the client equipment

4.6. Creating a map with the WeatherMap module for data visualization in the control and monitoring center

To create an interactive map for dynamic data visualization in the control and monitoring center, the WeatherMap module was used. The results of the configuration and execution of this task are the screen presented in Fig. 4.27.

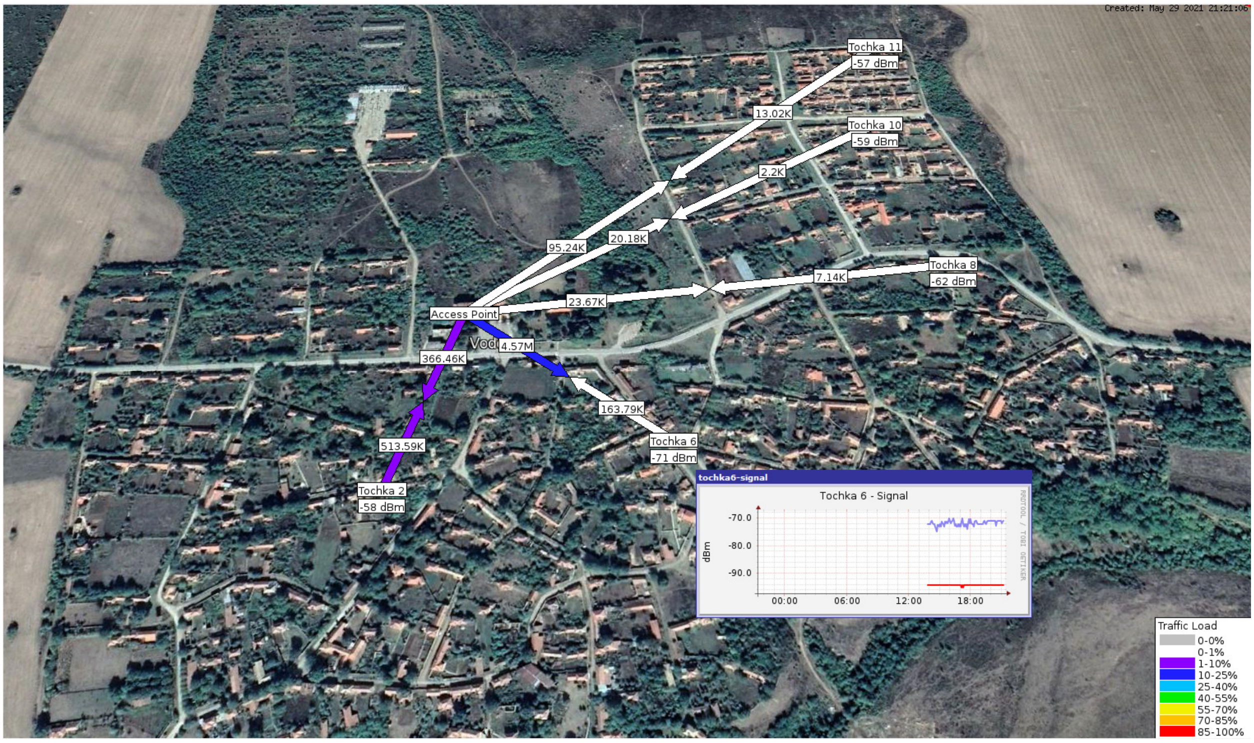


Fig. 4.27. Screen of the monitoring and management system for interactive visualization of the general status of the wireless communication network

Fig. 4.27 presents the main screen for interactive visualization of the general status of the wireless communication network in the developed monitoring system. The screen displays a real-time interactive map of the connected and active devices and the status of the wireless radio channels in the network. Additional detailed information can be easily called up by selecting the corresponding network element. Information about emergency events or deviations in the functioning and performance of the network is also visualized on this screen.

4.7. Event simulation for experimental testing of the system for intelligent monitoring and control of wireless communication networks

With the addition of the Thold module, the monitoring system is able to signal when emergency events occur in real time. Several tests will be performed for such events. One test will be a disruption of the base station's power supply and switching to backup power. The other test will be imitating a large signal attenuation and a breakdown in communication by rotating a client antenna so that the signal falls below a certain threshold. In order to be able to send these signals, the necessary alarm thresholds must be set.

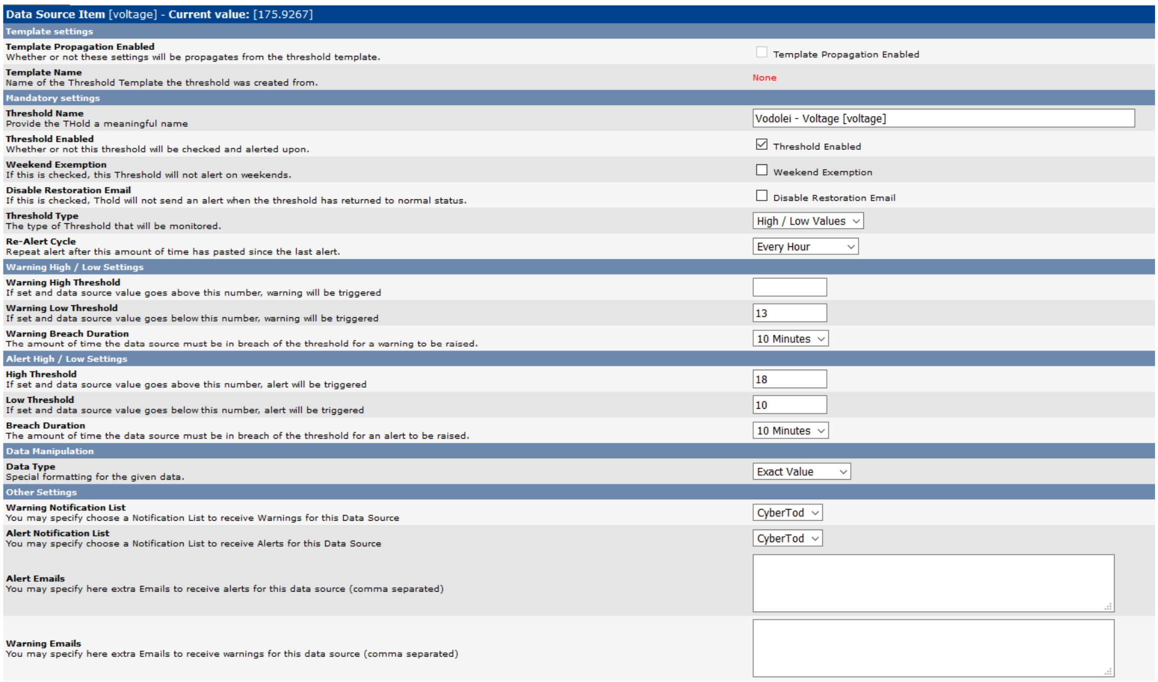


Fig. 4.29. Defining values to create a response threshold

It can be created a threshold value for just one data source or create a template to be used for sources of the same type with the same critical value threshold. It is also possible to add an alert for more than one source from a given graph.

Minimum and maximum threshold values are set, and a notification can be sent for deviations above or below their value. An interval is set during which a check is performed. In addition to precisely defined values, a warning can be sent for deviations by a certain percentage from the standard values of the source. One or more e-mail addresses are selected to which the notification should be sent. Both the addresses and the values are divided into warning and critical value.

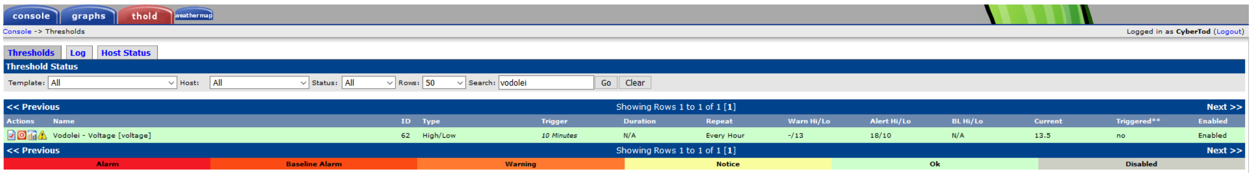


Fig. 4.30. Visualization of added value thresholds

4.7.1. Testing the system in the event of a power failure

Once a threshold for the voltage value has been created, the event simulation itself begins.:

1) The power supply unit is disconnected from the mains. The base station continues to operate. The power supply unit has switched the power supply to the connected battery. After a few minutes, a warning signal is received at the e-mail address entered in the threshold settings that the current voltage value is 12.6V with a minimum threshold of 13V.

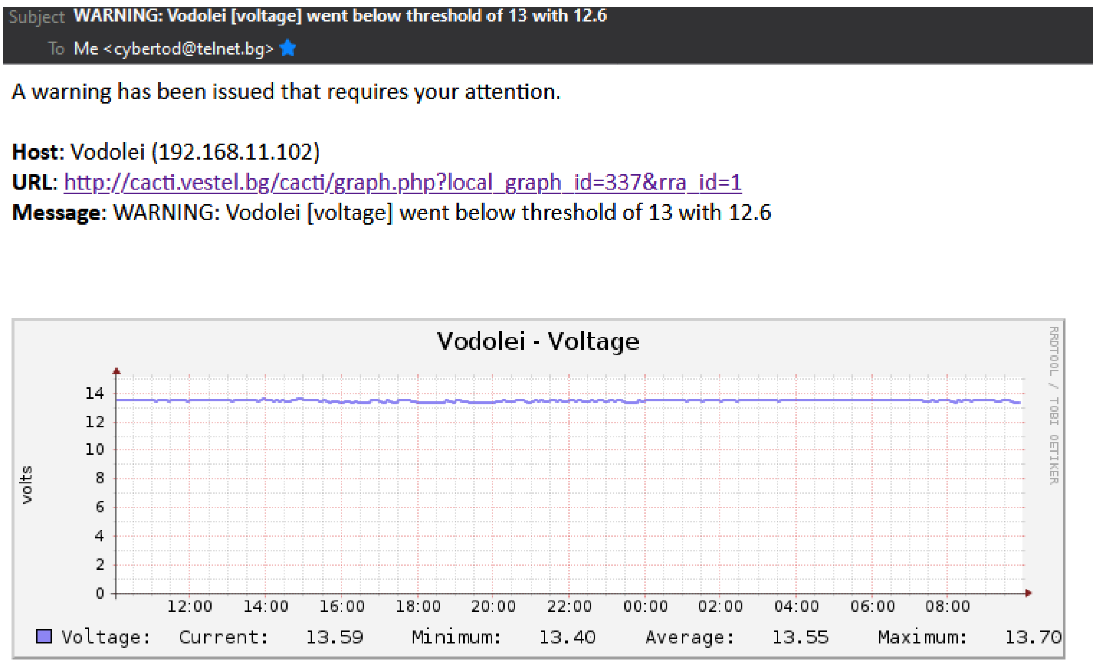
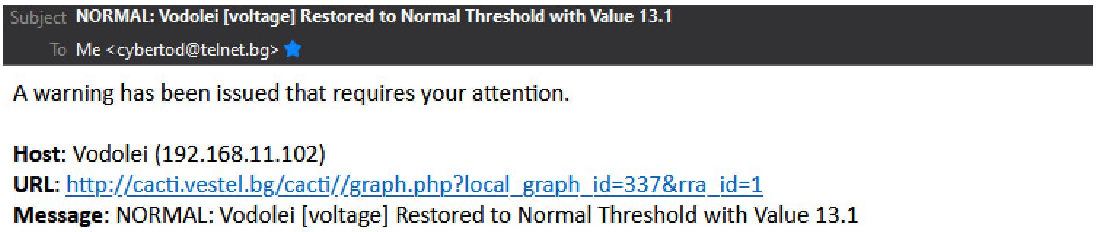


Fig. 4.31. Signaling for a drop in the set value below the defined threshold

2) A certain time is waited during which the power is left off. The base station continues to work stably. The battery used is 7Ah. Shortly after the power is turned on again, a notification is received by e-mail that the supply voltage value has been restored to the set norms.



Subject NORMAL: Vodolei [voltage] Restored to Normal Threshold with Value 13.1
To Me <cybertod@telnet.bg>

A warning has been issued that requires your attention.

Host: Vodolei (192.168.11.102)
URL: http://cacti.vestel.bg/cacti//graph.php?local_graph_id=337&rra_id=1
Message: NORMAL: Vodolei [voltage] Restored to Normal Threshold with Value 13.1

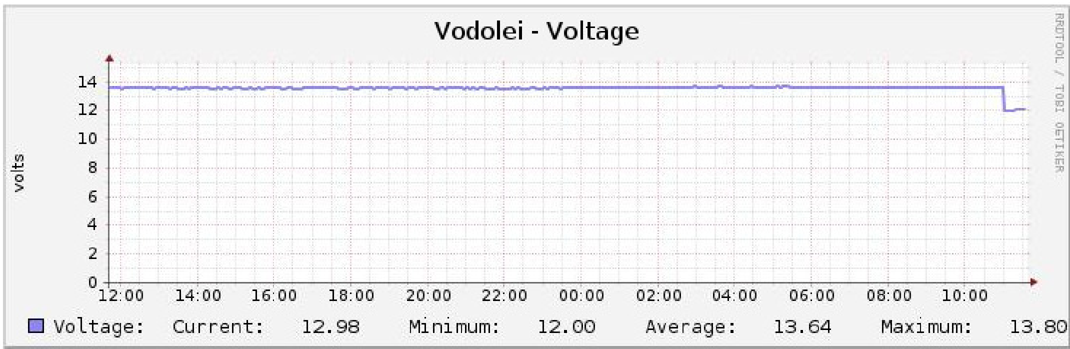
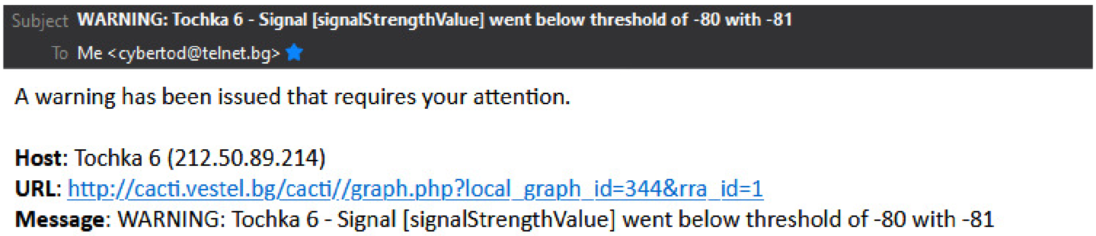


Fig. 4.32. Signaling for restoration of parameters to normal

4.7.2. Testing for degraded wireless connectivity with client equipment

Similar to the previous test, here a reduction in the signal level in the client equipment to a value that would interfere with the normal use of the radio connection will be simulated. The easiest way to do this is to rotate the transceiver antenna. Here a larger interval is set during which the check is to be performed, because the signal level can change within certain limits due to rain or other factors and there is no need to send unnecessary notifications.



Subject WARNING: Tochka 6 - Signal [signalStrengthValue] went below threshold of -80 with -81
To Me <cybertod@telnet.bg>

A warning has been issued that requires your attention.

Host: Tochka 6 (212.50.89.214)
URL: http://cacti.vestel.bg/cacti//graph.php?local_graph_id=344&rra_id=1
Message: WARNING: Tochka 6 - Signal [signalStrengthValue] went below threshold of -80 with -81

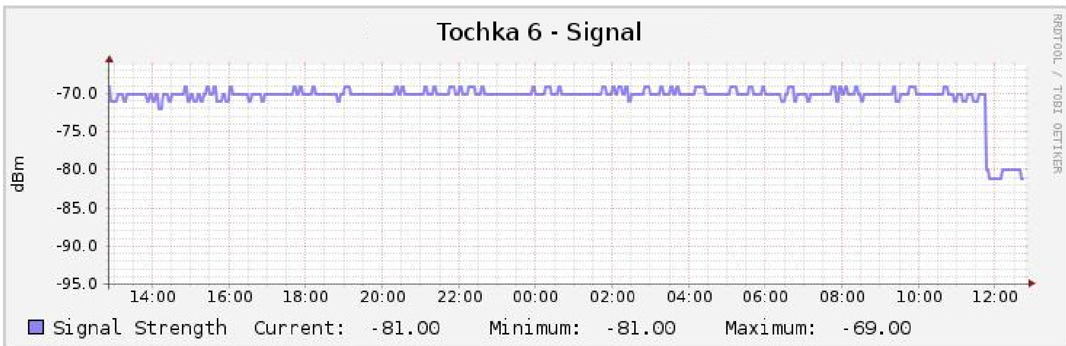


Fig. 4.33. Signaling when the signal is weak on a client device

The notification is received with a certain delay, which was the goal. Fig. 4.33 shows a result in which, after rotating the antenna by 60 degrees, the received signal level drops by about 10dB. In a real radio coverage built in this way, the control center will receive information in time and will be able to react before the network subscribers are left without service for a longer period of time.

4.8. Analysis and conclusions to Chapter 4

1. The developed system: allows flexibility and extensibility in data collection; has an implemented security control mechanism through detailed rights management; allows easy and seamless integration or removal of external additional modules, with the help of which functionalities are added; has flexible and powerful mechanisms for intuitive and interactive visualization of data on video walls in operational centers; can successfully integrate and extract technical data from physical devices using the classic SNMP protocol.
2. The developed system provides multi-component assessment of the wireless connection. Intelligent monitoring of radio channels is provided by simultaneously tracking various indicators - total network traffic (downlink and uplink), delay (ping latency), levels of the received radio signal and signal-to-noise ratio (SNR), etc.
3. An intelligent mechanism has been developed for switching from passive monitoring to active signaling. By implementing additional intelligent modules, the system becomes a tool for accident management, which automatically analyzes incoming data and sends notifications when predefined critical thresholds are crossed.
4. The developed intelligent system provides proactive response before service interruption for subscribers. Experimental simulations (main power outage and radio signal degradation) prove that the system detects deviations in parameters immediately, allowing staff to react in time before users lose connection.

CONCLUSION

The rapid growth of wireless communications on a global scale and the introduction of new generation technologies (such as Wi-Fi 7, 5G and future 6G architectures) highlight the need to move from conventional (reactive) management to real-time intelligent monitoring systems. The developed methodology successfully addresses the critical challenges associated with maintaining quality of service (QoS), transmission reliability and stability of connections in large-scale network structures (WPAN, WLAN, WWAN).

The main scientific and applied contribution of the development is the implementation of a holistic approach to assessing wireless connectivity. Multi-component analysis and data collection tools have been implemented. Instead of isolated tracking of single metrics, the proposed tools implement simultaneous and parallel monitoring of a complex of key technical indicators:

- Network traffic: systematic and differentiated analysis of capacity and load in the downlink and uplink directions.
- Time delays: precise tracking of delay (ping latency), which is a critical factor for the functioning of real-time applications.
- Radio channel quality: measurement of received radio signal levels and signal-to-noise ratio (SNR), providing an accurate assessment of the physical propagation environment

To ensure maximum compatibility with heterogeneous hardware infrastructure, the data collection tools successfully integrate the classic SNMP protocol. This allows for efficient extraction of low-latency technical information directly from physical devices, regardless of their manufacturer (multi-vendor environments).

The practical applicability of the methods is expanded by the development of powerful software mechanisms for intuitive data presentation through intelligent visualization and situational awareness:

- Building interactive logical maps on a real geographical background, which are animated in real time with current data on the status and load of the network.
- Adapting visualization interfaces for work in operational centers through video walls, which guarantees immediate reaction of administrators when locating anomalies.

The scientific and practical value of the work is materialized in the developed intelligent mechanism for transitioning from passive monitoring to active signaling and proactive response. By implementing additional intelligent modules, the system is transformed into a complete tool for accident management, which:

- Automatically analyzes incoming telemetry data streams.
- Identifies anomalies and immediately sends notifications when predefined critical thresholds are crossed.
- Prevents service interruptions for end subscribers by allowing operators to react before fatal signal degradation occurs.

The conducted experimental simulations (including severe operational scenarios such as power outages and artificial degradation of radio signal parameters) categorically confirm the stability and reliability of the proposed solutions. The system demonstrates high sensitivity and captures even the smallest deviations from the normal operating mode, which proves its maturity for implementation in critical corporate, industrial and urban wireless networks.

The developed methods and tools for intelligent monitoring successfully close the loop between theoretical mathematical modeling of radio channels and applied software management of modern digital infrastructure. They provide a technological basis for increasing the security, capacity and fault tolerance of wireless communication networks in the era of intensive digitalization.

CONTRIBUTIONS TO THE DISSERTATION WORK

Scientific-applied contributions:

1. A complex methodology for multi-criteria analysis and assessment of the state of wireless radio channels and an architectural model for proactive monitoring of wireless networks is developed, based on the effective combination of standard telemetry protocols (such as SNMP) with algorithms for dynamic monitoring of parameters in heterogeneous hardware infrastructure (multi-vendor environments).
2. Criteria and algorithmic rules are formulated for automatic identification of anomalies and emergency conditions, which allow mathematically based prediction of connection degradation before an actual communication breakdown occurs.
3. An innovative wireless channel model with an integrated intelligent noise and interference suppression algorithm is proposed and investigated. The model successfully solves the critical problem of the lack of correct channel state information (CSI) by implementing a specialized training module for filtering. This allows for more accurate reconstruction of CSI and achieving significantly lower mean square error (NMSE) in prediction compared to the application of traditional algorithms.

Applied contributions:

4. A specialized platform for intelligent monitoring is designed, software implemented and experimentally verified, which provides reliable collection and processing of real-time data on the status of the wireless infrastructure.
5. Software solutions for graphical interfaces are developed to increase situational awareness, including interactive logical maps on a real geographical background and optimized visualizations for video walls in dispatch and network operations centers (NOCs).
6. An automated signaling and event management module is developed, which automates the process of detecting and localizing problems in the radio channel of wireless communication networks. By conducting a series of tests in real conditions and simulated critical scenarios, the high accuracy, speed and fault tolerance of the developed solution are experimentally verified

LIST OF PUBLICATIONS ON THE DISSERTATION WORK

[A.1] Angelov K., N. Manchev, S. Sadinov, **M. Angelakis**, Application of LoRa in IoT home automation platform. International scientific conference UNITECH 2022, November 18-19, 2022, Gabrovo, Bulgaria, pp. I-228 - I-233, 2022 (ISSN: 2603-378X).

[A.2] **Angelakis M.**, Tashev P., Angelov K., Educational demonstration platform for IP-video streaming and monitoring of television content, Proceedings: VIII National Scientific Conference with International Participation TC Lovech "TechCo 2024", June 28, 2024, Lovech, ISSN - 3033-1323, pp. 112-116.

[A.3] **Angelakis M.**, Kypraios E., Angelov K., Universal integrated system for monitoring in communications, Proceedings: VIII National Scientific Conference with International Participation TC Lovech „TechCo 2024", June 28, 2024, Lovech, ISSN 2535-079X, pp.117-122.

[A.4] Popov V., Kypraios E., **Angelakis M.**, Implementation of 3D objects in video processing, using Blender, Student Scientific Session `2024, 18.10.2024, Gabrovo, ISSN: 1313-3055, Volume 1, pp. 84-89.

[A.5] Todorov N., Kypraios E., **Angelakis M.**, Monitoring the liquid level during bottling, through image processing and analysis, Student Scientific Session `2024, 18.10.2024, Gabrovo, ISSN: 1313-3055, Volume 1, pp. 90-95.

[A.6] **Angelakis M.**, Application of Wavelength Division Multiplexing Passive Optical Network (WDM-PON) technology for access networks, Proceedings: IX National Scientific Conference with International Participation TC Lovech "TechCo 2025", June 27, 2025, Lovech, ISSN 2535-079X, pp.145-150.

[A.7] Kypraios E., Sadinov S., **Angelakis M.**, Angelov, K., Study of the effectiveness of applying WDM-DCF compensation in fiber-optic communication systems. Proceedings: IX National Scientific Conference with International Participation TC Lovech "TechCo 2025", June 27, 2025, Lovech, ISSN: 3033-1323, pp.151-156.

[A.8] **Angelakis M.,** Research on a wireless communication channel model with an integrated intelligent interference suppression algorithm, International scientific conference UNITECH 2025, November 20-21, 2025, Gabrovo, Bulgaria, ISSN: 2603-378X, pp. 1-7.

TITLE: "METHODS AND MEANS FOR THE INTELLIGENT MONITORING AND CONTROL OF RADIO CHANNELS IN WIRELESS COMMUNICATION NETWORKS"

Author: Michail Georgios Angelakis

ABSTRACT

In Chapter 1, an analyzes of the current state and areas of research and development in the field of monitoring and control of wireless radio channels in wireless communication networks is conducted. The main problems of the communication environment in this type of networks are analyzed and summarized. As a result, the main goal and objectives of the dissertation work are formulated and motivated.

In Chapter 2, a generalized approach for analyzing signal attenuation and interference in wireless radio channels is presented and developed and studied on a model of a wireless channel for communication with a proposed innovative integrated intelligent algorithm for suppressing interference. The proposed algorithm is analyzed, and its effectiveness is proven through a study with synthetically generated input data for training the model and a comparative analysis of the results obtained with classical algorithms.

In Chapter 3, software planning and construction in a real environment of a wireless P2MP communication network for testing purposes are performed. An experimental study and analysis of the behavior of radio channels is carried out through monitoring and control of wireless radio coverage of the constructed test network. As a result, an approach for optimal planning and optimization of the parameters of wireless radio channels in wireless communication networks is synthesized.

In Chapter 4 of the dissertation, a conceptual design, practical implementation and research of an experimental model of a universal system for intelligent monitoring and control of wireless communication networks are presented. The software architecture of the system, the configuration of its key components and its effective implementation in a real environment for a site - the village of Vodoley are presented. Functional testing and verification of the system in various scenarios and conditions have been carried out, and the experimental results of the measurements carried out are duly presented, discussed and analyzed.

Keywords: wireless communication network, radio channel, channel state information, noise and interference suppression system, intelligent monitoring and control system