RIGA TECHNICAL UNIVERSITY
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RESEARCH AND IMPROVEMENT OF THE PERFORMANCE OF ROAD TRANSPORT WIRELESS COMMUNICATION NETWORKS

Summary of the Doctoral Thesis

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

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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.

Arnis Ancāns ………………………………….. (signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It consists of an Introduction; 5 chapters; Conclusion; 52 figures; 14 tables; 9 appendices; the total number of pages is 141, not including appendices. The Bibliography contains 182 titles.

ANNOTATION

Global development trends such as the increase in the number of cars, an increased number of smart devices with wireless network connections, and the rapid increase in the amount of transmitted information promote the demand for higher data exchange speed, mobility, and higher level of connectivity. Consequently, data transmission services are also required when users travel by vehicle. As the number of vehicles increases, the problems related to road safety and traffic flow management need to be addressed as well. These problems underline the need for modern, technically, and economically justified communication solutions for Intelligent Transport Systems (ITS). One of the wireless network technologies that can be used for ITS needs, in particular for providing car passengers with access to the data transmission network, is WLAN IEEE 802.11n/ac. The implementation of such WLAN-based automotive wireless access networks requires several issues to be addressed, mainly related to fast-moving objects. In practice, a two-rank wireless network is used, which can provide access to the Internet.

Several testbeds of a two-rank road transport communication network using WLAN IEEE 802.11n and LTE technologies were created and studied in the developed Doctoral Thesis. The change in the traffic characteristics of a two-rank communication network was experimentally assessed using LTE hardware from various manufacturers. The performance of such hybrid communication channels was studied depending on the velocity of mobile customers, the number of customers, and the traffic scenarios used. New relationships characterising the performance of the integrated IEEE 802.11n and LTE road transport networks and describing the dependence of network throughput on the velocity of mobile client movement were obtained. A single-rank IEEE 802.11ac technology-based automotive communications testbed has also been developed and studied within the Doctoral Thesis. An improved handover algorithm based on the IEEE 802.11v protocol has been developed and implemented during the research. The relationships describing the performance of such single-rank automotive communication network were theoretically evaluated.

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LIST OF ABBREVIATIONS

4G – fourth generation cellular technology
5G – fifth generation cellular technology
5G NR – 5G New Radio technology

A
ACK – Acknowledgement
AL throughput – Application Layer throughput
AP – Access Point

B
BSc – Base Scenario
BSS – Basic Service Set

C
C-V2X – Cellular V2X
CAV – Connected and Automated Vehicle

D
DHCP – Dynamic Host Configuration Protocol

E
ERDF – European Regional Development Fund
EU – European Union

F
FTP – File Transfer Protocol

G
GPS – Global Positioning System

H
HP – Hewlett-Packard Company

I
IEEE – Institute of Electrical and Electronics Engineers
IP – Internet Protocol
ITS – Intelligent Transport Systems

L
L4 – Layer 4; Transport Layer
L7 – Layer 7; Application Layer
LAA – Licensed Assisted Access
LAN – Local Area Network
LTE – Long Term Evolution
LTE-U – Long Term Evolution-Unlicensed
LWA – LTE–Wi-Fi Link Aggregation

M

MAC – Medium Access Control

MB – Megabyte

MSE – Mean Squared Error

O

OBU – On-Board Unit

OSI – Open System Interconnection

R

RSRP – Reference Signal Received Power

RSRQ – Reference Signal Received Quality

RSS – Received Signal Strength

RSSI – Received Signal Strength Indicator

RSU – Roadside Unit

S

Sc – Scenario

SINR – Signal to Interference Noise Ratio

SNMP – Simple Network Management Protocol

SSR – Sum of Squared Residuals

STA – 802.11 Station

T

TCP – Transmission Control Protocol

TH – Threshold

TL throughput – Transport Layer throughput

TM – Transition Management

V

V2I – Vehicle-to-Infrastructure

V2N – Vehicle-to-Network

V2P – Vehicle-to-Pedestrian

V2V – Vehicle-to-Vehicle

V2X – Vehicle-to-Everything

W

WAVE – Wireless Access in Vehicular Environment

Wi-Fi – Wireless Fidelity

WLAN – Wireless Local Area Network

WLC – Wireless LAN Controller

WPA – Wi-Fi Protected Access

GENERAL DESCRIPTION OF THE DOCTORAL THESIS

Topicality of the Research

The growing volume of data transmission in wireless communication networks and the demand for ubiquitous connectivity and mobility is placing ever-increasing demands on today's wireless networks. The information society requires high-level connectivity solutions, not only in a fixed environment but also on the road, i.e., while travelling by car.

The increase in the number of vehicles [53] and, hence, the increase in road congestion, causes several problems such as an increase in traffic incidents, traffic jams, and pollution. The projected sales of passenger cars in the European Union (EU) (Fig. 1) include several scenarios [53]. Unlike scenarios Sc1, Sc2, and Sc3 that consider Connected and Automated Vehicle (CAV) technologies in the base scenario (BSc), the impact of these technologies is not considered. The characteristics of curves of scenarios Sc1, Sc2, and Sc3 change depending on the projected level of technology development, legal regulations, and the level of technology adoption. Scenario Sc1 envisages a low level of development in these areas, whereas Sc2 envisages a medium level of development, and Sc3 envisages a high level of development in each of the areas. Depending on the scenario used, passenger car sales are projected to increase from 18 % up to 39 % in the period 2015–2025 and from 33 % to 51 % in the period 2015–2050. In the Sc3 scenario, the projected long-term decline in passenger car sales is related to the projected dominance of car-sharing services in the future, which could contribute to the declining demand for privately owned cars.

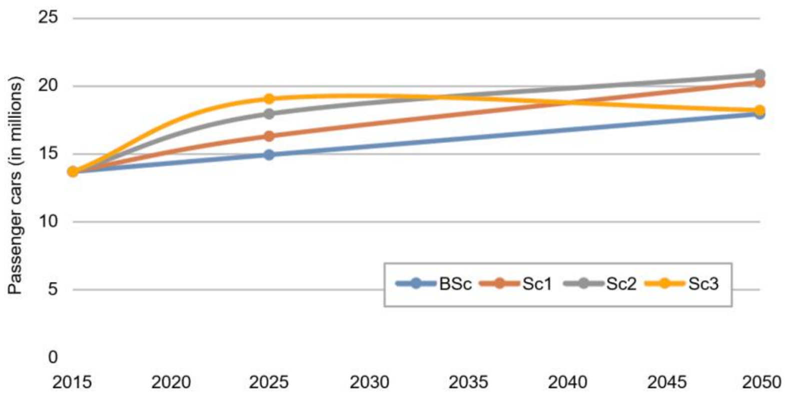


Fig. 1. Projected car sales in the EU under different scenarios [53].

According to the European Commission's data, the activity of passenger cars on the roads in the EU will increase by 9 % and 30 % in 2015–2025 and 2015–2050, respectively. Whereas truck activity on the roads will increase by 16 % and 46 % over these periods [53]. The increase in the projected activity on the roads is related to the positive impact of connected and autonomous cars, the increase in the number of cars, as well as to the projected increase in economic activity and growth. This means that people in general will spend more time travelling by car.

The above-mentioned problems associated with the increased number of cars can be effectively addressed through the Intelligent Transport Systems (ITS), also known as automated transport systems. ITS includes both private vehicles and commercial transport, as an increase in overall road safety can be achieved by involving all road participants, including pedestrians. In addition, ITS addresses problems related to both the vehicle and its passenger's access to the Internet while being on the move. Each car passenger is considered as a mobile client who shall be provided with access to the data transmission services.

Cisco's global forecast demonstrates that the ratio of smart devices with a mobile network connection to non-smart devices with a mobile network connection will increase to 73 % in 2022, compared to 53 % in 2017 [18]. Cisco also predicts that global mobile data traffic will increase almost sevenfold between 2017 and 2022, reaching 77 exabytes per month [18]. These forecasts clearly demonstrate a rapid increase in demand for the data network services.

Analysis of the trends discussed above leads one to conclude that vehicle passengers will actively use data transmission services while on the road. The considered trends justify the need for modern ITS communication solutions.

Aim and Tasks of the Doctoral Thesis

Based on the evaluation of the development directions of road transport communication networks, **the aim of the Doctoral Thesis** was defined – to study and evaluate the performance of integrated road transport communication networks based on IEEE 802.11n/ac and LTE standards, and to increase the performance of the IEEE 802.11ac wireless access network.

In order to achieve the aim brought into focus, the following **basic tasks** had to be performed:

1. To carry out research on the used and prospective telecommunications wireless network solutions in the road transport sector in accordance with the type of their application and to evaluate the future trends and directions of development of such networks.
2. To carry out research on the operation principles of WLAN technology and implemented security mechanisms.
3. To carry out research on the LTE technology and the main parameters of received LTE signal. To study possible WLAN and LTE convergence solutions.
4. To develop a testbed for an integrated WLAN and LTE automotive communication network. To evaluate its performance using LTE hardware from various manufacturers. To evaluate the performance of such a network with various numbers of clients and different scenarios of mobile client movement.
5. To define the parameters for the development of technical and economic justification of a two-rank WLAN and LTE road transport communication network and in accordance with it, to perform an evaluation of the technical and economic justification of such network.
6. To determine the relationship between the throughput of the integrated WLAN and LTE communication channel and the velocity of the vehicle (mobile client). This relationship shall be determined for both the transport layer (TL) throughput and

application layer (AL) throughput (also known as goodput). Experimental measurements are required for the determination of the relationships. The obtained measurement data need to be processed using statistical data processing methods.

7. To develop a monitoring solution for the LTE part of a two-rank communication network for obtaining statistical data on the signal strength and signal quality parameters of the LTE network.
8. To study IEEE 802.11k/r/v standards. To develop a solution for the improvement of the handover procedure in the WLAN to increase the overall performance of the automotive WLAN based communication network. To perform an experimental evaluation of performance parameters within the developed solution.
9. Using the data obtained experimentally in the WLAN testbed and theoretical calculations, to evaluate the relationship between the power level of the received signal and the distance to the transmitter. To evaluate the data channel throughput depending on the distance to the transmitter. In both cases, the fluctuations of power level of the received signal shall be considered.
10. To evaluate the obtained results and to recommend the use of the integrated WLAN and LTE wireless data transmission network in road transport communication networks.

Methodology of the Research

Mathematical calculations and analytical models have been used, as well as experimental measurements were performed in the field and in laboratory conditions in the implementation of the tasks and problem analysis of the Doctoral Thesis.

For the implementation of experimental measurements, several testbeds of the road transport communication networks were developed. Wireless data transmission network equipment from various manufacturers, e. g., HP (Hewlett-Packard), Cisco, Huawei, TP-Link, was used for the measurements. The implementation of the IEEE 802.11v standard and testing of its modified version was performed using TP-Link Archer C7 WLAN routers, where the original firmware was replaced by open-source firmware *OpenWrt*.

To generate the application layer (AL) data traffic and to evaluate AL throughput or goodput, response time, and handover delay parameters, *IxChariot* software [54] was used, while transport layer (TL) data traffic was generated and measured using *iPerf* software [55].

To approximate the experimentally obtained throughput results and to model extended scenarios, the *Multi-terminal system* model was used. To develop the relationship between data transmission rate and velocity of the mobile client movement, the experimentally obtained data were approximated using linear and nonlinear regression models. Whereas the calculations of the received signal power losses were performed using the *two-ray* signal propagation model supplemented with random signal fluctuations. Therefore, to describe the relationship, a *log-normal* model was used. The *Nakagami* distribution was used to describe the received signal fluctuations.

To evaluate the obtained results, statistical methods were used, e. g., the statistical dispersion parameters were calculated, and measurement and data approximation errors were determined.

Mathematical calculations were carried out using *Matlab* software, while the statistical processing of experimental measurement results was performed using *Excel* software. *Ekahau Pro* software was used to plan and evaluate WLAN coverage. Whereas the collection and visualisation of statistical data of the signal parameters received in the LTE network part of the testbed was performed using *Zabbix* software.

Research Results and Scientific Novelty

Acquisitions of the Doctoral Thesis

1. Technical and economic justification for an integrated WLAN and LTE automotive communication network has been developed. Technical parameters such as throughput and response time have been evaluated. Whereas parameters such as the solution costs and the mobile network offloading parameter, which is a newly introduced quantity, were used as efficiency indicators.
2. Using LTE hardware from various manufacturers, a different number of clients, and by applying different movement scenarios, experimental evaluation of the performance of two-rank IEEE 802.11n and LTE communication channel was performed, as well as the degree of data traffic self-similarity was evaluated.
3. A relationship was obtained between the communication channel throughput and the velocity of the vehicle (mobile client). The relationship has been determined for both TL throughput and AL throughput.
4. *802.11v network assisted* handover procedure solution has been developed, where the IEEE 802.11v standard was modified and experimentally implemented for use in IEEE 802.11ac road transport communication networks, which makes it possible to increase the performance of such road transport wireless communication networks. As part of the developed solution, the average AL throughput in the IEEE 802.11ac road transport testbed was increased, as well as the average network response time and handover delay were reduced.
5. Using the experimental data and theoretical calculations, the power level of the received signal and throughput depending on the distance to the transmitter were evaluated for the IEEE 802.11ac communication network. In calculations, the fluctuations of power level of the received signal were considered.

Main conclusions of the Doctoral Thesis

1. The development of an integrated WLAN and LTE road transport communication network is technically and economically justified when WLAN-based, LTE-concentrated mobile network offloading is used. It is a practical automotive communication network to ensure the transmission of large amounts of data and to organise access for car passengers to the Internet.

2. The performance of a two-rank WLAN and LTE communication network depends on the technical performance parameters of the network nodes. With different LTE routers, the AL throughput of an automotive wireless network can vary by 10–20 %. Changes in velocity of the mobile client movement, the number of clients and client traffic scenarios affect both the AL throughput of individual mobile clients and the overall performance of the wireless network.
3. Irrespective of which manufacturer's LTE router is used on a two-rank IEEE 802.11n and LTE network, the nature of the data traffic is not affected. This is demonstrated by the analysis of the results of experimental measurements, where parameters such as throughput, correlation coefficient, variance, and degree of traffic self-similarity were evaluated for the data traffic flows.
4. The handover procedure between wireless access points depends on the handover algorithm implemented in the client's device, the WLAN architecture solution, and the implemented wireless network security mechanisms.
5. Depending on the velocity of the vehicle (mobile client) (0–70 km/h), the integrated IEEE 802.11n and LTE communication channel throughput changes, following the second-order polynomial function.
6. In an integrated IEEE 802.11n and LTE communication network, overheads between L7 and L4 average up to 36 % at a velocity of the mobile client from 0 km/h to 70 km/h. This means that network throughput cannot be judged solely based on measurements made in the transport (L4) or lower layers.
7. In an IEEE 802.11ac network with fast-moving objects (>20 km/h), timely decision-making and execution of the handover procedure using the IEEE 802.11v standard *BSS Transition Management Query* and *BSS Transition Management Request* messages with the developed modification can increase the total wireless network performance, i.e., average AL throughput can be increased by up to 75 % and the average network response time can be reduced by 67 %, as well as it is possible to provide lower average handover delays compared to the *Standard* handover procedure, which does not use the IEEE 802.11v standard.
8. Both the theoretical calculations and the experimental observations and measurements performed demonstrate that in the IEEE 802.11ac network, as the mobile client moves away from the transmitter, the received signal power decreases, resulting in decreased throughput. The received signal power varies and fluctuates over time, and the fluctuations of the received signal power are caused by constructive and destructive interference between the components of multipath signal propagation, which in turn causes throughput fluctuations.

Practical Value of the Doctoral Thesis

- An integrated road transport wireless network testbed using IEEE 802.11n/ac and LTE technologies has been developed and researched.

- The performance of wireless network hardware that provides two-rank IEEE 802.11n and LTE communication channels has been experimentally evaluated. The experiments were performed in an environment close to the road traffic conditions.
- New relationships characterising the performance of the combined IEEE 802.11n and LTE road transport communication network have been obtained.
- An advanced handover solution *802.11v network assisted* handover based on modification of the IEEE 802.11v standard has been developed and experimentally evaluated in the IEEE 802.11ac network, which resulted in increased overall wireless network performance.

Application of the Doctoral Thesis results

- An application for the ERDF project "Smart Connectivity Solution for Automotive Communication Networks (SCAN)", No. 1.1.1.1/20/A/007 has been prepared.
- The results can be used for technically and economically justified, integrated WLAN and 4G LTE/5G automotive communication networks, as well as for 4G LTE and 5G network offloading solutions.
- The results can be used for the preparation of a recommendation with the aim to include the implemented IEEE 802.11v modification in the IEEE 802.11 standard, which allows the provision of an efficient handover procedure solution for fast-moving clients.

Theses to be Defended in the Doctoral Thesis

1. When implementing an integrated road transport wireless communication network based on IEEE 802.11n and LTE standards, regardless of the manufacturer and the LTE hardware used, the data flow of such network communication channel does not change its nature.
2. Depending on the velocity (0–70 km/h) of the vehicle (moving object), the throughput of the integrated communication channel based on IEEE 802.11n and LTE standards changes, following the second-order polynomial function.
3. The developed *802.11v network assisted* handover procedure solution in the IEEE 802.11ac network with fast-moving objects (>20 km/h) allows the overall performance of the wireless network to be increased, i.e., allows increasing of the average throughput at the application layer by 75 % and reduction of the average network response time by 67 %; it also allows the average handover delay to be reduced.

Approbation of the Research Results

The main results of the Doctoral Thesis have been presented at 7 international scientific conferences, as well as reflected in 8 publications in scientific journals, in 4 publications in full-text conference proceedings, and in 1 chapter of a scientific monograph.

Reports at international scientific conferences

1. **Ancans A.**, Petersons E., Umanskis A. Hybrid Vehicular IEEE 802.11n and LTE Wireless Network Performance Evaluation in Non-Stationary Mode of Motion // *Advances in Wireless and Optical Communications (RTUWO)*. **Latvia**, Riga, 15–16 November 2018.
2. **Ancans A.**, Petersons E., Ipatovs A. Vehicular Wireless Network Access Controller Parameter Estimation // *Progress in Electromagnetics Research Symposium (PIERS)*. **Singapore**, Singapore, 19–22 November 2017.
3. **Ancans A.**, Bogdanovs N., Petersons E., Ipatovs A. Integrated Wireless Network Performance Estimation for Moving Vehicles // *Advances in Wireless and Optical Communications (RTUWO)*. **Latvia**, Riga, 2–3 November 2017.
4. **Ancans A.**, Petersons E. Wireless LAN and LTE Unified Data Channel Performance Evaluation at Various Types of Equipment and Measurement Methods of a Moving Object // *Riga Technical University 57th International Scientific Conference*. **Latvia**, Riga, 14–18 October 2016.
5. Ancans G., Stankevicius E., Bobrovs V., **Ancans A.** Analysis on Interference Impact of Wi-Fi on Digital Terrestrial Television Broadcasting // *Wireless Telecommunications Symposium (WTS). Global Wireless Communications: Europe and Beyond*. **Great Britain**, London, 18–20 April 2016.
6. **Ancans A.**, Petersons E., Ipatovs A. Development of a Measurement System for Evaluation of Heterogeneous Wireless Networks Performance Parameters // *Riga Technical University 56th International Scientific Conference*. **Latvia**, Riga, 14–16 October 2015.
7. **Ancans A.**, Ipatovs A. Analysis of Routing Protocols in Wireless Networks with Moving Objects // *Riga Technical University 55th International Scientific Conference*. **Latvia**, Riga, 14–16 October 2014.

Chapter in the scientific monograph

1. Jerjomins R., **Ancans A.**, Petersons E., Gerina-Ancane A. Improving Handover Mechanism in Vehicular WiFi Networks. In: *ICTE in Transportation and Logistics 2019, Lecture Notes in Intelligent Transportation and Infrastructure (ICTE ToL 2019, LNITI).* Ginters E., Ruiz Estrada M., Piera Eroles M., eds. **Switzerland**, Cham: Springer, 2020, pp. 243–261.

Publications in scientific journals

1. **Ancans A.**, Petersons E., Jerjomins R., Grabs E., Ancans G., Ipatovs A. Evaluation of received signal power level and throughput depending on distance to transmitter in testbed for automotive WLAN IEEE 802.11ac communication network // *Latvian Journal of Physics and Technical Sciences* (accepted for publication).

2. **Ancans A.**, Petersons E., Ancans G., Stetjuha M., Ipatovs A., Stankevicius E. Technical and Economic Analysis of Transport Telecommunication Infrastructure // *Procedia Computer Science*. 2019, No. 149, pp. 206–214.
3. **Ancans A.**, Petersons E. The Relationship between Transport Wireless Network Throughput and Vehicle Speed // *Automatic Control and Computer Sciences (AC&CS)*. 2018, Vol. 52, Iss. 4, pp. 297–305.
4. Ancans G., Stafecka A., Bobrovs V., **Ancans A.**, Caiko J. Analysis of Characteristics and Requirements for 5G Mobile Communication Systems // *Latvian Journal of Physics and Technical Sciences*. 2017, Vol. 54, Iss. 4, pp. 69–78.
5. Ancans G., Bobrovs V., **Ancans A.**, Kalibatiene D. Spectrum Considerations for 5G Mobile Communication Systems // *Procedia Computer Science*. 2017, Vol. 104, pp. 509–516.
6. **Ancans A.**, Bogdanovs N., Petersons E., Ancans G., Umanskis A., Vishnevskiy V. Evaluation of Wi-Fi and LTE Integrated Channel Performance with Different Hardware Implementation for Moving Objects // *Procedia Computer Science*. 2017, Vol. 104, pp. 493–500.
7. Ancans G., Stankevicius E., Bobrovs V., **Ancans A.** Analysis on Interference Impact of Wi-Fi on Digital Terrestrial Television Broadcasting // *International Journal of Interdisciplinary Telecommunications and Networking (IJITN)*. 2016, Vol. 8, Iss. 1, pp. 35–44.
8. Bogdanovs N., **Ancans A.**, Martinsons K., Petersons E. Estimating the Speed of an Integrated Wireless Network for Transportation Applications // *Automatic Control and Computer Sciences (AC&CS)*. 2014, Vol. 48, Iss. 5, pp. 274–281.

Publications in full-text conference proceedings

1. **Ancans A.**, Petersons E., Umanskis A. Hybrid Vehicular IEEE 802.11n and LTE Wireless Network Performance Evaluation in Non-Stationary Mode of Motion // *Proceedings of Advances in Wireless and Optical Communications (RTUWO)*. Latvia, Riga, 15–16 November 2018, pp. 213–213.
2. **Ancans A.**, Petersons E., Ipatovs A. Vehicular Wireless Network Access Controller Parameter Estimation // *Progress in Electromagnetics Research Symposium (PIERS)*. Singapore, 19–22 November 2017, pp. 2152–2159.
3. **Ancans A.**, Bogdanovs N., Petersons E., Ipatovs A. Integrated Wireless Network Performance Estimation for Moving Vehicles // *Proceedings of Advances in Wireless and Optical Communications (RTUWO)*. Latvia, Riga, 2–3 November 2017, pp. 203–207.
4. Ancans G., Stankevicius E., Bobrovs V., **Ancans A.** Analysis on Interference Impact of Wi-Fi on Digital Terrestrial Television Broadcasting // *Proceedings of Wireless Telecommunications Symposium (WTS). Global Wireless Communications: Europe and Beyond.* United Kingdom, London, 18–20 April 2016, p. 13.

Scope and Structure of the Doctoral Thesis

The total number of pages of the Doctoral Thesis is 141. It contains five chapters, conclusions, the bibliography, and nine appendices.

The introduction of Chapter 1 presents the main trends justifying the topicality of the research. It is followed by an overview of ITS systems and a description of the key issues that these systems address. Possible ITS development directions are given as well as a review of prospective communication network technologies. Trends that justify the selection of wireless communication technologies included in the research have been presented in the chapter. The main problems existing in the automotive wireless communication networks, when WLAN IEEE 802.11n/ac and LTE technologies are used, are discussed below, as well as a review of similar research is provided. At the end of the chapter, the main research directions of the Doctoral Thesis are defined, and the summary of the work performed within the framework of the Doctoral Thesis is also given.

A review of the WLAN and LTE technologies has been performed in Chapter 2 of the Doctoral Thesis. Issues such as the convergence of WLAN and LTE networks are studied with the aim of increasing the mobility of WLAN clients and a detailed study of the available security mechanisms in WLAN networks has also been carried out. The performance of experimental road transport networks based on IEEE 802.11n and LTE technologies have been evaluated further in the chapter. The performance of the wireless network is also evaluated for a stationary case, using a mathematical model of the *Multi-terminal system*. Technical and economic justification of a heterogeneous two-rank Wi-Fi and LTE road transport communication network is presented at the end of the chapter.

The developed relationships between the integrated IEEE 802.11n and LTE communication channel TL throughput or AL throughput and velocities of vehicle (mobile client) movement are demonstrated in Chapter 3 of the Doctoral Thesis. Within the framework of the chapter, a solution for monitoring the LTE technology signal strength and signal quality parameters has been developed. An analysis of the obtained results is given in the chapter.

IEEE 802.11k/r/v standards, which can be used to improve the handover procedure in IEEE 802.11ac networks, are evaluated within the framework of Chapter 4. The chapter is continued with a description of the developed advanced handover algorithm based on the IEEE 802.11v standard. An experimental performance evaluation of the developed solution and analysis of the obtained results is included in the chapter as well.

In Chapter 5, the relationship between the power level of the received signal and the distance to the transmitter is evaluated. The calculations use a *log-normal* model, which takes the fluctuations of the received signal into account, characterised by the *Nakagami* distribution. Using the Shannon's theorem and previous calculations, the throughput of the WLAN as the mobile client moves away from the transmitter is theoretically estimated. The theoretically calculated throughput results are compared with the experimentally obtained data at the end of the chapter.

The main conclusions of the research are summarised and further research directions are defined at the end of the Doctoral Thesis. Lists of conferences, publications, and projects, the results of experimental measurements, the *Matlab* codes used in the calculations, the technical specification data of the equipment used in the implemented testbeds, and the main settings for the measurements are included in the appendices.

CONTENT OF THE DOCTORAL THESIS

Chapter 1

An assessment of the development directions of transport communication networks and the main trends and problems are discussed in the **first chapter** of the Doctoral Thesis.

Sub-chapter 1.1 includes an overview of ITS systems and it can be concluded that ITS applications include road participants (vehicles, their passengers, and pedestrians), road transport infrastructure, traffic management, and communication solutions for the remote data service systems [31]. There are three main groups of services where ITS can be used: 1) road safety and warning; 2) traffic flow management and transport system services; 3) infotainment [44], [47], [48].

The category of infotainment services applies specifically to the vehicle passengers who need to have access to the Internet. Infotainment services shall be segregated from the road safety, warning, and transport system service functions to avoid affecting these critical features [47].

Several ITS projects are currently being developed around the world, using various transport communication network technologies that provide Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) data exchange. One of the ITS transport communication network technologies is dedicated short range communications, whereas the leading technologies, Wireless Access in Vehicular Environment (WAVE) and intelligent transport system technology ITS-G5 should also be mentioned [52]. These technologies are based on the IEEE 802.11p standard [48]. The main disadvantages of the technologies based on the IEEE 802.11p standard are the relatively low throughput and the fact that the overall performance of the network decreases as network congestion increases [52]. It is planned that IEEE 802.11p will be replaced by a new standard IEEE 802.11bd in the future [13], [90]. Several other current WLAN (Wireless Local Area Network) standards are also considered for the provision of certain ITS functions: IEEE 802.11n [28], IEEE 802.11ac [28], and IEEE 802.11ax [19], [22], as well as the IEEE 802.11be that is currently under development [34].

The technologies that use mobile cellular networks can also be used to provide ITS functions. The developed LTE C-V2X (Cellular Vehicle-to-Everything) technology is designed to work on an LTE network, while the 5G C-V2X technology currently under development, also referred to as 5G NR-V2X, is designed to work on a 5G network [17]. Mobile network technologies such as 4G LTE or LTE (Long Term Evolution) [20], [32] and the 5G technology [10], [17], [35] can also be used to meet specific ITS needs. 5G wireless access includes both 5G NR (New Radio) and the advanced versions of the LTE (LTE Evolution) [9]. 5G radio networks are expected to consist of networks based on NR and LTE technology [20], [51], as well as on WLAN technologies [24].

The existing ITS systems (ITS-G5/WAVE, LTE-V2X) are not designed to provide Internet access to the vehicle passengers for the transmission of large data amounts [14], [15]. The forecast for Wi-Fi traffic demonstrates that 51 % of the total IP (Internet Protocol) traffic will flow through the Wi-Fi network by 2022, compared to 43 % in 2017. Data traffic will be provided both by mobile dual-mode smart devices and Wi-Fi only devices [18]. By 2022, the offloaded traffic from mobile devices is projected to increase to approximately 59 %, where data traffic transmitted from mobile devices is routed via Wi-Fi networks or femtocells [16], [18].

A combined block scheme of transport communication network technologies (Fig. 2) has been developed in accordance with the ITS technologies discussed above and the evaluation of the forecasts for data traffic by access technology and trends in how mobile networks will be offloaded.

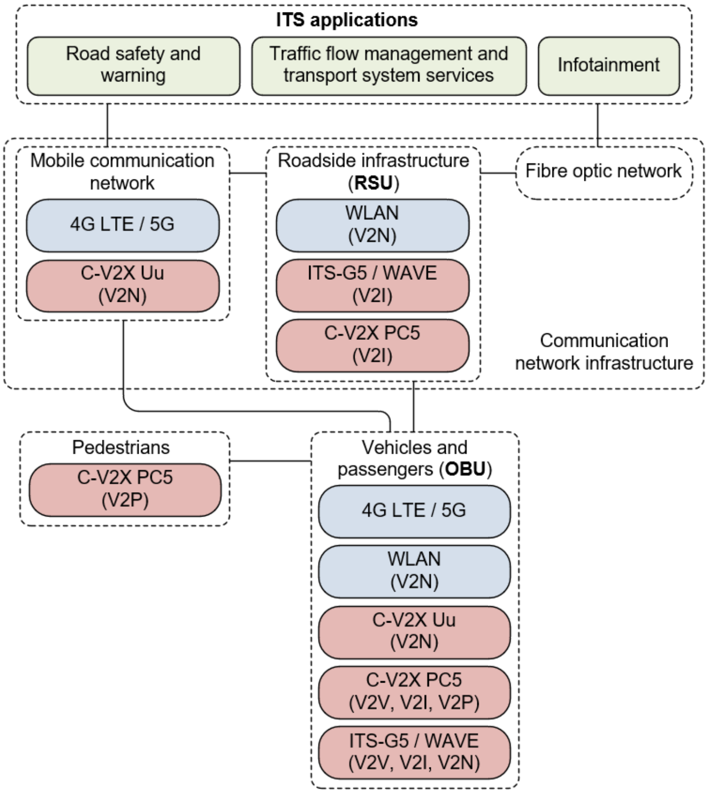


Fig. 2. Combined scheme of ITS communication network technologies.

The analysis of the above facts and trends on current wireless network technologies allows one to conclude that IEEE 802.11n/ac (WLAN) technologies can be used to provide road vehicle passengers with access to the Internet. Therefore, a combination of the considered individual communication technologies can be used to provide complete ITS services.

The main problems arising from the use of WLAN technology for mobile client access to the data network are related to the decrease in performance (throughput) with increasing velocity of mobile client movement [12]. This is mainly related to the execution of the client handover procedure between the AP (Access Point), which becomes unstable as driving speed increases and may have a latency.

In practice, a two-rank communication network is used, where the WLAN access network is in the first rank and 4G LTE or 5G technology or the fibre optic network can be used in the second rank. Therefore, a performance evaluation is also needed for a two-rank communication network.

In Sub-chapter 1.2, it is demonstrated that scientists around the world are working on new research projects related to the capability of the IEEE 802.11 standard technology to provide broadband wireless data transmission channels, both to enable vehicle passengers to access the Internet, and to provide vehicles with a wireless data transmission connection for solving various specific tasks [33], [36]–[38], [41], [42]. One of the key performance parameters evaluated in the analysed studies is the throughput of data channels. However, there have been no previous studies that have experimentally investigated the relationships between the throughput of automotive communication networks and the velocity of a mobile user, using different wireless network hardware, different movement scenarios, and changing the number of clients. Also, all previous studies related to the improvement of the handover procedure in WLAN automotive communication networks using IEEE 802.11k/r/v standards are theoretically justified but have not been experimentally verified.

Chapter 2

In the **second chapter** of the Doctoral Thesis, the two-rank wireless communication networks are studied, with the first rank formed by the IEEE 802.11n technology and the second rank formed by the LTE technology. The performance of such networks and possibilities to use them for automotive communications are evaluated experimentally.

An overview of WLAN technologies including issues related to security mechanisms is given in **Sub-chapter 2.1.** It is concluded that the performance of wireless network and the nature of data traffic is affected by 802.11 MAC (Medium Access Control) layer incremental data transmission rate adjustment at the beginning of session and 802.11 MAC layer retransmission mechanism of lost frames. Wireless network performance and the nature of traffic are also affected at the TCP (Transmission Control Protocol) layer, where flow control and network congestion control algorithms that are executed throughout the session are implemented; therefore, as a result, these algorithms, and in particular the TCP slow-start mechanism, significantly reduce the AL throughput (goodput) [26], [46], [49]. In the 802.11 MAC layer, where the scanning, open system authentication and association procedures are performed, the scan procedure contributes to the largest input for the increase in handover delay. It accounts for up to 90 % of the total delay of all these procedures [21], [27], [40].

In transport IEEE 802.11 networks, it is recommended to move to the centralised WLAN management using Wireless LAN Controllers (WLCs). The centralised WLAN management facilitates the maintenance of wireless networks through control plane functions, as well as offers a unified level of security and ensures the coordinated operation of control plane functions [28]. The WLAN security mechanisms used to authenticate mobile clients have an impact on handover delay, which is particularly critical in automotive communication networks. A dialogue between the wireless network controller and the authentication server, as well as the generation and exchange of cryptographic keys between the client and the AP or WLC can take a considerable amount of time [19], [22]. This shall be considered when designing automotive communication networks. In automotive communication networks with a centralised WLAN architecture, it is recommended to implement WPA2-Enterprise or WPA3-Enterprise security mechanisms that currently provide the highest level of security in wireless networks, to be integrated with fast handover procedure solutions [1], [19]. To ensure a seamless handover procedure, the time-consuming DHCP (Dynamic Host Configuration Protocol) procedure shall be avoided, and the client shall be provided with an option to save the IP address [22].

A review of LTE technology is provided in **Sub-chapter 2.2**, whereas in **Sub-chapter 2.3**, it is established that solutions for combining WLAN and mobile network technologies (LTE or 5G) can provide the necessary mobility in WLAN-based automotive networks, in places where WLAN coverage is not available. This approach allows the overall capacity of mobile networks to be increased and ensures the offloading of base mobile network technologies as well. Solutions such as LTE-U (LTE in Unlicensed) / LAA (Licensed Assisted Access) [50], LWA (LTE–Wi-Fi Link Aggregation), and MPTCP (Multipath TCP) [39] can be used.

The performance of a two-rank IEEE 802.11n and LTE automotive communication network (Fig. 3) was studied and experimental measurements in field conditions [2] were performed in **Sub-chapter 2.4**. The testbed configuration allows data transmission not only in the WLAN network, but also via the public mobile LTE network to the remote FTP (File Transfer Protocol) server. AL throughput measurements were performed between the remote server and the IEEE 802.11n mobile client. A portable workstation placed in a vehicle was used as a mobile wireless network client.

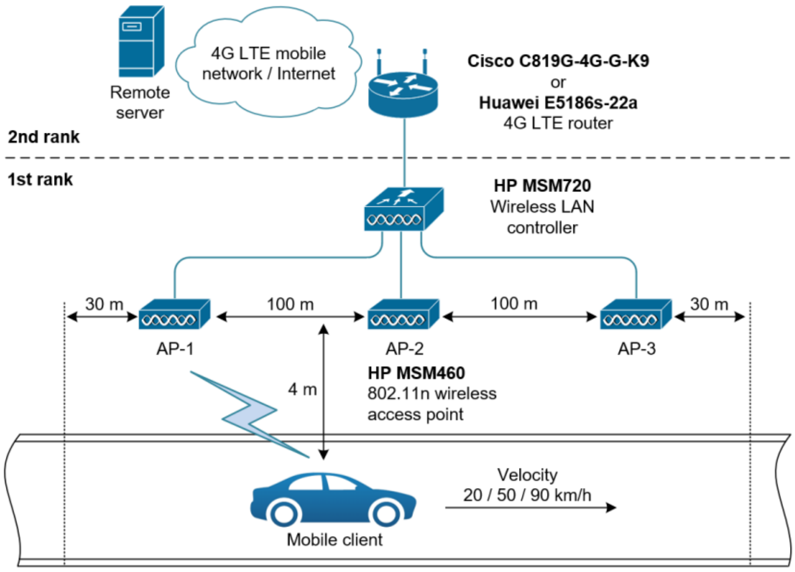


Fig. 3. Network topology of testbed.

LTE routers from two different manufacturers (Cisco and Huawei) were used to evaluate the potential impact on the integrated Wi-Fi and LTE channel AL throughput. Measurements were performed with the same vehicle at different velocities (0 km/h, 20 km/h, 50 km/h, and 90 km/h).

Several factors can affect overall network performance and the nature of the traffic, e.g., the performance of the individual hardware used, which depends on parameters such as processor performance, buffer size, and supported IEEE 802.11 and mobile cellular network standards. As the velocity of vehicles increases, the mobile client is forced to perform handover procedures between wireless access points more often. Therefore, the time of active data transmission in the AP zone decreases and proportionally more time is spent on the organisation and execution of the handover procedure, which results in the decrease of average throughput. In addition, there are possible influences from various external sources. At higher movement velocities, the reflection of radio waves is intensified. Therefore, the likelihood that client data may be lost or corrupted is increased.

According to the obtained experimental results (Fig. 4), it can be concluded that the performance of the Wi-Fi and LTE integrated communication channel depends on the technical parameters of the LTE router used, and they may have different interference immunity. With different LTE routers, the AL throughput of an automotive wireless network can vary by 10–20 %. The average AL throughput of a data connection depends on the duration of the handover procedures. At a mobile client's velocity of 20 km/h, the handover procedure between wireless access points is performed properly. At higher velocities, the AL throughput degrades and at 90 km/h, the handover procedure between the APs becomes unstable.

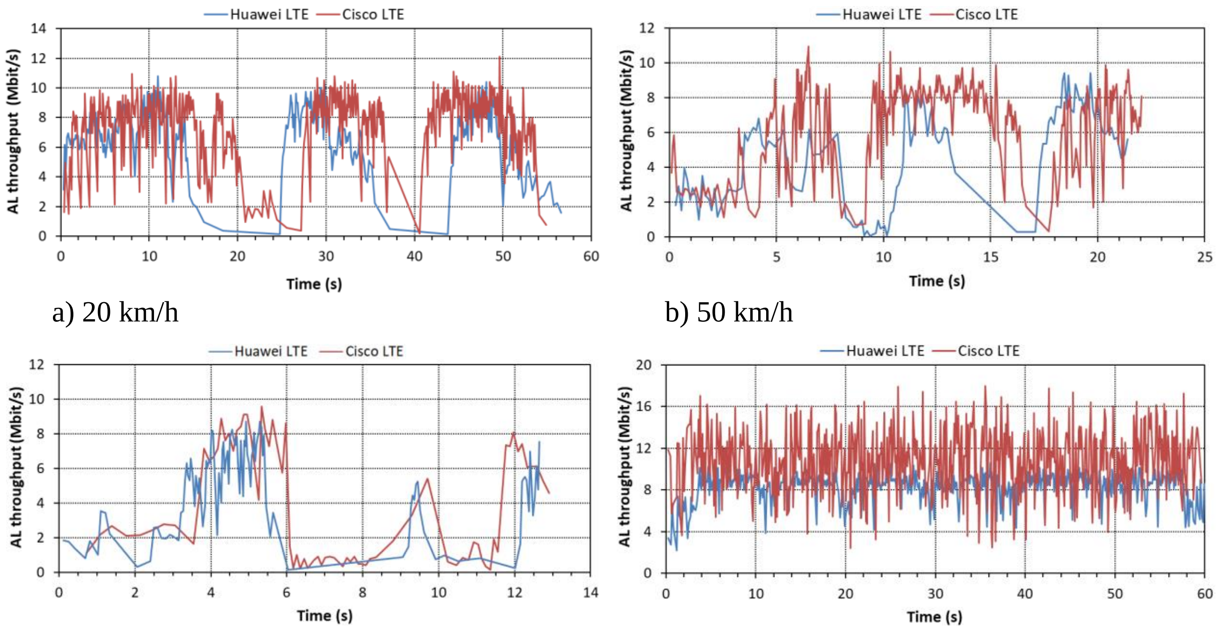


Fig. 4. Comparison of AL throughput using various LTE hardware at various client movement velocities.

In Sub-chapter 2.5, similarly to Sub-chapter 2.4, a testbed of a two-rank IEEE 802.11n and LTE automotive communication network where its performance was studied at different numbers of mobile customers and different traffic scenarios was implemented [3]. In this case, one or two mobile clients (vehicles) and one or two remote servers were used. The rest of the testbed configuration remained unchanged during the measurements. AL throughput measurements were performed with one and two mobile clients at various velocities (20 km/h and 50 km/h). Calculated average AL throughput values $\bar{\eta}$ and variance D for traffic flows η_{A1} and η_{A2} of individual customers A1 and A2, respectively, $\bar{\eta}_{A1}$ and $D_{\eta A1}$, as well as $\bar{\eta}_{A2}$

and $D_{\eta A2}$ are presented in Table 1. The total average AL throughput between the two clients was then calculated $\bar{\eta}_{A1A2}$, as well as the correlation coefficients $K_{\eta A1 \eta A2}$ between the sets of AL throughput values of the two clients. The total variance was also determined $D_{\eta A1 \eta A2}$.

The moment vehicles move along the Wi-Fi infrastructure and roam from one AP coverage area to another, data traffic drops. The AL throughput decreases from the maximum values to zero, and when the handover process is completed, the AL throughput gradually increases again to its maximum values. As fluctuations in the AL throughput values are large, the variance values are large as well.

Table 1

Experimentally Obtained Average AL Throughput and Calculated Values of Correlation Coefficient and Variance

Velocity *v*, km/h	**Movement scenario**	**$\bar{\eta}$, Mbit/s**		**Total**	$K_{\eta A1 \eta A2}$	***D***		**Total**
		$\bar{\eta}_{A1}$	$\bar{\eta}_{A2}$	$\bar{\eta}_{A1A2}$, **Mbit/s**		$D_{\eta A1}$	$D_{\eta A2}$	$D_{\eta A1 \eta A2}$
20	**one following another**	4.70	5.67	5.19	–0.06	8.28	5.50	13.66
	in parallel	6.68	4.12	5.40	0.14	7.17	5.14	12.59
	one towards another	7.15	5.99	6.57	0.21	9.99	4.10	14.51
50	**one following another**	4.25	4.41	4.33	0.19	4.06	5.31	9.75
	in parallel	7.90	3.23	5.57	0.38	10.96	4.71	16.43
	one towards another	6.30	5.64	5.97	–0.23	5.53	9.32	14.39

In Table 1, it is demonstrated that there is a correlation between the AL throughput of the clients of both vehicles, however, it is weak ($K_{\eta A1 \eta A2} < 0.5$) [11]. This is related to the fact that both vehicle clients use the same wireless network resources (AP and WLC). As the resource capacity of the automotive Wi-Fi based communication network implemented in the testbed is intended for a large number of clients, it can be expected that with an increase in the number of clients, the correlation coefficient will also increase.

After the analysis of the experimentally obtained AL throughput results, it can be concluded that the AL throughput depends on the mobile client movement scenarios, on the velocity of the client movement, and on the number of mobile clients simultaneously located in the AP service area. This affects both the individual AL throughput of mobile clients and the overall performance of the wireless network. The simultaneous presence of several mobile clients in a wireless network means a struggle for the wireless network resources. This is also reflected in the obtained measurement graphs in the form of irregular traffic drops and decreased average AL throughput.

In Sub-chapter 2.6, similar to Sub-chapters 2.4 and 2.5, a two-rank IEEE 802.11n and LTE automotive communication network testbed was implemented. By using the *Absolute Moments* method, the *Hurst* parameter (*H*) was evaluated and analysed for the experimentally obtained AL throughput traffic, in scenarios with one and two mobile clients (an appropriate number of remote FTP servers was provided) at various vehicle velocities: 20 km/h, 50 km/h, and 90 km/h [6]. The experimentally obtained results demonstrate that as the number of users in the wireless network increases, the Hurst parameter changes in the range of 0.7–0.89, therefore, it can be concluded that the data traffic transmitted in the measurements is self-similar. It is expected that as the number of mobile clients continues to increase, the H parameter will increase as well.

In **Section 2.7**, the total AL throughput of the wireless network was evaluated experimentally and analytically, depending on the amount of incoming data flows of clients in static mode. The individual AL throughput for one client at various numbers of clients was determined as well. The testbed consisted of one AP and two workstations, i.e., a server and a client or performance endpoints, which generate individual data flows of clients (from 1 to 4) (Fig. 5).

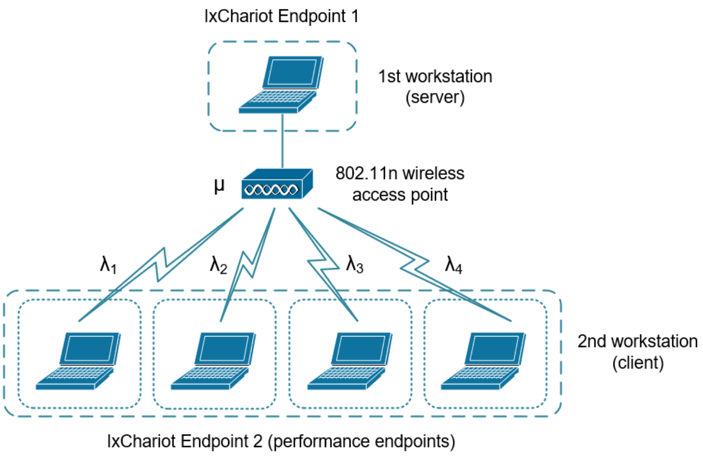


Fig. 5. Scheme of experimental measurements.

The mathematical model of the *Multi-terminal system* was used for the theoretical evaluation [6]. The network performance (AL throughput) in accordance with this model can be given as:

$$\eta = (1 - p_0)\mu, \tag{1}$$

$$\eta_1 = (1 - p_0)\frac{\mu}{M}, \tag{2}$$

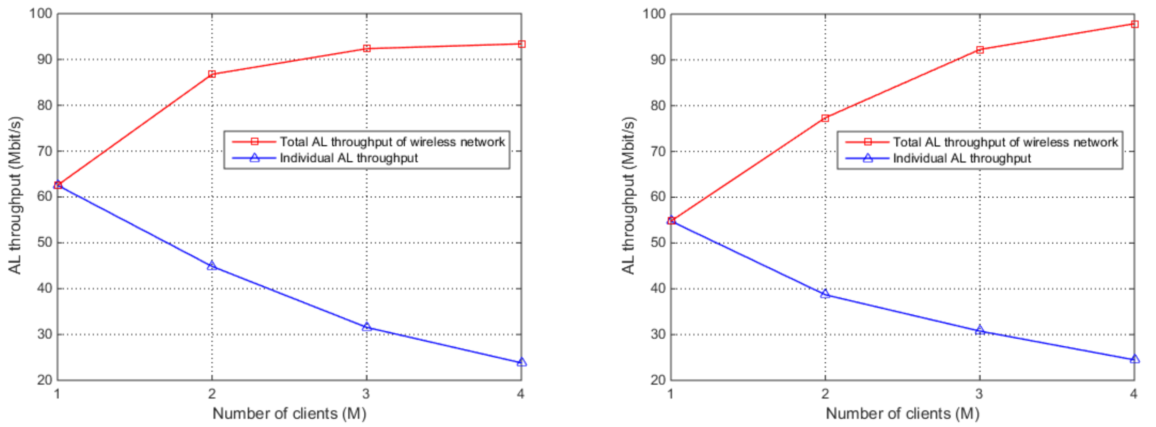
$$p_0 = \left[\sum_{k=0}^{M} \frac{M!}{(M-k)!}\left(\frac{\lambda}{\mu}\right)^k\right]^{-1} = \left[\sum_{k=0}^{M} \frac{M!}{(M-k)!}\rho^k\right]^{-1}, \tag{3}$$

where λ is the intensity of incoming requests; μ is the processing intensity of the requests; p_0 is the probability that the channel is free, i.e., the system will not receive requests; η_1 is the AL throughput of one client depending on the number of clients M; ρ is the network load factor.

By applying the considered model, the throughput of the automotive wireless communication network and its dependence on the number of incoming flows in the AP coverage area can be determined. Figs. 6 (a) and (b) summarise the experimentally obtained results of the AL throughput and the results calculated using the *Multi-terminal system* model.

The individual AL throughput for one client and the total wireless network AL throughput at various numbers of clients was determined. From the obtained results, it can be concluded that the difference between the experimental and the analytical data is within 16 %.

It can be seen from Figs. 6 (a) and (b) that the individual AL throughput per client decreases as the number of clients in the network increases. The customer's individual throughput depends on the performance of each customer's hardware. Whereas the total wireless network AL throughput increases with the increase of the number of wireless clients, as the performance of wireless network nodes is designed for a large number of clients. Due to the operation of the TCP mechanism, the increase in AL throughput is nonlinear. As the number of clients continues to grow, the upper limit of the performance of network node (AP) is reached.

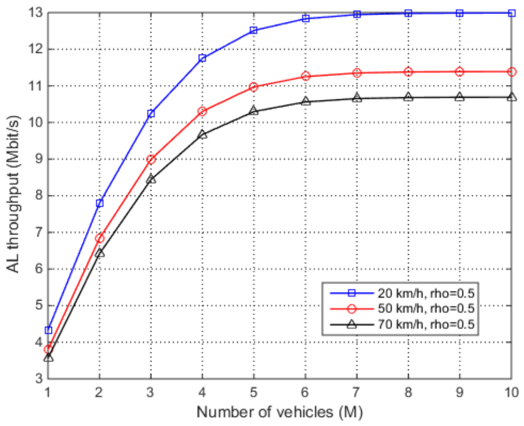


a) Experimental measurements b) Mathematical model

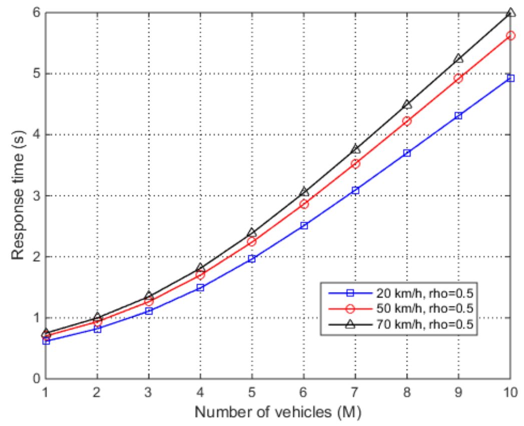
Fig. 6. The determined relationships between the total and individual AL throughput and the number of clients.

Technical and economic justification of an integrated Wi-Fi and LTE communication channel and direct LTE channel was carried out within the framework of **Sub-chapter 2.8**. Technical characteristics such as the AL throughput [4] and response time, efficiency indicators such as the cost and mobile network offloading parameter were also determined in the evaluation. Technical parameters were evaluated for the integrated Wi-Fi–LTE channel only [5]. The experimental AL throughput results of the two-rank vehicle communication network were used in the Sub-chapter. For the approximation of the experimental results for the general case and the determination of the AL throughput η of the system as well as the average response time $\overline{T}$, the *Multi-terminal system* model was used. The network performance, in this case, the AL throughput η in accordance with the model used, can be determined by the expression (1).

In Fig. 7 (a), the obtained relationship between the network AL throughput η and the number of vehicles (clients) M at various movement velocities v (20 km/h, 50 km/h, and 70 km/h) and the network load factor $\rho = 0.5$ is shown. It can be seen from the obtained results, that the maximum system AL throughput is obtained when $M = 9$.



a)



b)

Fig. 7. (a) AL throughput of the two-rank wireless network depending on the number of vehicles, velocity, and network load; (b) Average response time depending on the number of vehicles, velocity, and network load.

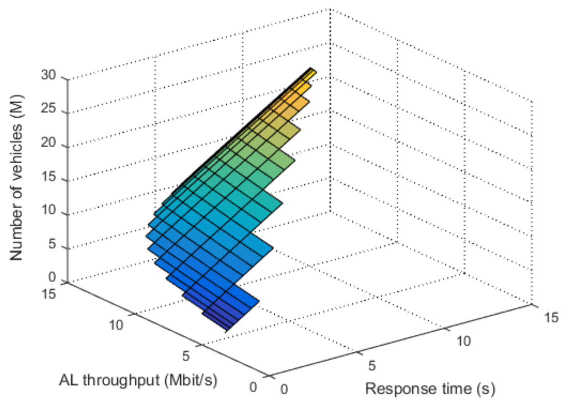
In accordance with [13], the system average response time is:

$$\overline{T} = \frac{M}{\mu(1 - p_0)} - \frac{1}{\lambda}. \tag{4}$$

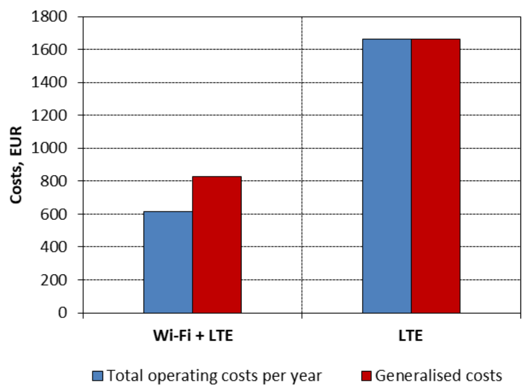
In Fig. 7 (b), the obtained relationship between the average response time $\overline{T}$ and the number of vehicles (clients) M at different movement velocities, as well as the network load factor $\rho = 0.5$ is shown.

The relationship of the AL throughput and the response time depending on the number of vehicles (clients) on the road is shown in Fig. 8 (a) ($v = 20$ km/h; $\rho = 0.2$; $M = 26$).

The estimated costs of the automotive telecommunication networks studied are given in Fig. 8 (b). In the case of 6 clients, where the direct LTE channel is allocated to each client, the total and generalised costs of these LTE connections exceed infrastructure construction and maintenance costs of Wi-Fi and LTE based solution in a 260 m long road section, where single LTE connection is used.



a)



b)

Fig. 8. (a) Dependence of such technical parameters as AL throughput and response time on the number of vehicles; (b) The costs of automotive communication networks.

Wi-Fi based and LTE concentrated offloading allows to unload the mobile network and reduces the annual total costs of the road transport communication network. The analysis of technical and economic justification results for the direct LTE channel and integrated Wi-Fi and LTE communication channel allows the conclusion to be made that the use of a hybrid Wi-Fi and LTE automotive communication network for large data transmission such as updating route maps or transmitting video information, as well as providing vehicle passengers with access to the Internet, is technically and economically justified.

Chapter 3

In the **third chapter** of the Doctoral Thesis, the performed experimental measurements, the processing of the obtained measurement results, and the approximation of data for obtaining the relationship between the throughput of the transport communication network and the velocity of the vehicle is described.

In Sub-chapter 3.1, the prepared testbed for experimental measurements (Fig. 9) and methodology of measurements are described. Both the TL throughput and AL throughput [4], [8] were evaluated during the experimental measurements. *iPerf* (*TCP* traffic) and *IxChariot* (*FTP* traffic) software were used to determine the maximum TL throughput and AL throughput, respectively.

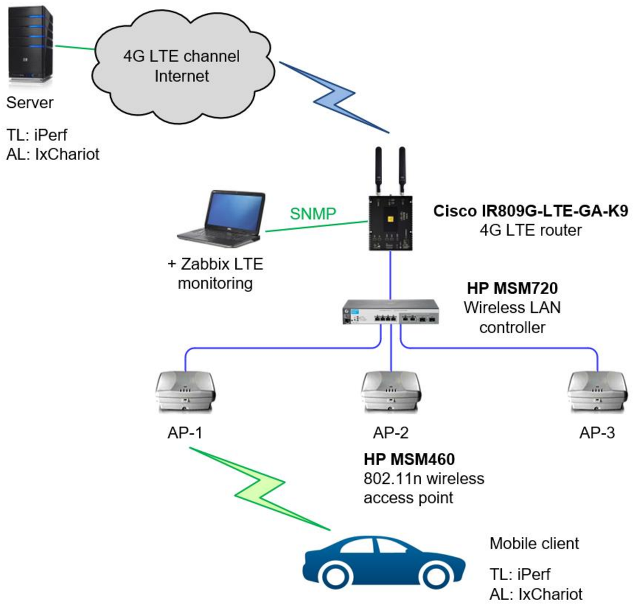


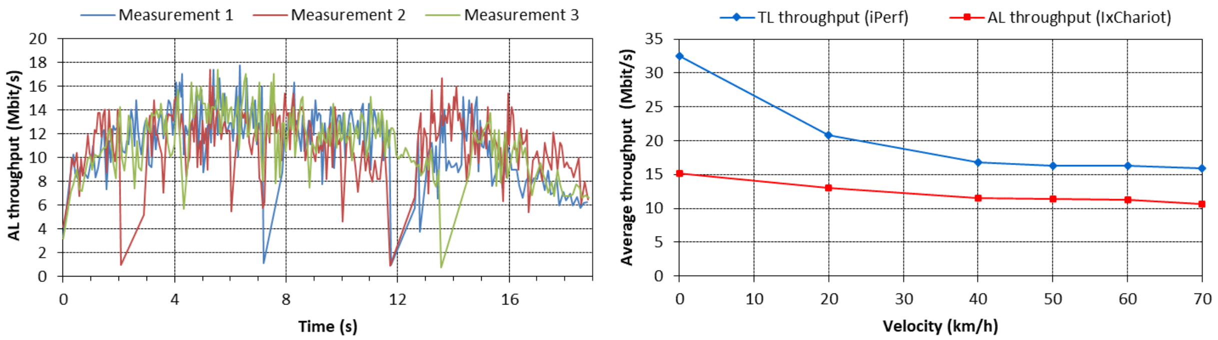
Fig. 9. Network topology of testbed.

In all measurements, one vehicle (mobile client) was used. The measurements were performed at different velocities of the vehicle: 0 km/h, 20 km/h, 40 km/h, 50 km/h, 60 km/h, 70 km/h.

In **Sub-chapter 3.2**, a solution for monitoring the LTE technology signal strength and signal quality parameters in the *Zabbix* monitoring system has been developed [56]. A monitoring template of LTE signal parameters was developed for a Cisco LTE router, where data acquisition is performed using SNMP (Simple Network Management Protocol) protocol.

With this solution, the signal strength of the LTE mobile network RSSI (Received Signal Strength Indicator) and the mobile network quality parameters RSRP (Reference Signal Received Power), RSRQ (Reference Signal Received Quality), and SINR (Signal to Interference Noise Ratio) have been monitored. The used Packet Service or mobile network access technology and Cell ID have been monitored as well.

In Sub-chapter 3.3, the results of experimental measurements are summarised and evaluated. As an example, the results of AL throughput measurements obtained with *IxChariot* software at a mobile client movement velocity of 50 km/h are shown in Fig. 10 (a).



a) b)

Fig. 10. (a) AL throughput measurement results at vehicle velocity of 50 km/h; (b) The average determined TL throughput and AL throughput of the communication channel depending on the velocity of the vehicle.

In Table 2, the information on the average data transmission rates obtained in the experimental measurements in the two-rank communication network, depending on the vehicle velocity and the software used, is summarised.

Table 2

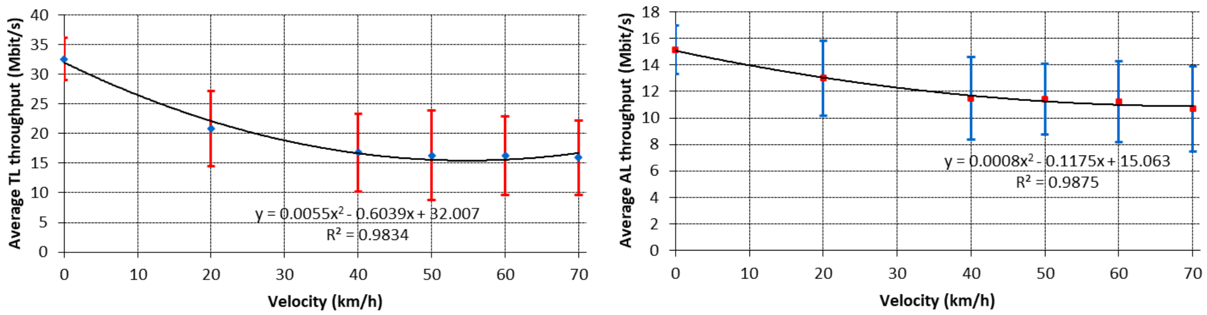
Average Throughput Depending on the Velocity of a Vehicle in the Two-rank Network

Vehicle velocity *v*, km/h	**Average throughput and errors**						**Percentage difference, %**
	Average TL throughput $\bar{\varphi}$ *(iPerf)*, Mbit/s	**Average standard error $s_{\bar{\varphi}}$, Mbit/s**	**Average relative standard error $s_{\bar{\varphi}\%}$, %**	**Average AL throughput $\bar{\eta}$ *(IxChariot)*, Mbit/s**	**Average standard error $s_{\bar{\eta}}$, Mbit/s**	**Average relative standard error $s_{\bar{\eta}\%}$, %**	
0	32.56	±0.46	1.43	15.11	±0.06	0.37	54
20	20.86	±0.91	4.34	12.99	±0.10	0.79	38
40	16.78	±1.30	7.82	11.48	±0.18	1.70	32
50	16.32	±1.74	10.81	11.39	±0.17	1.50	30
60	16.25	±1.60	10.10	11.24	±0.22	1.90	31
70	15.93	±1.68	10.62	10.69	±0.24	2.24	33

Summarising (Table 2) the calculated average TL throughput and AL throughput values, the obtained relationships for the average dependence of TL throughput and AL throughput on the velocity of mobile client's movement are shown in Fig. 10 (b). When processing and analysing the experimentally obtained data of AL throughput (OSI (Open System Interconnection) Layer 7 (L7)) and TL throughput (OSI Layer 4 (L4)), the introduced OSI model interlayer overheads have been determined. The overheads between L7 and L4 averaged up to 36 % at the velocities of a mobile client from 0 km/h to 70 km/h. Overheads are caused by header, acknowledgment (ACK) messages, and the TCP retransmission mechanism introduced by these layers. The main reasons for the organised retransmission of data over the network by the TCP protocol are data transmission errors and data traffic congestions in the network, which lead to the loss of data packets [45].

Using linear and nonlinear regression models, the experimentally obtained data were approximated to determine the function that best describes the obtained measurement data (Table 2 and Fig. 10 (b)), i.e., which gives the smallest approximation error. This allows one to conclude, according to which law the average values of TL throughput and AL throughput change depending on the velocity of movement; thus a new relationships will be obtained.

By evaluating the obtained approximation quality and accuracy (approximation error) criteria – coefficient of determination R^2, the sum of squared residuals SSR, and the mean squared error (MSE), it can be concluded that the best approximation results for the measurement data of the average TL throughput and the average AL throughput are obtained by a polynomial function (Figs. 11 (a) and (b)).



a) Approximation with a polynomial function b) Approximation with a polynomial function

Fig. 11. Approximation of experimental data for the average (a) TL throughput and (b) AL throughput.

It is concluded that the values of network average TL throughput and AL throughput depending on the movement velocity vary in a similar way, and the experimentally obtained relationships are most accurately described with a minimal error by the second-order polynomial function:

$$y(x) = Ax^2 + Bx + C, \tag{5}$$

where y is total network throughput (TL throughput or AL throughput), x is the movement velocity v, and A, B, C are the polynomial function coefficients.

The obtained approximation function is quadratic, and for data approximation, the downward segment of the approximation curve (parabola) is used, where the extreme is at the bottom at movement velocities from 0 km/h to 70 km/h.

Chapter 4

In the **fourth chapter of the** Doctoral Thesis, the improvement of the WLAN handover procedure and the evaluation of the obtained implementation is described.

In Sub-chapter 4.1, a review of IEEE 802.11k/r/v standards is provided [36], [42]. The IEEE 802.11v standard *BSS Transition Management Query*, *BSS Transition Management Request*, and *BSS Transition Management Response* message formats are discussed in detail [29].

In **Sub-chapter 4.2,** new handover algorithms based on a modified IEEE 802.11v standard were developed [30]. Summarised *Standard*, developed *802.11v network directed* (manual) and *802.11v network assisted* scheme of handover algorithms is shown in Fig. 12. In the experimental measurements, each algorithm was tested separately.

The main difference and efficiency of the developed *802.11v network assisted* handover solution in comparison with the *Standard* handover solution lies in two aspects: 1) the associated AP sends information regarding the next AP to the client, thus the client does not have to spend time on network scanning; 2) the associated AP sends a special command to the client to carry out the mandatory handover to the new AP.

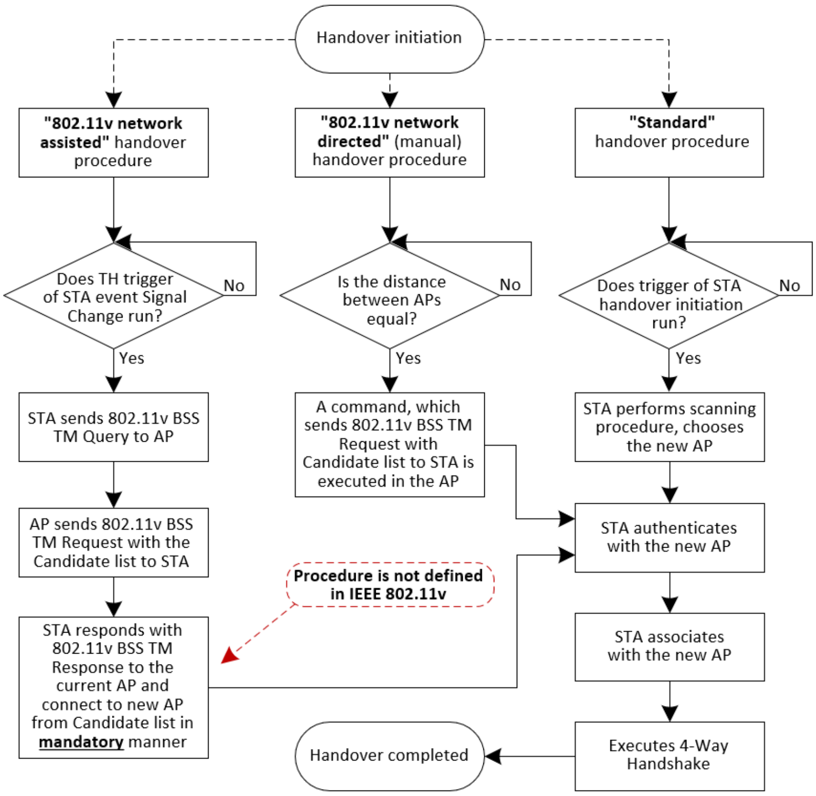


Fig. 12. Summarised scheme of handover algorithms.

In Sub-chapter 4.3, the implementation of several IEEE 802.11ac wireless network testbeds (Fig. 13) for the experimental measurements is described. The experiments were performed by implementing the handover algorithms described in Sub-chapter 4.2. One vehicle (with mobile client) moving at various velocities was used in the experiments: 20 km/h, 50 km/h, 70 km/h, and 90 km/h. The AL throughput, response time, and the handover delays were experimentally evaluated.

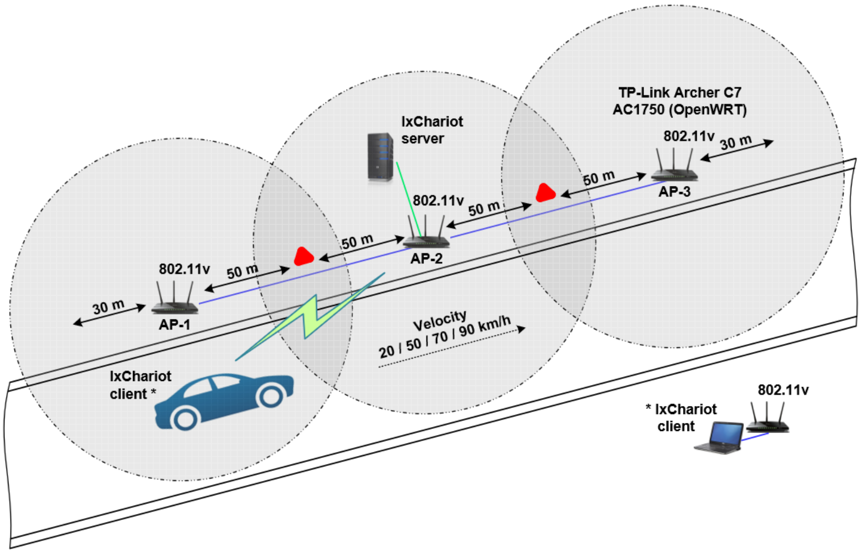
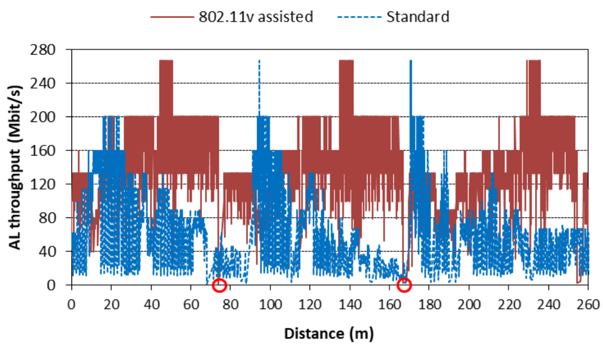


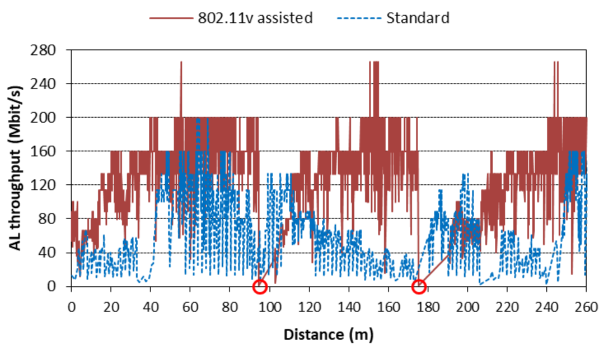
Fig. 13. WLAN IEEE 802.11ac automotive communication network testbed with the introduced modified IEEE 802.11v standard.

In **Sub-chapter 4.4**, the performance parameters (AL throughput, response time, and handover delay) obtained in the experimental measurements are evaluated.

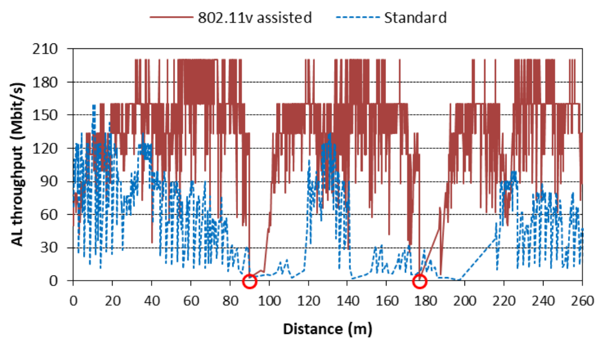
For comparison, experimentally obtained AL throughput graphs for *Standard* and *802.11v network assisted* handover procedure mechanisms at various vehicle velocities in the IEEE 802.11ac network are shown in Figs. 14 (a)–(d).



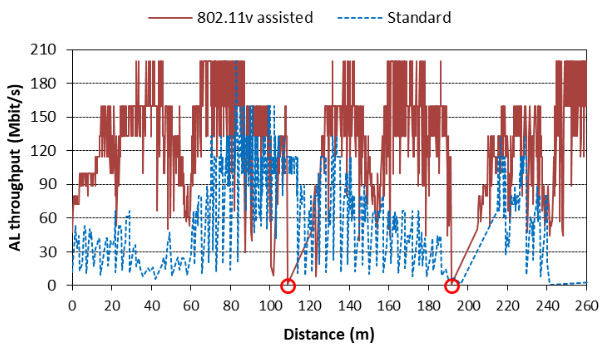
a) 20 km/h



b) 50 km/h



c) 70 km/h



d) 90 km/h

Fig. 14. AL throughput at a velocity of 20 km/h, 50 km/h, 70 km/h, and 90 km/h using 802.11v network assisted and Standard handover methods.

In the case of the *Standard* handover procedure, at movement velocities >20 km/h, the handover has a delay and in addition at 90 km/h the handover is not performed correctly, because one of the testbed APs can be ignored and omitted.

In Fig. 15 (a), the calculated average AL throughput characteristic curves, where the experimentally obtained measurement data at various velocities of a mobile client movement and by using different handover procedure methods were used for the calculations, are shown.

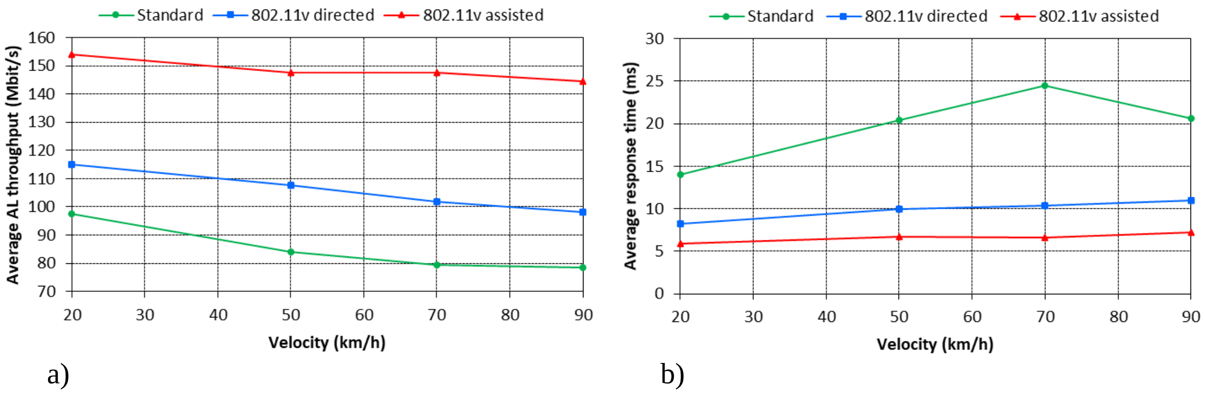
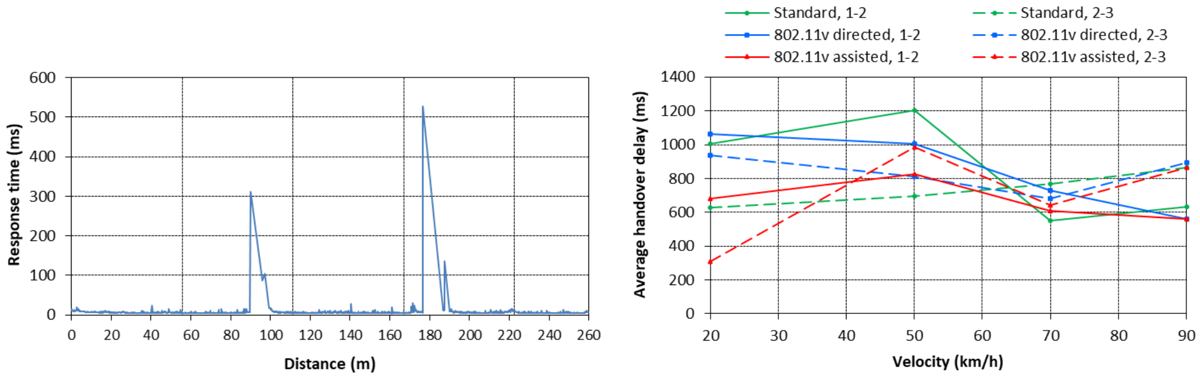


Fig. 15. (a) Average AL throughput; (b) Average response time.

It can be concluded from the obtained results that, the developed *802.11v network assisted* handover procedure gives the highest average value of AL throughput and the lowest dispersion parameters (standard deviation and coefficient of variation). An attention shall be paid to the obtained dispersion parameters, as they characterise the dependence of the average value of AL throughput changes on the velocity of movement. The smaller the dispersion parameters, the smaller the decrease in the average value of AL throughput at higher movement velocities.

In Fig. 15 (b), the calculated average response time characteristic curves, where the experimentally obtained measurement data at various velocities of mobile client movement and by using different handover procedure methods were used for the calculations, are shown. As the mobile client's velocity increases, the response time of the network increases as well. Each handover procedure increases the total network response time value. In the case of the *Standard* handover procedure (Fig. 15 (b)), the decrease in the average response time characteristic curve at 90 km/h can be explained by the fact that in this case, the mobile client has not performed the handover between all the APs. The lowest average response time value and the lowest calculated dispersion parameters are ensured by the developed *802.11v network assisted* handover procedure solution.

Based on the experimentally obtained response time graphs, the approximate duration or delay of each handover procedure was determined. In the obtained graphs, the handover delays are observed as the increases of the response time values (peaks), and their moments in time coincide precisely with the drops in data traffic observed in the AL throughput graphs. As an example, the response time graph for the case of the *802.11v network assisted* handover procedure at the client's movement velocity of 70 km/h is given in Fig. 16 (a).



a) b)

Fig. 16. (a) The response time at 70 km/h and 802.11v network assisted handover; (b) Average handover delay between AP pairs using different handover methods.

The experimentally estimated average handover delays between AP-1 and AP-2, as well as between AP-2 and AP-3, using different handover procedure methods at various clients' movement velocities are shown in Fig. 16 (b). It can be concluded from the obtained results that the lowest average handover delays were achieved using the *802.11v network assisted* handover solution.

The analysis of the obtained experimental results allows the conclusion to be made that a timely decision on the handover procedure and the use of the IEEE 802.11v standard *BSS Transition Management Query* and *BSS Transition Management Request* messages with the developed modification in conjunction with the IEEE 802.11ac standard can be used for fast-moving objects (>20 km/h) to provide a handover procedure. Therefore, the average AL throughput was increased by 75 % compared to the *Standard* handover, where the IEEE 802.11v standard was not used. The average network response time was reduced by 67 % as well and reduced average handover delays were provided.

Chapter 5

In the **fifth chapter** of the Doctoral Thesis**,** using both experimental data and theoretical calculations, vehicle communication channel performance parameters such as the received signal power and communication channel throughput depending on the vehicle's distance to the transmitter were determined. The calculations also consider the fluctuations of the received signal, which are related to the multipath propagation of the signal [7].

In Sub-chapter 5.1, the dependence of the signal power on the distance to the transmitter is determined. It has been experimentally observed that as the mobile client moves away from the AP (Fig. 17), the power level *P* of the received signal (in this case RSS (Received Signal Strength)) decreases. It has also been observed that the level of the RSS signal not only decreases but fluctuates around its average value as well. Experimental measurements were performed on a single-rank IEEE 802.11ac network using a standard wireless network client. The experimentally obtained data [23], [30] were used in the following theoretical calculations (6).

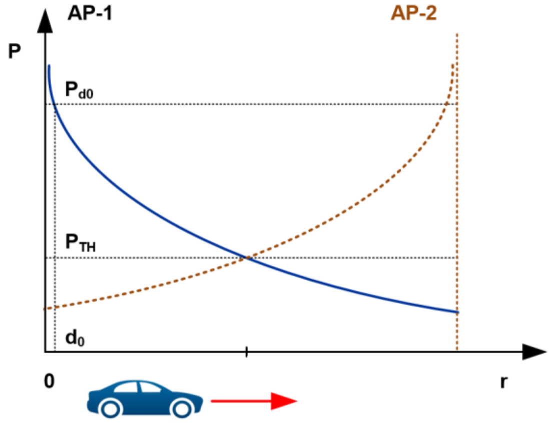


Fig. 17. Alteration of the received signal power parameter *P* depending on the distance to the transmitter.

Using a *two-ray flat-earth* model [23] and adding random fluctuations, a *log-normal* model is obtained. The notation of the model in general form is given by Equation (6). The model allows the power level *P* of the received signal to be determined depending on distance *r* between the transmitter and the receiver [23], [25], [27].

$$P(r) = P(d_0) - 10u\log_{10}\left(\frac{r}{d_0}\right) + X_\sigma, \tag{6}$$

where $P(r)$ is the power of the received signal (corresponds to RSS) depending on *r*, dBm; d_0 is the distance from the wireless access point (AP) to the vehicle, m; *r* is the distance between the transmitter and receiver, m; $P(d_0)$ is the power of the received signal, when the client is directly in front of the wireless access point, dBm; *u* is the path loss exponent; X_σ is the random variables, dB.

A distribution of received signal, which can be modelled by *Rayleigh* or *Rician* statistics is a *Nakagami* distribution (7).

$$f(x;\alpha,\omega) = \frac{2\alpha^\alpha x^{2\alpha-1}}{\omega^\alpha \Gamma(\alpha)} \mathrm{e}^{\frac{-\alpha x^2}{\omega}}, \tag{7}$$

where α is a shape parameter (if $\alpha = 1$, then it is the *Rayleigh* distribution; if $\alpha > 1$, then it is the *Rician* distribution); ω is the estimation of the average power in the fading envelope; *x* is general random number which is exposed to the *Nakagami* distribution.

The average value of the received signal power fluctuations is calculated by Expression (8).

$$\bar{X}_\sigma = \int_0^\infty x f(x;\alpha,\omega)\mathrm{d}x = \int_0^\infty x\left(\frac{2\alpha^\alpha x^{2\alpha-1}}{\omega^\alpha \Gamma(\alpha)} \mathrm{e}^{\frac{-\alpha x^2}{\omega}}\right)\mathrm{d}x. \tag{8}$$

In the calculations, it is admitted that $\alpha = 1$, consequently, Expression (8) is simplified:

$$\bar{X}_\sigma = \int_0^\infty \frac{2x^2}{\omega} \mathrm{e}^{\frac{-x^2}{\omega}}\mathrm{d}x. \tag{9}$$

Using Expression (9) and additional calculations, the effect of the added signal fluctuations X_σ on $P(r)$ was determined (Fig. 18).

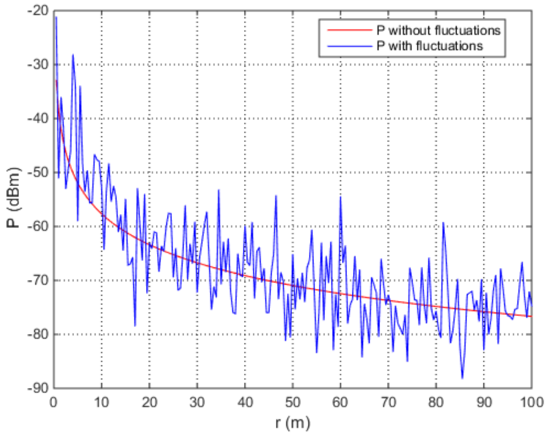


Fig. 18. Theoretically calculated power of the received signal *P* depending on the distance to the transmitter without and with power fluctuations.

In **Sub-chapter 5.2**, the throughput dependence on the received signal power level and the distance to the transmitter is determined.

The *Shannon's* frequency channel capacity theorem (*Shannon's* theorem) was used to calculate the upper limit of the communication channel throughput or channel capacity *C* [10], [43]:

$$C = B\log_2\left(1 + \frac{S}{N}\right), \tag{10}$$

where *C* is the capacity of frequency channel, bit/s; *B* is the frequency channel bandwidth, Hz; *S* is the average power of the received signal in the channel, W; *N* is the average power of noise or interference in the channel, W.

Using Expressions (10) and (6), the theoretical throughput *C* for an ideal communication channel was calculated. Variable *S* corresponds to parameter $P(r)$ of Expression (6). The obtained result is given below (Fig. 19), it can be seen how the communication channel maximum throughput (capacity) *C* changes depending on the received signal power level *P*, without and with the fluctuations of the received signal power.

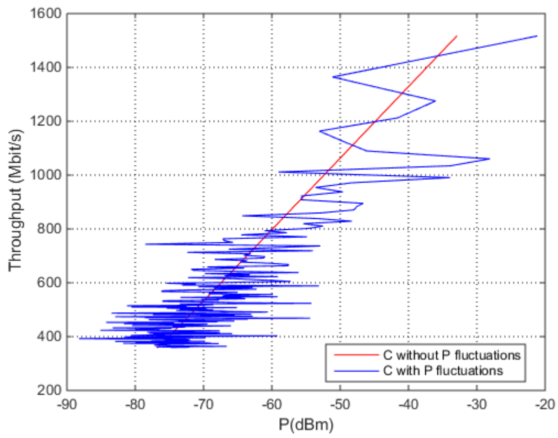


Fig. 19. Theoretically calculated throughput *C* depending on the received signal power *P* without and with power fluctuations.

The data channel throughput *C* depending on the distance to the transmitter has been calculated. The theoretically obtained throughput results (red and blue curves) were combined in the same graph with the experimentally obtained AL throughput results (green curve) (Fig. 20).

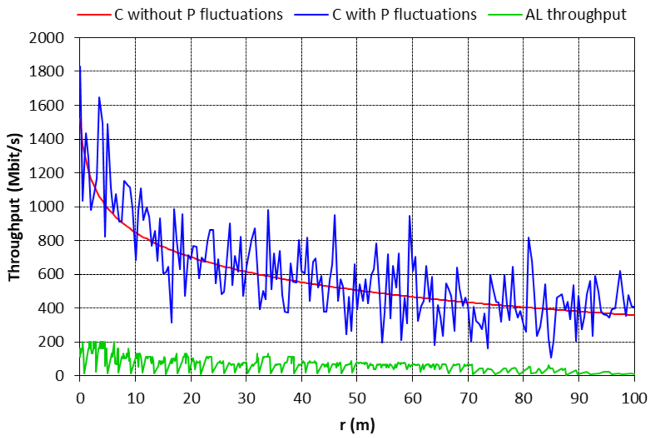


Fig. 20. Theoretically calculated throughput *C* without and with *P* fluctuations and experimentally obtained AL throughput depending on the distance to the transmitter.

Both the theoretical calculations and the experimental observations and measurements performed demonstrate that in the WLAN network, as the mobile client moves away from the transmitter, the received signal power decreases resulting in decreased throughput. The received signal power *P* varies and fluctuates over time. The fluctuations of power level of the received signal are caused by constructive and destructive interference between the components of the multipath signal propagation. It causes throughput fluctuations as well. The theoretically calculated wireless communication channel capacity or the maximum possible throughput *C* is several times higher than the experimentally obtained AL throughput. The trend and nature of the curves are similar, but the absolute values differ, because Shannon’s theorem determines the data transmission rate for an ideal channel, it is a physical environment, and the effects of higher layers of the OSI model are not considered in the calculations.

MAIN RESULTS OF THE DOCTORAL THESIS

During the fulfilment of the defined tasks, the following **main results and conclusions of the Doctoral Thesis have been obtained**:

1. The development of an integrated WLAN and LTE road transport communication network is technically and economically justified when WLAN-based, LTE-concentrated mobile network offloading is used. It is a practical automotive communication network to ensure the transmission of large amounts of data and to organise access for car passengers to the Internet.
2. The performance of a two-rank WLAN and LTE communication network depends on the technical performance parameters of the network nodes. With different LTE routers, the AL throughput of an automotive wireless network can vary by 10–20 %. Changes in velocity of the mobile client movement, the number of clients and client traffic scenarios affect both the AL throughput of individual mobile clients and the overall performance of the wireless network.
3. Irrespective of which manufacturer's LTE router is used on a two-rank IEEE 802.11n and LTE network, the nature of the data traffic is not affected. This is demonstrated by the analysis of the results of experimental measurements, where parameters such as throughput, correlation coefficient, variance, and degree of traffic self-similarity were evaluated for the data traffic flows.
4. The handover procedure between wireless access points depends on the handover algorithm implemented in the client's device, the WLAN architecture solution, and the implemented wireless network security mechanisms.
5. Depending on the velocity of the vehicle (mobile client) (0–70 km/h), the integrated IEEE 802.11n and LTE communication channel throughput changes in accordance with the second-order polynomial function.
6. In an integrated IEEE 802.11n and LTE communication network, overheads between L7 and L4 average up to 36 % at a velocity of the mobile client from 0 km/h to 70 km/h. This means that network throughput cannot be judged solely based on measurements made in the transport (L4) or lower layers.
7. In an IEEE 802.11ac network with fast-moving objects (>20 km/h), timely decision-making and execution of the handover procedure using the IEEE 802.11v standard *BSS Transition Management Query* and *BSS Transition Management Request* messages with the developed modification can increase the total wireless network performance, i.e., average AL throughput can be increased by up to 75 % and the average network response time can be reduced by 67 %, as well as it is possible to provide lower average handover delays compared to the *Standard* handover procedure, which does not use the IEEE 802.11v standard.
8. Both the theoretical calculations and the experimental observations and measurements performed demonstrate that in the IEEE 802.11ac network, as the mobile client moves away from the transmitter, the received signal power decreases, resulting in decreased throughput. The received signal power varies and fluctuates over time, and the

fluctuations of the received signal power are caused by constructive and destructive interference between the components of multipath signal propagation, which in turn causes throughput fluctuations.

The results of the completed research are summarised and the possible **further research directions** are defined in the Doctoral Thesis:

1. Development of mobility extension solutions for WLAN-based road transport communication network customers and performance evaluation of the developed solutions. The connectivity solution would provide the use of adaptive WLAN and 4G LTE/5G communication channels in problematic coverage areas. The proposed solution in the ITS networks would allow the provision of stable broadband data transmission services and would be focused on multimedia data transmission.
2. An advanced study of the IEEE 802.11k standard and the development of a solution for providing an auto-completed database with the wireless access points (APs) *Candidate List* that also contains the APs' GPS data. The handover algorithm could be supplemented with new AP selection metrics, such as the customer's positioning data, and the direction and velocity of the customer's movement. Evaluation of the performance and efficiency of the developed solutions.

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