1862
RIGA TECHNICAL
UNIVERSITY

Deniss Brodņevs

ANALYSIS OF THE PERFORMANCE OF CELLULAR MOBILE NETWORKS FOR THE REMOTE-CONTROL SYSTEMS OF UNMANNED AERIAL VEHICLES

Summary of the Doctoral Thesis

RTU Press
Riga 2021

RIGA TECHNICAL UNIVERSITY
Faculty of Mechanical Engineering, Transport and Aeronautics
Institute of Aeronautics

Deniss Brodņevs
Doctoral Student of the Study Programme “Transport”

ANALYSIS OF THE PERFORMANCE OF CELLULAR MOBILE NETWORKS FOR THE REMOTE-CONTROL SYSTEMS OF UNMANNED AERIAL VEHICLES

Summary of the Doctoral Thesis

Scientific supervisor
Professor Dr. habil. sc. ing.
VITĀLIJS PAVELKO

RTU Press
Riga 2021

Brodņevs D., Analysis of the Performance of Cellular Mobile Networks for The Remote-Control Systems of Unmanned Aerial Vehicles. Summary of the Doctoral Thesis. – Riga: RTU Press, 2021. – 42 p.

Published in accordance with the decision of Promotion Council No. P-22 of 26 February 2021, Minutes No. 04030-9.12.1/4.

doi.org/10.7250/9789934227097
ISBN 978-9934-22-709-7 (pdf)

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

To be granted the scientific degree of Doctor of Science (Ph. D.), the present Doctoral Thesis has been submitted for the defence at the open meeting of RTU Promotion Council on 17 December 2021 at the Faculty of Mechanical Engineering, Transport and Aeronautics of Riga Technical University, 6B Ķīpsalas Street, Room 204.

OFFICIAL REVIEWERS

Professor Dr. habil. sc. ing. Volodymyr Kharchenko
National Aviation University, Ukraine

Professor Dr. sc. ing. Ramunas Kikutis
Vilnius Gediminas Technical University, Lithuania

Professor Dr. habil. sc. ing. Vladimirs Šestakovs
Riga Technical University, Latvia

DECLARATION OF ACADEMIC INTEGRITY

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

Name Surname ……………………………. (signature)
Date: ………………………

The Doctoral Thesis has been written in English. It consists of an Introduction; 4 Chapters; Conclusion; 111 figures; 29 tables; 0 appendices; the total number of pages is 141 not including appendices. The Bibliography contains 103 titles.

LIST OF ABBREVIATIONS

2D – Two-dimensional
2G – Second generation mobile networks
3G – Third generation mobile networks
4G – Fourth Generation
AGL – Above Ground Level
AMC – Automatic Modulation and Coding
BS – Base Station
C2 – Command and Control
CID – Cell ID
COTS – Commercial-of-the-shelf
D2D – Device-to-Device
D2WAN – Device-to-WAN
DAN – Double Attached Node
DC-HSPA+ – evolved Dual Carrier High Speed Packet Access protocol
DNS – Dynamic Name Server
Ec/Io – Energy per chip to interference power ratio
EDGE – Enhanced Data Rates for GSM Evolution
ETSI – European Telecommunications Standards Institute
FPV – First Person View
GCS – Ground Control Station
GPS – Global Positioning System
GSM – Global System for Mobile communications
HARQ – Hybrid Automatic ReQuest
HF – High Frequency
HSPA – High Speed Packet Access
HSPA+ – evolved High Speed Packet Access
ICAO – International Civil Aviation Organization
ICMP – Internet Control Message Protocol
IP – Internet Protocol
IPDV – IP Packet Delay Variation
IPPM –IP Performance Metrics Working Group
IPTD – IP Packet Transfer Delay
ITU – International Telecommunication Union
KPI – Key Performance Indicator
LOS – Line-of-Sight
LTE – Long Term Evolution mobile networks
LTE-A – Long Term Evolution – Advanced (4G mobile network)
MASL – Altitude above mean Sea Level
MB – Mobile Broadband
MIMO – Multiple-Input and Multiple-Output
MPTCP – Multipath TCP

OSPPt – Test based on Probability Plot of Ordered Statistics
PIFA – Planar Inverted-F Antenna
PRP – Parallel Redundancy Protocol
RC – Remote-Control
RCV – Remote-Controlled Vehicle
RPA – Remotely Piloted Aircraft
RPAS – Remotely Piloted Aircraft System
RSCP – Received Signal Code Power
RSRP – Reference Signal Received Power
RSSI – Received Signal Strength Indicator
RTT – Round-Trip Time (two-way delay)
SAN – Single Attached Node
SINR – Signal to Interference plus Noise Ratio
STDEV – Standard Deviation
TCP – Transmission Control Protocol
UE – mobile User Equipment
UHF – Ultra-High Frequency
UMTS – Universal Mobile Telecommunication System
VHF – Very High Frequency
vi – virtual instrument (LabVIEW executive file)
VLOS – Visual Line-of-Sight
WAN – Wide Area Network

SUMMARY

GENERAL CHARACTERIZATION OF THE THESIS

Urgency of the Research

Today, a new industry with great economical potential starts to be created on the base of Unmanned Aerial Vehicles (UAV). The UAV operates as a part of a system called an Unmanned Aerial System (UAS). In order to be able to operate under remote control, any UAS requires a reliable command (Remote Control (RC)) and control (telemetry) link. In ICAO terminology such link is termed to as Command and Control or “C2 link” [1].

At the date, the VHF and UHF frequencies are commonly used to implement C2 link. Frequencies in these bands generally propagate in a Radio Line-of-Sight (RLOS) manner (it is worth noting here that the radio waves propagation model for UAV and RPAS differs from the traditional model, which is valid for terrestrial wireless communication, since communication occurs between equipment located on the ground and in the air). The main problem is that UAV flight takes place at a relatively low altitude (typically allowed altitude is up to 120 m above ground level (ALG), while in some populated areas the maximum altitude is set to 50 m AGL. Low altitudes, as well as the ability to quickly change altitude and speed of flight, increase the likelihood that the traditional radio link becomes obstructed. This in itself drastically reduces maximum ranges of flight where reliable operation of the C2 link can be guaranteed.

The use of the cellular data transfer services (e.g. 2G, 3G, LTE, 5G) can significantly increase the range of C2 link operation. However, cellular mobile data transfer services up to LTE incl. were originally designed for terrestrial users. The performance of these services for flying users is not guaranteed. The mission of the Thesis is the evaluation of the suitability of data transfer over mobile cellular networks for C2 link implementation for low-flying (up to 120 m) UAVs.

Mission of the Thesis

The goal of the research is the evaluation of the suitability of the data transfer over LTE mobile cellular networks for "Command and Control Link" implementation for low-flying (up to 120 m), small size (group 1) UAVs.

Tasks

1. Development of the delay requirements for the wireless "C2 Link" of low-flying UAVs.
2. Determination of the type of distribution law of delay values of the LTE mobile data transfer service.
3. Experimental estimation of delay values in various cells of cellular mobile network.
4. Analysis of the compliance of the delays of mobile data transfer to the requirements of a "C2 Link" of low-flying UAVs.
5. Experimental evaluation of the impact of the mobility of terrestrial users on the performance of 3G and LTE mobile data transfer services.
6. Experimental evaluation of the impact of flying altitude on the performance of 3G and LTE mobile data transfer services.
7. Application of the parallel redundancy to increase the reliability and reduce the delays of a "C2 Link".

Methodology

Theoretical and experimental means were used to achieve the goals and objectives.

An experimental study involves conducting field experiments within the existing operating cellular networks of Latvia. Mobile 3G/LTE dongles were used as the main means for conducting experimental evaluations of the key performance indicators (KPI) of mobile cellular network's radio links and data transfer. The evaluations were performed in the cases of stationary placed equipment on the ground, as well as mobile equipment on the ground and in the air. For this, the dongles were stationary located, or transported by a car, or lifted by the 450 mm drone with a companion computer attached to it, or flied by lightweight airplane.

The first mobile dongle was Huawei 3372h. The Huawei E3372h is equipped with two PIFA antennas (for the receiver diversity) and is a 24th category 3G device which supports 64-QAM modulation and can be operational in dual cell DC-HSPA+ mode and a LTE Cat 4 device which supports operation in LTE cells with 20 MHz bandwidth. By default, it operates in the Hi-Link mode (CdcEthernet). In this mode it operates as a NAT server and emulates a virtual network card (NDIS), and its configuration is done via the web interface. Since the indicators of a radio network performance should be logged too, the device was reprogrammed into stick mode (RAS) (firmware 21.315.01.00.143_M_01). The stick mode enables access to the set of standard serial AT-commands and reports.

The second device was Huawei ME909s-120. This is Cat 24 and LTE Cat 4 device. The main difference with the E3372h is that this module has no built-in antennas, allows to search for LTE cell (the E3372h allows search in 2G and 3G modes only) and by default operates in MB (Mobile Broadband) mode. In order to get access to its serial AT-commands and reports, the device was switched to debug mode, thus debug drivers were used too.

All the radio network parameters were reported by the 3G/LTE dongles (Huawei 3372h or Huawei ME909s-120). The travelling speed and location were obtained via the Global Sat BU-353-S4 GPS receiver.

All the experimental data as well as the speed and altitude (reported by the GPS receiver) have been captured via the virtual instrument (vi), created in the LabVIEW environment. The proposed vi performed decoding of the data and allowed export of the experimental data into MS Excel files.

The delays of data transfer service generally were evaluated via the ICMP packets to exclude the impact from the fast acknowledgement by Base Station (BS). The ICMP requests were generated by the standard utility "ping". In some special cases another type of packets were used, where data flows were generated by the Netperf and IPerf software.

The post-processing of the experimental data was performed in the MS Excel software. The data transfer KPI were evaluated in accordance with ITU recommendation T-REC-Y.1541 [2].

The theoretical background of the research is the theory of reliability. The analyses of delays and their properties were carried out via the methods of probability theory and mathematical statistics, namely: analysis of the suitability of distribution law via the probabilistic paper, as well as using the goodness-of-fit tests; estimation of distribution parameters using the maximum likelihood method, as well as using fractals (under the accepted hypothesis of the distribution law); description of the parameters of the delays via the system of random variables; description of the delays in the redundant system via the minimum function. The majority of calculations as well as the data processing were done in the MATLAB and MS Excel environments.

Scientific Novelty

Scientific novelty lies in proving the suitability and limits to applicability of the LTE mobile data transfer for implementing wireless C2 link for low-flying, small size (group 1) UAVs. This is achieved by estimating the predicted delays based on experimental estimates of delays in the cells of mobile LTE network. The effects of specific situations arising during various kinds of mobility or flights over the earth's surface are also evaluated.

- The Thesis contains the goodness-of-fit tests of a statistical hypothesis of the delays in the LTE cells. It is proved that in order to obtain estimates of the average delay and delay jitter with satisfactory accuracy, it is possible to accept that the delays in LTE cells obey the logarithmically normal distribution law.
- A method for description the delays in an overall mobile cellular network using a multivariate distribution function of the delay distribution parameters of individual cells is proposed.
- The Thesis contains a list of factors that leads to temporary increased delays in 3G (HSPA+ and above) data transfer service, when the user equipment (UE) is moving on the ground.
- The Thesis states the problems that lead to temporary increased delays /increased packet loss rate in 3G (HSPA+ and above) data transfer service when UE is flying over the earth's surface. It has been found that the same problems are also applicable to the LTE systems and may lead to degraded performance of the LTE data transfer service too.
- The efficiency of parallel redundancy application in mobile data transfer services has been proven. A method for predicting delays in the redundant network solution with known packet loss rates is proposed. The method is applicable to various number of parallel redundant networks.

Practical Utility

Practical utility lies in providing the numerical values of the characteristics as well as the limits to applicability of the communication channel for implementing wireless C2 link via the LTE mobile data transfer for low-flying UAVs.
The Thesis contains the requirements for network delays for the wireless RC and FPV channels of lightweight UAVs.

- The Thesis contains the numerical characteristics of the delays of the Tele2-LV LTE network. The proposed characteristics of the delays are described via two-dimensional distribution function of the delay distribution parameters of individual cells, assuming that the delays in LTE cells fit with the logarithmically normal distribution. The proposed model can be used to assess the compliance of LTE network delays with the required delays in specific cases in order to assess the appropriateness of LTE network as a communications channel solution.
- The Thesis contains the method of quick estimation of the logarithmically normal distribution parameters, based on known values of minimal RTT_{min} and average

$RTT_{average}$ values. This approach is convenient, since the "ping" utility reports these statistics in ready to use manner. The recommendations on the required number of measurements in LTE networks are also provided.

- The Thesis contains the recommended de-jittering buffer sizes of FPV video channel that should be used in LTE network. The proposed values are estimated using the numerical characteristics of the delays of the Tele2-LV LTE network.
- The thesis contains the limits to applicability of the LTE network for implementing wireless C2 link for low-flying UAVs. The values of the proposed limits are established considering the developed requirements for the FPV and RC channels as well as the experimentally obtained numerical characteristics of the delays of the LTE Tele2 network.
- The Thesis contains the proposed method which allows to evaluate the coverage area of base stations in the air.
- The Thesis contains the experimental evaluation of the applicability of PRP and MPTCP redundant software solution implementations that previously were not implemented and tested in cellular mobile networks. The experimental data of the performance of PRP and MPTCP redundant solutions confirmed the effectiveness of the application of these redundant solutions in LTE networks. The recommendations on the selection of cellular data transfer services for the redundant solution are also provided.

Theses to be Defended

- The developed requirements for data transfer network delays for the RC and FPV wireless channels are applicable to low-flying, small size UAVs.
- The delay values in LTE network cells can be described by the parameter estimates of the lognormal distribution. This approach does not introduce noticeable errors in determining the average delay and delay jitter values.
- Evaluation of delays in overall cellular network should be carried out separately in each cell; the results should not be mixed.
- The application of the two-dimensional (bivariate) system of the distribution parameters of the delays of LTE cells with approximation according to the normal law is an effective solution to the description of delays of the entire LTE network.
- The delays in the LTE network allow the use of this network as a wireless solution for the RC of a UAV by a trained pilot.
- Assuming sufficient coverage of the cellular network, the UAV can be piloted through the FPV via the LTE network if video codecs can operate with a packet loss rate of 1 %. At the same time, the size of the de-jittering buffer should correspond (to be dynamically adjusted) to the IPDV value determined at the level of 0.99. The use of a buffer with a constant size in the video channel in the LTE network does not allow to get the required delays in the video channel.
- The performance of 3G / LTE networks for flying users is subject to negative effects, such as strong interference and more frequent handovers. The use of soft handover (like in 3G networks) in case of complex aerial coverage leads to massive operation of the

soft handoff function, which leads to a significant increase in delays, jitter and packet reordering.

- The vertical coverage of 2G/3G/LTE base stations can be experimentally evaluated by running the built-in search function of the communication module. Such approach allows to obtain a full coverage map instead of getting radio signal quality indicators only for the selected base station.
- The implementation of the parallel redundancy in the LTE networks is the effective solution.
- Application of a parallel redundancy in 3G / LTE networks is an efficient solution to increase the availability and the performance of a C2 Link.
- The delays in the redundant network solution can be predicted by using the proposed method. The proposed method uses the statistics from the "ping" utility and is more intuitive than the existing approach based on the Markov chain method.

Approbation of the Results

The results, proposed in the Thesis, were presented in the following scientific conferences:

1. International Scientific Practical Conference "Transport systems, logistics and engineering": Mini UAV long- range communication link challenge, Riga, Latvia: Riga Aeronautical Institute, 2016.
2. RTU 57th international scientific conference: "Transport – Aerospace and transport engineering": Experimental study of the quality of data transmission service of Latvian mobile operators, Riga, Latvia: Riga Technical University, 2016.
3. RTU 58th international scientific conference "Transport and aerospace engineering": Mobile user equipment reliable cellular data transfer service solution, Riga, Latvia: Riga Technical University, 2017.
4. "IEEE 58th International Scientific Conference on Power and Electrical Engineering (RTUCON)": High-Reliability Low-Latency Cellular Network Communication Solution for Static or Moving Ground Equipment Control, Riga, Latvia: Riga Technical University, 2017.
5. "IEEE 59th International Scientific Conference on Power and Electrical Engineering (RTUCON)": Reliable data communication link implementation via cellular LTE services for static or moving ground equipment control, Riga, Latvia: Riga Technical University, 2018.
6. RTU 60th international scientific conference "Transport": Measurements of signal coverage and quality of 3G / LTE mobile networks at high altitudes using a remotely piloted aircraft system, Riga, Latvia: Riga Technical University, 2019.
7. "IEEE 60th International Scientific Conference on Power and Electrical Engineering (RTUCON)": Method for estimating delays in parallel redundant data transfer networks, Riga, Latvia: Riga Technical University, 2019.
8. RTU 61st international scientific conference "Aviation transport": UAV Control via Mobile Cellular Networks., Riga, Latvia: Riga Technical University, 2020.

9. "IEEE Microwave Theory and Techniques in Wireless Communications (MTTW)": An Approach to Constructing a Model of Delays in Cells of a Cellular Network Based on Experimentally Obtained Data, Riga, Latvia: Riga Technical University, 2020.

The results, proposed in the Thesis, were published in the following scientific papers:

1. D. Brodnevs and A. Kutins, "An Experimental Study of Ground-Based Equipment Real Time Data Transfer Possibility by Using Cellular Networks," *Electr. Control Commun. Eng.*, vol. 12, no. 1, pp. 11–19, Jul. 2017. Indexing: Web of Science.
2. D. Brodnevs and A. Bezdel, "High-reliability low-latency cellular network communication solution for static or moving ground equipment control," in *Proc. IEEE 58th Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, 2017, pp. 1–6. Indexing: IEEE, Scopus, Web of Science.
3. D. Brodnevs and A. Kutins, "Cellular networks selection for the remote control vehicles' control channel setup with parallel redundancy," *J. Mod. Technol. Eng.,* vol. 3, no. 1, pp. 63–74, 2018.
4. D. Brodnevs, "Development of a Flexible Software Solution for Controlling Unmanned Air Vehicles via the Internet," *Transp. Aerosp. Eng.*, vol. 6, no. 1, pp. 37–43, 2018.
5. D. Brodnevs and A. Kutins, "Reliable data communication link implementation via cellular LTE services for static or moving ground equipment control," in *Proc. IEEE 59th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, 2018, pp. 1–6. Indexing: IEEE, Scopus, Web of Science.
6. D. Brodnevs and A. Kutins, "Deterioration Causes Evaluation of Third Generation Cellular LTE Services for Moving Unmanned Terrestrial and Aerial Systems," *Electr. Control Commun. Eng.*, vol. 14, no. 2, pp. 141–148, 2018. Indexing: Web of Science.
7. D. Brodnevs and M. Hauka, "Method for estimating delays in parallel redundant data transfer networks," in *Proc. IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON),* 2019, pp. 1–6. Indexing: IEEE, Scopus, Web of Science.
8. D. Brodnevs and A. Kutins, "An Approach to Constructing a Model of Delays in Cells of a Cellular Network Based on Experimentally Obtained Data," in *Proc. IEEE Microwave Theory and Techniques in Wireless Communications (MTTW)*, 2020, pp. 206–211. Indexing: IEEE, Scopus, Web of Science.
9. D. Brodnevs and A. Kutins, "Requirements of End-to-End Delays in Remote Control Channel for Remotely Piloted Aerial Systems," *IEEE Aerosp. Electron. Syst. Mag.*, vol. 36, no. 2, pp. 18–27, 2021. Indexing: IEEE, Scopus, Web of Science.

Structure of the Thesis

Chapter 1 contains the review of existing solutions for wireless command and control links of UAVs.

Chapter 2 contains an analysis of the delays in 3G and LTE cellular mobile networks as well as provides a review of the technological aspects of 3G and LTE cellular mobile networks that have a major impact on the data transfer quality. The experimental evaluation of the impact of mobility on the delays in 3G and LTE networks is provided. The chapter also presents the proof of application of a distribution law on delay values, which is applicable to LTE networks, as well as recommendations on the required number of measurements to estimate the parameters with the required probability of tolerance. It describes a method that allows to estimate the distribution parameters from known *RTTmin* and *RTTaverage* values, which are reported by the well-known "ping" utility. A two-dimensional system of random variables of the delays in LTE of Tele2-LV cells is also provided. The requirements of delays for C2 Link which were developed based on a literature review are provided. Finally, an analysis of the suitability of delays of real working LTE mobile network for the command and control link (C2 link) is provided.

Chapter 3 contains an analysis of limiting factors that reduce the performance of 3G and LTE at high altitudes.

Chapter 4 contains a mathematical model for estimating the delays in the resultant redundant network, as well as its experimental verification if two redundant LTE networks are used. It also contains a description of two experimental setups of redundant solutions (PRP and Multipath TCP) that has not been previously tested in cellular networks.

1. REVIEW OF EXISTING SOLUTIONS FOR WIRELESS LINK IMPLEMENTATION OF UNMANNED AERIAL SYSTEM (UAS)

Analysis of existing UAS communication systems shows that existing solutions utilize the frequencies of the VHF and UHF bands, which is mainly related to the size of the antennas and the complexity of the hardware implementation. Radio waves of the VHF and UHF bands propagate along the line-of-sight (LOS), which significantly limits the maximum range of stable radio reception. It should also be noted that the radiated power of the transmitters of such devices is limited by the power of the UAV battery, as well as in accordance with the requirements of ETSI. Limitations, imposed on radiated power, even more reduce the range of stable radio reception.

Typically, Commercial-of-the-shelf (COTS) are used in a typical radio system implementation of RPA. These include IEEE 802.11 and IEEE 802.15 devices. The theoretical maximum range of such radio devices is up to 15 km, however, in real rough terrain, the maximum range of communication between the ground control station (GCS) and UAV is usually not more than 2 km.

The use of long-distance solutions (e.g. Lora) theoretically allows to get a maximum range of communication up to 10 km, whereas in real life the range is limited to the coverage area of the LoraWAN service operator (in Latvia LoraWAN service is provided by TET (former Lattelekom)). However, the use of LoraWAN services in C2 link implementation is doubtful due to the very low data transfer speeds in this service.

The use of HF over horizon communications solutions, as well as satellite communications, for small RPAs is not possible due to the cumbersomeness of the radio communication equipment, antenna sizes, and the power consumption of these systems.

The possibility of using motionless flying drones as radio relay stations to extend the radio transmission zone has been widely covered in scientific papers, however, such solutions are economically feasible only in special cases.

For today, the use of cellular data services (2G, 3G, LTE) is considered as a possible small-sized and low-cost solution to significantly increase the maximum distance of the communication channel. There are several projects already available that allow to use not only standard radio communication solutions but also cellular data services [3]–[7]. These solutions allow the utilization of cellular data service only as an alternative and on the basis of “your own risk”.

2. EVALUATION OF DELAYS IN CELLULAR MOBILE NETWORKS

Before proceeding to a detailed experimental evaluation of the operation of 3G and LTE services, it is necessary to evaluate the performance of already deployed networks to confirm that the experimentally obtained data will be valid for the analysis. A preliminary experimental evaluation was carried out as follows: stationary computers with Huawei 3372h 3G / LTE dongles were located in the institute building. Two endpoints were chosen: (1) a server located in the university building and (2) google free DNS server. Two endpoints were used to determine the cause if massive packet loss acquires the network of cellular operator or path to the wired server. All dongles were locked in the appropriate mode (3G or LTE). Each of the dongles was equipped with a SIM card of one of the operators: LMT, Tele2-LV and Bite-LV.

According to the results of the evaluation, it can be concluded that in 2016, LTE networks had not yet been fully implemented in Riga, while 3G (HSPA+ and DC-HSPA+) provided the claimed delays and packet loss. It should be noted that in case of congestion, 3G HSPA+ networks and above have the ability to transfer part of users to a low-speed channel (usually referred to as UMTS mode). This leads to nearly 4 times increase of delays but allows to keep the number of lost packets within reasonably low limits. LTE networks do not have this capability, and in case of congestion, some of the packets get dropped (lost).

The experiment in the LTE network was repeated in 2018, using only the Tele2 network. The experiment confirmed that the LTE service has become stable and can be used for further experimental evaluations.

2.1. Application of the distribution law to the delay values in LTE cell

Based on the RTT values, obtained during the previous study of the LTE network in 2018, Cumulative Distribution Function (CDF) graphs were constructed. Next, a preliminary visual assessment, of the applicable distribution law was carried out via the *Distribution Fitter* addon of MATLAB. In this graphical test, a sample with RTT ordered data is compared with expected values of ordered statistics of gamma, lognormal, normal and Weibull distributions and is presented in Fig. 2.1. To evaluate the delays of a real-working busy network, the RTT data of the B3 band was used in the assessment.

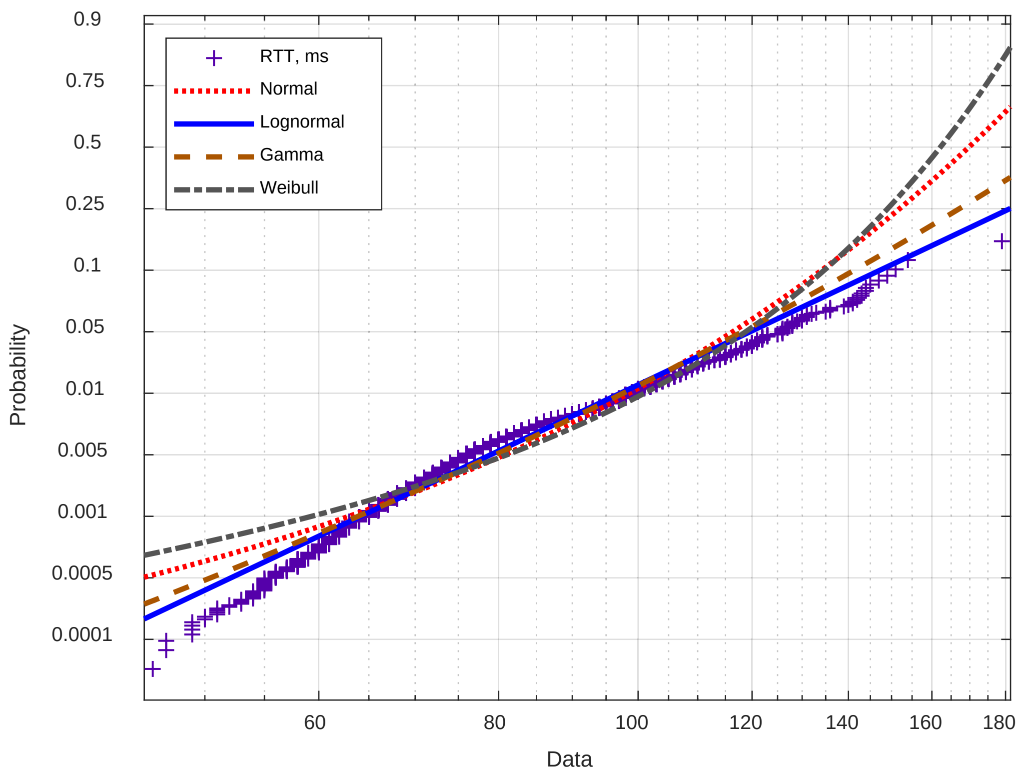


Fig. 2.1 Probability plot of the ordered RTT values of B3 LTE band compared to normal, log-normal, gamma and Weibull distributions.

A preliminary visual assessment indicates that the RTTs of LTE network most closely fit the log-normal distribution law, while the next closest one is the gamma distribution. Now, the hypothesis must be quantitatively verified. The hypothesis on type of distribution will be tested via two methods. The first one is the goodness-of-fit method, called "Test Based on Probability Plot of Ordered Statistics", or OSPPT, suggested by professor Jury Paramonov [8]. The value of the statistics of the goodness of fit test of the assumed distribution function is defined as follows:

$$OSPPt = \sqrt{\sum_{i=1}^{n} \frac{(\acute{x}_i - x_i)^2}{ns^2}}, \tag{2.1}$$

where

OSPPt – the statistic of the OSPPTest;

x_i – ordered expected values $x_i = \acute{\theta}_0 + \acute{\theta}_1 E(\dot{X}_i)$;

$\acute{\theta}_0$ and $\acute{\theta}_1$ – estimates of θ_0 and θ_1 parameters;

$\acute{x}_i$ – ordered observations (experimentally obtained data);

s^2 – $s^2 = \sum_{i=1}^{n} \frac{(x_i - \bar{x})}{n}$;

n – the number of observations.

The value of the *OSPPt* statistic is determined using regression analysis and is invariant to the number of samples. The expected values x_i from population of the expected CDF as well as the observations $\acute{x}_i$ form discrete functions with the limited number of values n. In order to reduce the error, caused by the discrete behavior of x_i, the Monte-Carlo method is used: the expected values are generated $N_{MCorderStatistic}$ times, and the values of x_i for each position *i* are averaged.

The critical region of the OSPPt test of the hypothesis under consideration is defined by the inequality (3.2).

$$OSPPt = \sqrt{\sum_{i=1}^{n} \frac{(\acute{x}_i - x_i)^2}{ns^2}} > C_{alfa}, \tag{2.2}$$

where

C_{alfa} – the boundary for the critical region;
alfa – significance level.

Thus, if $OSPPt > C_{alfa}$, then the test of the goodness-of-fit of the assumed distribution is failed for the given confidence level *1-alfa*.

The C_{alfa} is the *OSPPt* statistic. The *C* values are calculated for two ordered populations X_1 and X_2 of the expected CDFs of the assumed distribution. These calculations are made N_{MCalfa} times. Further, the C_{alfa} value is defined as the fractal of the approximating normal distribution.

$$C = \sqrt{\sum_{i=1}^{n} \frac{\left(\acute{x}_{1\_i} - \acute{x}_{2\_i}\right)^2}{ns^2}} \tag{2.3}$$

Typically, IP Performance Metrics Working Group (IPPM) compliance tests are conducted using 5 % significance. Therefore, value C_{alfa} is calculated as the fractal of the probability 1 – 0.05 = 0.95.

To make sure that the network load was not changed significantly, only the first 2000 samples were analyzed. A graphical representation of the RTT values (in log scale) and the statistics of deviations (scaled to 95 %) for the log-normal hypothesis are shown in Figs. 2.2 and 2.4 respectively.

The value of C_{alfa} of 0.039906 is significantly less that the value of OSPPt = 0.14972, therefore, the hypothesis should to be rejected. For more clarity, the histogram of OSPPt statistics for C_{alfa} values is shown in Fig. 2.3. Here, the value of C_{alfa} is a fractal of (1 – *alfa*) = 0.95.

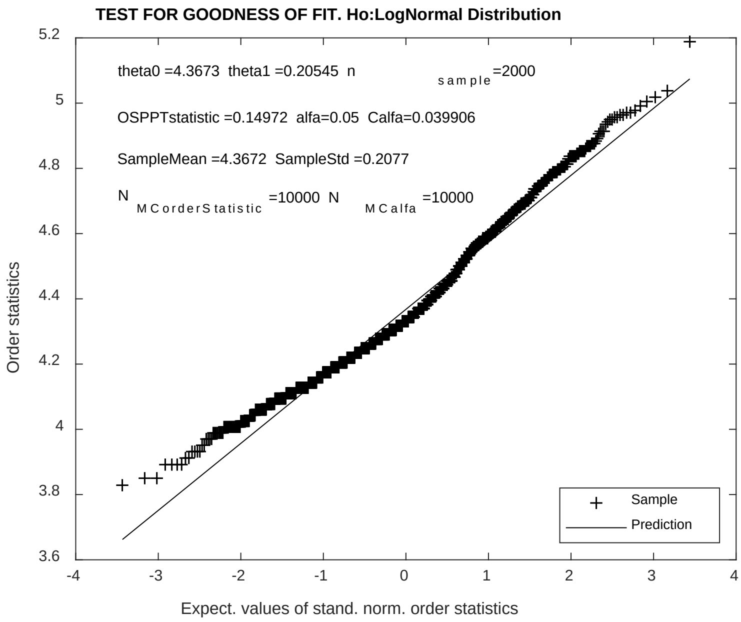


Fig. 2.2. Test for goodness-of-fit for the log-normal distribution.

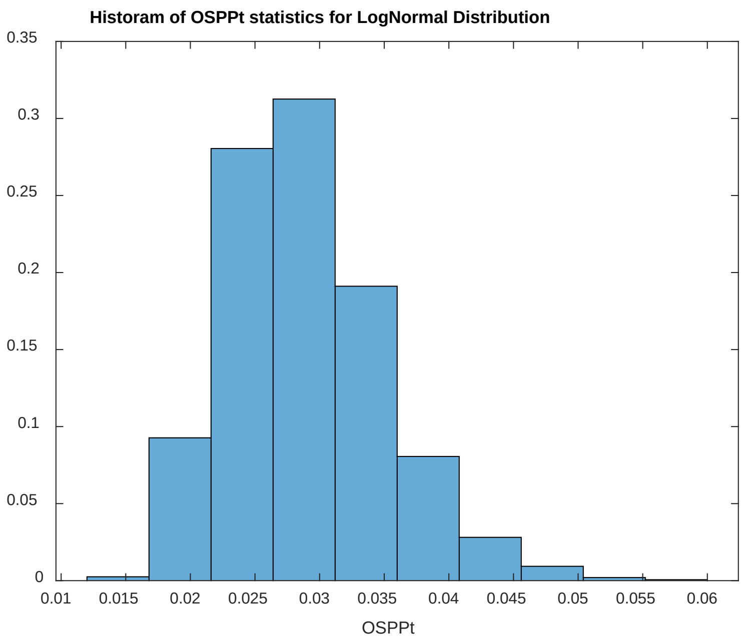


Fig. 2.3 Histogram of OSPPt statistics for C_{alfa} for the log-normal distribution hypothesis.

The histogram of deviations Δx of the observed data from the expected log-normal data is shown in Fig. 2.4. The values are converted back to natural scale. The x scale is scaled to the level of 95 %. As can be seen, 95 % of deviations are less than 5.4892 %. The deviations Δx of the observed data $\acute{x}_i$ from the expected data x_i are defined by (2.4).

$$\Delta x_i = abs\left(\frac{\acute{x}_i - x_i}{x_i}\right) \cdot 100\ \% \tag{2.4}$$

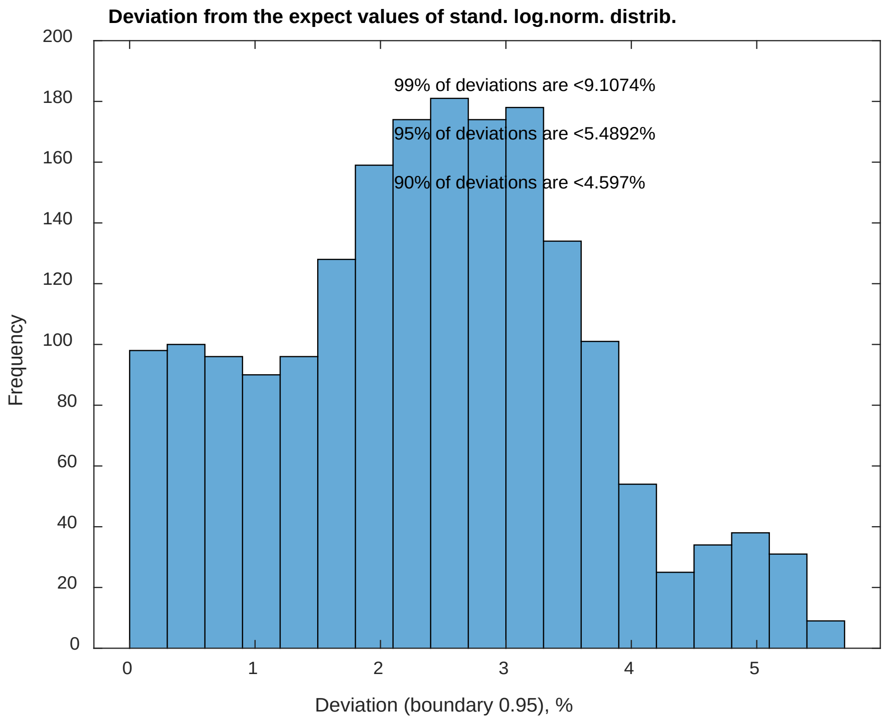


Fig. 2.4. Histogram of the observed data deviations from the expected log-normal data.

The illustrations of the evaluation of gamma, normal and Weibull (SEV in log scale) hypotheses are not provided in the summary to save the space. The values of the OSPPt for the log-normal, gamma, normal and Weibull (SEV in log scale) hypotheses are summarized in Table 2.1.

Table 2.1

Values of the OSPPt Statistics for Log-normal, Gamma, Normal, and Weibull Distribution Hypotheses

Distribution	OSPPt	C_{alfa}	Deviation from the expected (at the 0.90 boundary), %	Deviation from the expected (at the 0.95 boundary), %	Deviation from the expected (at the 0.99 boundary), %
Log-normal	0.14972	0.039906	4.5970	5.4892	9.1074
Gamma	0.17586	0.043469	5.5239	9.1548	17.8372
Normal	0.26687	0.039949	8.4735	13.7242	31.8879
Weibull	0.37532	0.06546	11.0790	16.8631	28.9140

The data of the OSPP test analysis indicates that the delays of the LTE cell do not fit to any of the distribution functions, tested with the confidence level of 95 %.

Further, the delays of the LTE cell will be tested in accordance with the Anderson-Darling goodness-of-fit test, or ADT. The ADT test is suggested for various metric tests of the network performance [9], [10]. Here, the uncorrected ADT statistic A is defined by (2.5).

$$A = -n - \frac{1}{n}\sum_{i=1}^{n}\left((2i-1)\left(lnF(X_i) + ln\left(1 - F(X_{n-i+1})\right)\right)\right), \quad (2.5)$$

where

A	– the statistic of the ADTest;
n	– the number of observations;
$F(X_i)$	– the CDF of the specified distribution;
X_i	– ordered sample data.

The same $n = 2000$ samples will be tested in accordance with ADT. The level of significance also is set to 5 %. The ADT will be performed for the log-normal, gamma, normal and Weibull distributions in the MATLAB application via the *adtest* function. The parameters of these distributions are unknown, and their estimates are obtained via the maximum likelihood method. The results for the log-normal, gamma, normal and Weibull hypotheses are summarized in Table 2.2, where A is the value of the statistic of ADT; P is the probability of observing an A statistic more extreme than the observed value under the null hypothesis; CV_{alpha} is the critical value for the given level of significance.

Table 2.2

Values of the ADT Statistics for Log-normal, Gamma, Normal and Weibull Distribution Hypotheses

Null hypothesis	P	A	$CV_{0.05}$
Log-normal	< 0.0005	15.786	0.75161
Gamma	< 0.0005	23.001	0.75161
Normal	< 0.0005	41.833	0.75161
Weibull	< 0.0005	59.394	0.76506

The results of the ADT analysis indicate that the delays of the LTE cell do not fit to any of the distribution functions, tested with the confidence level of 95 %, since in all cases $A > CV$ and p values are very low.

Even though the delays of LTE cell do not fit to any distribution law, tested with the confidence level of 95 %, these are mostly fit to logarithmically normal distribution. Note that 95 % of delay values deviate from the expected log-normal distributed data for less than 5.4892 %. Further, in Fig. 2.1 it is shown that the majority of deviations of the observed delay values from the expected log-normal distributed values occur at very low and very high values. First of all, the minimum value of the delay in the network is defined by the implementation of the network backhaul and can be reached if the network is used by single user only, whereas the logarithmically-normal distribution function is a continuous probability function and, therefore, has no minimum value at all. On the other hand, the maximum values of the delays in reality are limited to the maximum acceptable delay, after which the packet is considered lost and can be requested to be resent again. Therefore, it is not entirely correct to compare these maximum values with the continuous probability function.

2.1.1 Assuming the logarithmically normal distribution

Since the moderate values of the delays of LTE cell almost fit to log-normal distribution and only very high and low values deviate from this, let us assume that the delays of LTE cell obey the logarithmically normal distribution. Under this assumption, let us verify the accuracy of the prediction of delay average value and packet jitter value.

First of all, let us estimate the parameters of log-normal distribution. The distribution function parameters estimation can be done via various methods, but the Maximum Likelihood Method (MLM) is recommended here because it is more applicable for processing of censored observations.

First n = 2000 values of the experimental data, mentioned in Chapter 2, will be analyzed via the MLM. The parameter estimates are $\hat{\theta}_0 = 4.367$ and $\hat{\theta}_1 = 0.20557$ respectively. Since only the first 2000 values of the experimental data were analyzed, these also will be analyzed to estimate RTT mean and jitter values. Further, 2000 values of random variables will be generated with the assumption that the distribution function is log-normal and its parameters θ_0 and θ_1 are equal to estimated values $\hat{\theta}_0 = 4.367$ and $\hat{\theta}_1 = 0.20557$. The packet jitter is calculated as an average deviation from the network mean latency and is calculated using equation described in RFC3550 [11].

Experimental data for first 2000 RTT values is the following: average *RTT* = 80.62 ms; average *jitter* = 18.45 ms. For n = 2000 calculated values, if $\hat{\theta}_0 = 4.367$ and $\hat{\theta}_1 = 0.20557$ and assuming log-normal distribution, the results are the following: average *RTT* = 80.67 ms (error = 0.062 %); average *jitter* = 18.40 ms (error = 0.27 %). Errors are calculated with respect to the experimental data. The data is summarized in Table 2.3.

Table 2.3

Experimentally Obtained Values and Calculated Values Assuming Log-normal Distribution

	RTT_{mean}, ms	*Jitter*, ms
Experimentally obtained, first n = 2000 values	80.62	18.45
Calculated n = 2000 values, assuming log-normal distribution and estimates of $\hat{\theta}_0$ and $\hat{\theta}_1$ from first n = 2000 observations	80.67	18.40
Error, %	0.062	0.270

Thus, in order to obtain estimates of the average delay and delay jitter with satisfactory accuracy, it is possible to accept that the delays in LTE cells obey the logarithmically normal distribution law. Therefore, in further chapters we will assume that the delays in LTE cells fit to logarithmically normal distribution.

2.1.2 Quick method for estimating the delay distribution parameters in LTE cell

Confirmation of the hypothesis that the RTT values can be described by using the log-normal distribution law allows us to describe the RTTs of a specific LTE cell using only the distribution parameter values $\theta_0 = \mu$ = *median* and $\theta_1 = \sigma$ = *STDEV*, which is very convenient. However, in order to determine the distribution parameters via the maximum likelihood method, it is necessary to use cumbersome calculations with large amount of computing resources. In addition, the "ping" utility interface does not allow to get the entire array of delays required for the maximum likelihood analysis.

In order to simplify the process of determining the parameters of the log-normal distribution as much as possible, the following method was proposed. The method is based on the known values of the average and minimum T_{avrg} and T_{min} delays. Note that the values of T_{avrg} and T_{min} are known from the standard "ping" report. Accepting the hypothesis that the quantile T_{min}

equals $\Phi^{-1}(-3\sigma)$, we can determine the parameters $\theta_0 = \mu = median$ and $\theta_1 = \sigma = STDEV$ of the distribution function by solving the system of equations:

$$\begin{cases} \sigma = \chi_p + \sqrt{\chi_p{}^2 \pm 2\ln\left(\frac{Tavrg}{Tmin}\right)} \\ \mu = \ln(Tmin) - \chi_p\sigma \end{cases} \Rightarrow \begin{cases} \sigma = -3 + \sqrt{9 + 2\ln\left(\frac{Tavrg}{Tmin}\right)} \\ \mu = \ln(Tmin) + 3\sigma \end{cases}. \quad (2.6)$$

To confidently determine the distribution parameters from known T_{avrg} and T_{min}, it is necessary to clarify the required number of measurements. Let us define the number of measurements to get at least one value T_{min}, which is defined as $p_1 = 0.0014$ quartile. This can be done via binomial distributions for the specified probability p^*.

$$n = \frac{\ln(1-p^*)}{\ln(1-p_1)} = \frac{\ln(1-0.99)}{\ln(1-0.0014)} \cong 3289 \quad (2.7)$$

$$n = \frac{\ln(1-p^*)}{\ln(1-p_1)} = \frac{\ln(1-0.999)}{\ln(1-0.0014)} \cong 4931 \quad (2.8)$$

Therefore, with the probability of 99 %, at least one T_{min} value will appear if the number of measured RTT values is at least 3289; the probability of 99.9 % will require at least 4931 measured RTT values.

When evaluating RTT values, packet loss rate should also be evaluated. The required number of measurements for the packet loss estimation can be found by applying confidence limits (CI). Thus, for the typical packet loss rate $p = 10^{-4}$, for the CI of ±30 % and probability to hit in $\beta = 0.9$ we will have

$$n = \frac{t_\beta^2 \cdot (1-p)}{p \cdot (k-1)^2} = \frac{2.576^2 \cdot (1-0.0001)}{0.0001 \cdot (1.3-1)^2} = 299909\ . \quad (2.9)$$

Or for the typical packet loss rate $p = 10^{-4}$, for the CI of ±10 % and probability to hit in $\beta = 0.9$ we will have

$$n = \frac{t_\beta^2 \cdot (1-p)}{p \cdot (k-1)^2} = \frac{1.643^2 \cdot (1-0.0001)}{0.0001 \cdot (1.1-1)^2} = 2699179\ . \quad (2.10)$$

Therefore, for a typical value of packet loss is 10^{-4} [12] in HSPA+ networks and above, 299 909 RTT measurements are required for confidence intervals of ±30 % with a 0.9 probability of falling into a given range; the confidence intervals of ±10 % and 0.9 probability of falling into a given range, 2 699 179 measurements will be required. With so many measurements, there is no doubt that the value of T_{min} will already take its reliable value.

2.2. Experimental evaluation of the impact of mobility on delays in the 3G and LTE cellular networks

All of the above-mentioned measurements were carried out using a fixed 3G/LTE dongle. Now it is necessary to evaluate the feasibility of taking measurements of RTT in motion in order to be able to perform measurements in different cells without stopping a car.

The Huawei 3372h dongle was used to perform these experiments. To make it easier to record network parameters (such as signal strength, interference, Cell ID of the active cell, etc.), the dongle has been reprogrammed into Stick (RAS) mode. In this mode, the Huawei 3372h opens its PC UI serial port, allowing to access the above-mentioned information.

For the convenience of recording RTTs, parameters of the mobile network as well as GPS coordinates and ground speed, a virtual instrument (vi) was created in the LabVIEW environment. This tool is not only capable of collecting all data, decoding it and writing it to a common table, but also allows to conveniently export data to MS Excel.

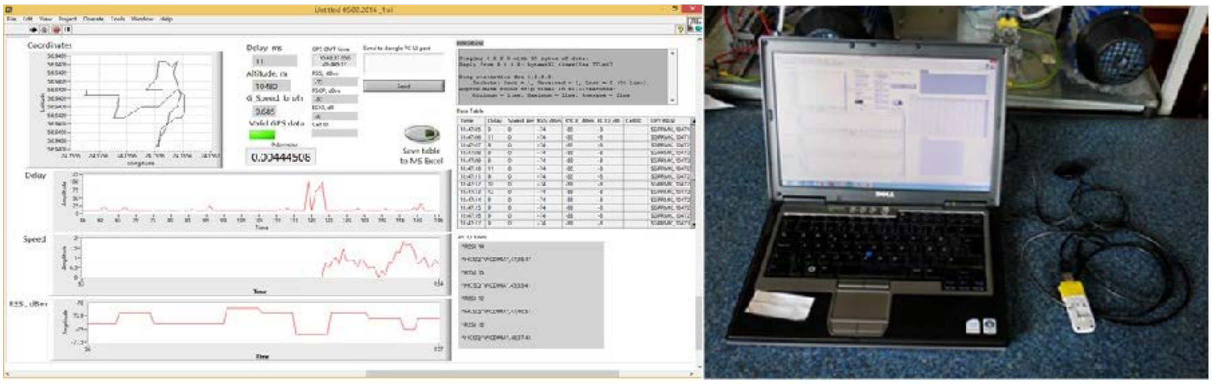


Fig. 2.5. Data acquisition system.

For the following experiments, the dongle was fixed on a wooden mount and located at a distance of 1 m from the car.

According to the results of experiments, the following conclusions can be made:

- The performance of 3G networks (HSPA+ and above) does not depend on travelling speed (tested up to 100 km/h) or accelerations. The handover process did not lead to increased delays provided that the signal level is sufficient. However, it should be noted that when the direction of motion was changed, some of RTT values become increased. However, this effect did not have repeatable results and therefore could not be described. Also, these networks tend to remain in UMTS mode if a short-term signal loss appears.
- The performance of LTE-class networks does not depend either on speed or on accelerations or direction changes.

2.3. Evaluation of delays in the cellular network of a particular cellular operator

Since it was proved that LTE network performance does not depend on whether the terminal moves or remains stationary (in most cases, the same applies to 3G HSPA+ and above), it is possible to perform measurements in different cells from a moving car without the need for long stops to perform the measurements.

The performance of mobile networks depends not only on the technology used (GPRS, EDGE, HSPA, HSPA+, DC-HSPA+, LTE, LTE-A, etc.) but also on the implementation of terrestrial backhaul of base stations. In experiments in motion, changes in the average value of the delays were already noticeable depending on the cell used. Therefore, it was necessary to perform measurements in different LTE cells within the same operator to characterize the overall LTE network.

First, let us prove that with a satisfactory signal level, network performance depends mainly on the implementation of its terrestrial backhaul as well as on the load on each cell. To do this, two Huawei 3372h dongles were installed in the car, all the parameters from dongles were registered by the vi in LabVIEW. The first modem was sending an ICMP request to the google free DNS server (located on the WAN network), as well as to the second dongle. The second dongle was equipped with a SIM card with a real IP address. The peculiarity of the operation of 3G and LTE networks is that traffic always passes through their core networks. Thus, echo-requests to the server located in the WAN pass through the terrestrial backhaul and wireless interface twice; in the case of requests to the second dongle, requests also pass through the terrestrial backhaul twice (because direct device-to-device (D2D) connections are not implemented in 3G and LTE networks). The results of measurements of RTT values were pre-processed as follows: first, all values obtained with a signal level worse than recommended [13] are thrown out, after which each cell is processed separately. The analysis of experimental data showed that the increase or decrease in the delay from one cell to the next occurred proportionally for both the server located in the WAN and the request for the second dongle. Thus, we can make an unambiguous conclusion that if the level and quality of the radio signal are sufficient, the performance of the 3G HSPA+ and LTE cells is mainly determined by the implementation of their terrestrial backhaul, in particular the "first mile link". Therefore, the existing myth that both mobile devices must necessarily be within the same cell to achieve the best performance is untenable: when moving to the next cell, delays can either increase or decrease, or they may not change. It should also be noted that 3G cells showed a larger spread of average delays than LTE cells. This is due to the fact that many 3G cells were gradually upgraded from UMTS to HSPA+, while their terrestrial backhaul was not replaced.

In the experiment described above, the analysis was performed for five 3G cells and for six LTE cells. Despite the small number of cells, the results already indicate a large spread in RTTs of different cells. For a comprehensive description of the RTTs of the entire LTE network within one operator, it is necessary to make and analyze a larger number of measurements on different cells.

2.3.1 Development of a model of delays in the LTE cellular network based on experimentally obtained data

The evaluation of the delays of various LTE cells was carried out in the Tele2-LV network. The evaluation of 2G/3G cells was not carried out due to the obsolescence of these technologies. The experimental evaluation was carried out as follows: two dongles were fixed in the car; in order to reduce the effect of antenna patterns, both dongles were aligned equally; the first dongle sent ICMP requests to the second dongle (D2D scenario) and to google free dns server (D2WAN scenario); the parameters of the radio signals from both dongles were recorded, as well as their registration in the cells; the car moved twice using public roads at distances of 230 km. In the first case, both dongles were operated in the B3 band, in the second – in the B20 band. Further, the experimental data were processed as follows: first, the data obtained at the RSSI signal level < –80dBm (based on Cisco recommendations [13]) was discarded, after which the data was sorted by CID when both dongles were registered in the same cell. Packets delayed for more than 1 second were considered lost and were not taken into account in further analysis. Further, assuming the hypothesis that delays in LTE networks are subject to the logarithmically normal distribution law, estimates of distribution parameters for each of the cells were determined. The detailed explanation of the methodology can be found in [14].

By displaying the estimates of distribution parameters $\hat{\theta}_1 = \hat{\mu}$ (median) along the x axis and $\hat{\theta}_2 = \hat{\sigma}$ (standard deviation) along the y axis, the measurement results are visualized in Fig. 2.6.

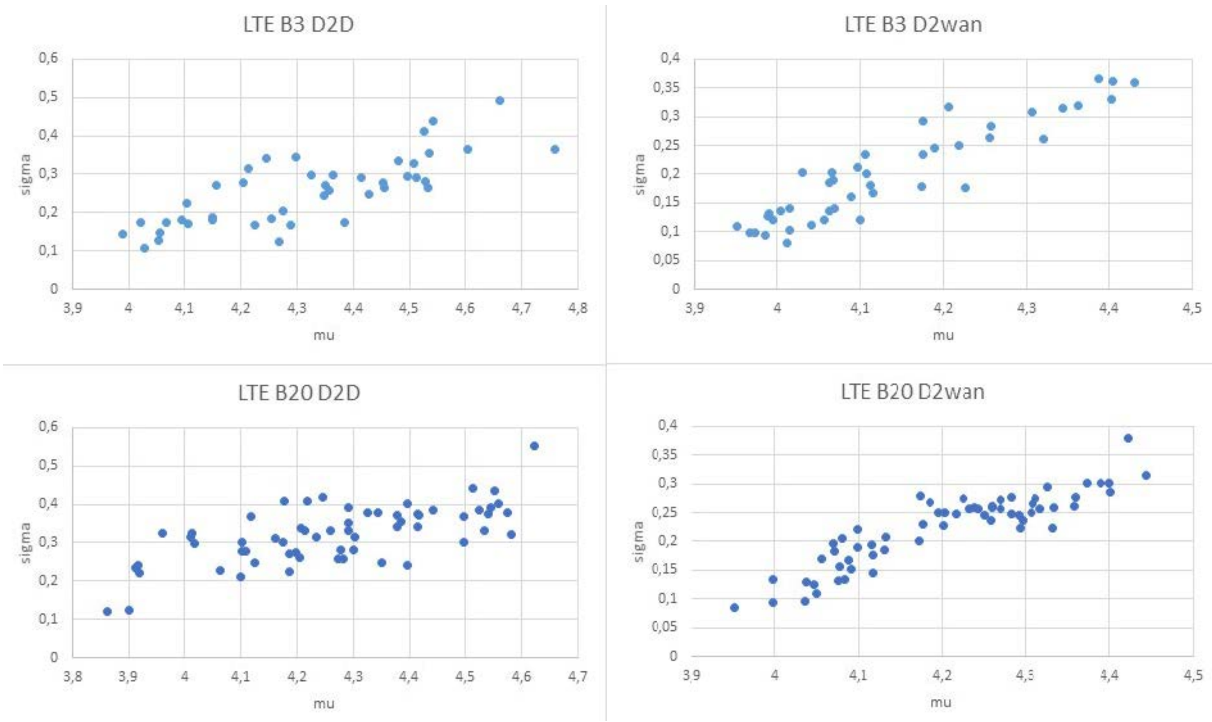


Fig. 2.6. Estimates of parameters of log-normal distributions for D2D and D2WAN scenarios for B3 and B20 bands.

The location of the points in the graphs indicates a positive correlation between the distribution parameters of delays estimated for different LTE base stations. Now let us assume that the obtained parameter estimates are equal to parameters $\hat{\mu} = \mu$ and $\hat{\sigma} = \sigma$. Since the operation of cells is independent of one another, the values μ and σ for each of the cells are also independent of each other. Thus, one can easily find unbiased estimates of mathematical expectations (median) $\widehat{m}_\mu$ and $\widehat{m}_\sigma$, standard deviations $\widehat{\sigma}_\mu$ and $\widehat{\sigma}_\sigma$, as well as the correlation coefficient $\hat{r}_{\mu\sigma}$ for a two-dimensional system of random variables μ and σ of delays in each LTE cell. The evaluation results are shown in Table 2.4.

Table 2.4

Parameter Estimates of the System of Random Variables of the Delays of the Tele2-LV LTE Network

Mode	LTE B3		LTE B20	
Scenario	D2D	D2wan	D2D	D2wan
$\hat{m}_{\mu}$	4.321111854	4.137481307	4.263534974	4.200827382
$\hat{m}_{\sigma}$	0.258320572	0.202567894	0.322766576	0.221865836
$\hat{D}_{\mu}$	0.037543165	0.019163568	0.037950614	0.014353549
$\hat{D}_{\sigma}$	0.008008621	0.007172750	0.005791700	0.003842329
$\hat{\sigma}_{\mu}$	0.193760587	0.138432539	0.194809174	0.119806296
$\hat{\sigma}_{\sigma}$	0.089490898	0.084692087	0.076103222	0.061986520
$\hat{r}_{\mu\sigma}$	0.777179594	0.920297543	0.691265663	0.894327522

2.4. Development of delay requirements for the C2 link

There are currently no unified requirements for the quality of radio channels for UASs. Therefore, first, it is necessary to establish the requirements for assessing the feasibility of implementing C2 link through 3G or LTE data services. In the Thesis these requirements are characterized using existing requirements for similar systems [2], [15]–[20], as well as on the basis of experimental studies of the maximum allowable delays in the aircraft control channels [21], [22]. Based on the above analysis, the following requirements can be specified:

- The “ideal” overall two-way delay (from the command input and to the feedback display) should be ≤ 150 ms for a typical pilot; and not more than 200 ms to prevent oscillations (if none of helping technologies (e.g. PID controllers) are used).
- The “ideal” overall two-way delay (from the command input and to the feedback display) should be ≤ 310 ms for an experienced pilot; whereas up to 400 ms are also “acceptable”.
- In the case when FPV is used as feedback, the video channel overall (inc. processing time of the codecs) one-way delay should be ≤ 150 ms (assuming 0 latency in the command data transfer line).

Before starting to evaluate the performance of 3G and LTE services, we should also mention the aspects of the operation of 3G (HSPA and higher) and LTE data transfer systems. The main goal of creating the aforementioned cellular systems was to increase the data transfer rate. For this reason, automatic modulation and coding (AMC) chooses a modulation scheme so that the packet error rate becomes equal to 10 % [23]. Further, the lost packets are retransmitted by the hybrid automatic request (HARQ) mechanisms, implemented in the base station (BS) and user equipment (UE). This allows to achieve highest data rates, but it is at the cost of increased packet jitter. To prevent TCP mechanisms from trying to re-send lost data in parallel with HARQ mechanism, the BS breaks the TCP session by automatically sending acknowledgement to the sender (for TCP packets only). This fact does not allow to use the ACK arrival time for measuring the RTT of overall network. For this reason, ICMP packets will be used in the following evaluations (unless otherwise specified).

2.5. Analysis of compliance of delays in the LTE cellular network with the C2 link requirements

After the delays in the LTE cells of the Tele2-LV cellular operator have been characterized, we can start to evaluate the possibility to create the C2 link via the existing LTE service.

In Section 2.4, the following requirements for the RC channel were defined:

- ≤ 150 ms is recommended for a typical pilot (with the limit at 200 ms);
- ≤ 310 ms is recommended for an experienced pilot (with the limit at 400 ms).

In Section 2.4, the following requirement for the FPV channel was defined:

- overall one-way delay should be ≤ 150 ms (this implies the impact of the de-jittering buffer, as well as codec's processing time).

Assuming that "zerolatency" codecs are used (like in H.264, where one packet is processed at a time), the overall delay will consist of a data transfer line delay plus de-jittering buffer delay. Let us assume that the de-jittering buffer delay is equal to IPDV value. The IPDV value states the difference between the upper bound on the 0.999 quantile of IPTD minus the minimum IPTD.

To obtain the results, let us utilize the system of random variables of the Tele2-LV LTE network, operating in B20 band in D2D scenario. The evaluations will be made based on the assumption that RTT values of LTE cells obey the log-normal distribution. Fig. 2.7 shows simulated (blue dots) and experimental (yellow markers) parameters of log-normal distribution of delays in cells. The simulation results consist of 50,000 simulated distribution parameters. The simulation is done using normal distribution law approximation of the system of random variables, and the experimental data is used from Table 2.4.

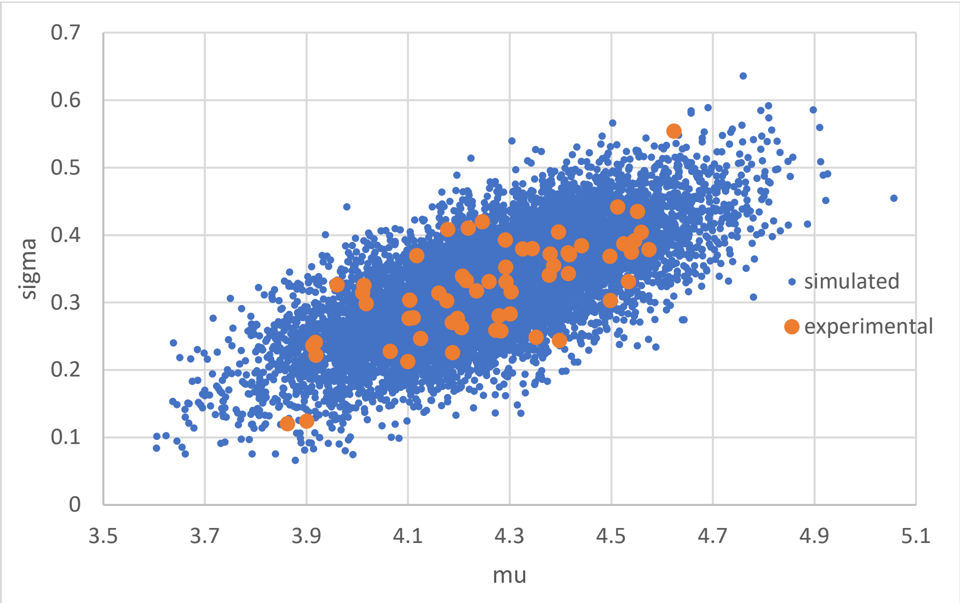


Fig. 2.7. Parameters of log-normal distributions of RTTs of different LTE cells (D2D scenario of LTE-to-LTE in band B20, Tele2-LV).

The RTT for RC-operations will be expressed from the simulated data of the system of random variables assuming its normal approximation. The RTT will be expressed at the 0.999 quantile (with the aim to show that the RTT in 99.9 % will not be greater than value specified.

The estimation of the 0.999 quantile $\Phi^{-1}(0.999)$ will be done assuming that RTT of LTE cells are logarithmically normally distributed.

The problem is that IPDV metrics use latency (one-way delay) rather than RTT (two-way delay). It is known that in 3G and LTE networks, the uplink channel has lower performance than the downlink channel. However, in our case, delays were measured between two dongles, which means that the RTT value includes the delay values of two uplink channels and two downlink channels. Since both dongles were located at a distance of 1 m from each other and were oriented identically, we can conclude that the signal levels were the same, which in turn means that the selected AMC schemes were also the same. Of course, this approach is only possible for the D2D scenario. Considering all the above mentioned, the distribution parameters for latency estimation in D2D scenario (assuming log-normal distribution) will be calculated as follows:

$$\theta_{0\ RTT} = \mu_{RTT} = \ln(2) + \theta_{0\ latency} = \ln(2) + \mu_{latency} \tag{2.11}$$

$$\theta_{1\ RTT} = \sigma_{RTT} = \theta_{1\ latency} = \sigma_{latency}\ . \tag{2.12}$$

The results show that the performance of only 25 % of LTE cells guarantee that at least 99.9 % of RTT will be below 150 ms and only 53 % of LTE cells guarantee that at least 99.9 % of RTT will be below 200 ms, therefore the delay in LTE network in many cases is not suitable for the RC operations for a typical pilot.

The results show that the performance of 88 % of LTE cells guarantee that at least 99.9 % of RTT will be below 310 ms and 97 % of LTE cells guarantee that at least 99.9 % of RTT will be below 400 ms (which is the maximum allowed RTT for an experienced pilot). This indicates that the experienced pilot can perform RC operations via the LTE network (note that sometimes an experienced pilot will have to provide more mental effort, as RTT will be greater than 310 ms).

For the FPV the size of a de-jittering buffer should be specified first. The experimental data shows that the de-jittering buffer of 310 ms will be sufficient in 99.9 % of times. Next, assuming the constant length of the de-jittering buffer of 310 ms (that will be sufficient in 99.9 % of times, producing 0.1 % packet drop), the latencies should be specified as minimum latency plus de-jittering buffer. In this case none of LTE cells will satisfy the requirements for the FPV of < 150 ms if a 310 ms constant size de-jittering buffer is used.

Now, let us assume that the de-jittering buffer is adaptive and is equal to the IPDV value. Since no additional space is considered in the de-jittering buffer, the FPV channel will operate with the constant latency of 0.999 quantile of the latency of the given cell. In this case only 86 % of LTE cells will satisfy the required latency of < 150 ms with the packet drop rate of 0.1 %.

Since modern video codecs can accept packet loss up to 1 % [16], the upped bound for the IPDV can be set to 0.99. The experimental data indicates that 98 % of all LTE cells will provide satisfactory latencies for the FPV target of < 150 ms, if the de-jittering buffer is equal to IPDV, estimated to 0.99 boundary (1 % packet loss target). Please note that all the mentioned above assumes zero latency in codecs and camera, as well as ideal IPDV estimation for the adaptive de-jittering buffer sizing.

Once again, note that all of the above data is only valid for cases when the signals level and quality are “good” (as per this reference [13]).

3. ANALYSIS OF THE IMPACT OF FLYING ALTITUDE ON THE PERFORMANCE OF CELLULAR DATA TRANSFER SERVICES

2G, 3G, LTE networks were designed for terrestrial users, so base station antennas are downtilted. The available field studies [24], [25] stated that despite downtilted antennas cellular network coverage up to 300 m height above ground level (AGL) is sufficient to promise possible UAV control over existing cellular data transfer services.

Theoretically, with increasing flight altitude, the UE should gain direct visibility with an increasing number of BSs. This, in turn, should lead to an increased interference, which was observed in many measuring companies in 2018, as in [26], [27].

In this research, the initial familiarization with the situation was carried out in mid-2017. At that time, the repeated checking of the operability of LTE networks has not been performed, therefore 3G service was used. The Huawei 3372h dongle was located in a light aircraft which flew over the Spilve airfield. Two laps were performed. The flight was affected by a strong gusty side wind. In the first lap, the airplane was piloted by an inexperienced pilot, in the second – the airplane was piloted by an experienced instructor, as a result of which the flight was much more stable. The measurement results are presented in Fig. 3.1. The first plot shows RTT, lost packets, ground speed and altitude above mean sea level (MASL); the second plot shows network performance indicators: RSSI (left *Y* axis, blue curve in dBm); *Ec*/*Io* (right *Y* axis, red curve in dB). RTT values were measured to the google free DNS server (ip: 8.8.8.8) using LMT network.

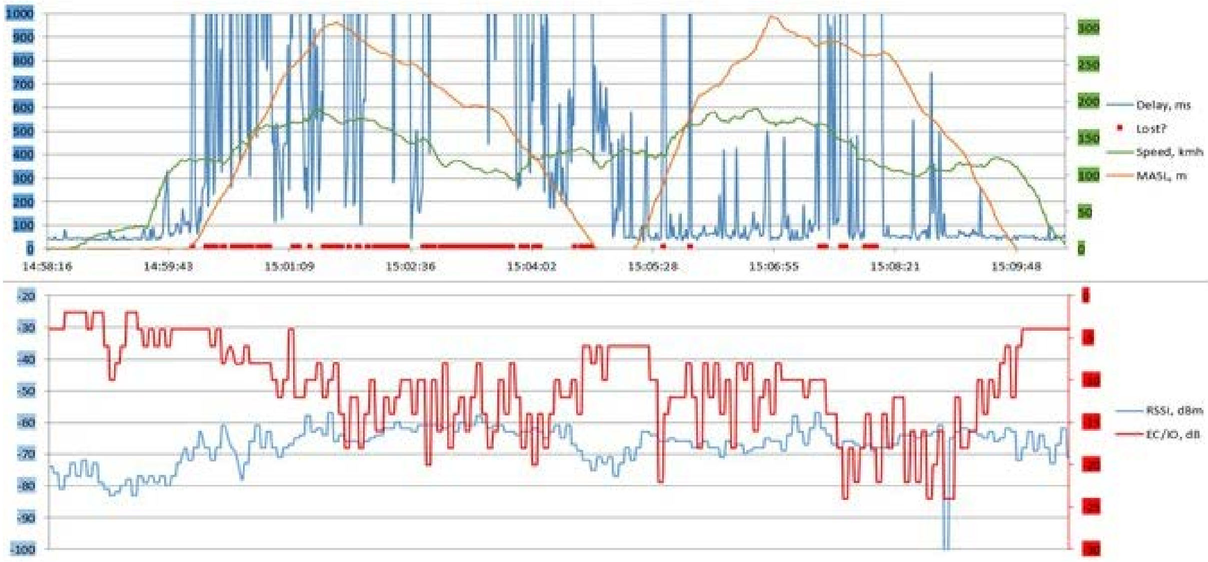


Fig. 3.1. Network performance during ground roll, two laps with one take-off and one go-around, as well as one landing.

The results of the experiment show that despite the similar indications of the quality of the radio signal, in the first round the delays are much less stable and the number of lost packets is very large. This can only be explained by the fact that the flight on the second lap under the guidance of the experienced instructor was much more stable. Also, it is possible to see the well-known fact that with increasing height, interference increases (the *Ec* /*Io* index decreases).

Obtaining of repeatable results using an airplane is too expensive, therefore, in 2018, a quadcopter was used for this purpose. It was equipped with Raspberry PI 3B companion computer running under Gentoo Linux, as well as the Huawei 3372h dongle attached to it. Vertical flight was carried out on the left side of the Spilve meadows, far away from roads, zone of passage of small aircrafts and interfering objects. Climbing was carried out at a climb rate of 1 m/s, after which at a height of 115 m the drone was hovered for 15 seconds and then landed with the descent rate of 1 m/s. RTT were measured to a ground station equipped with a second Huawei 3372h. From the Huawei 3372h located on the ground, delays were also measured to google free DNS server, which turned out to be stable and without packet loss. The experimental results of the 3G Tele2-LV network showed similar results to those obtained in the 3G LMT network in 2017 using an airplane. Unfortunately, at that time the hardware implementation did not yet allow receiving data on the level of the radio signal, therefore this parameter is not shown.

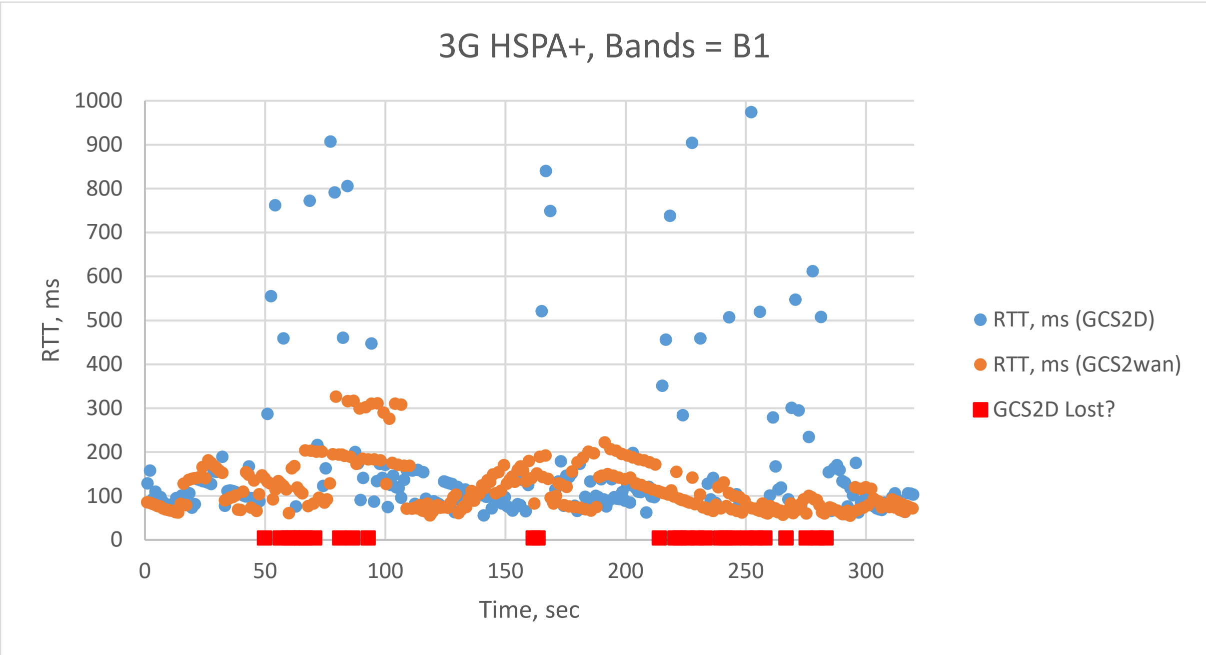


Fig. 3.2. RTT of ground station to drone (GSC2D) and ground station to google free DNS server (GCS2WAN) in 3G HSPA+ B1 band.

Then, similar experiment was conducted in the LTE Tele2-LV network. The results showed that the delays in the LTE network do not depend on the height and rate of climb/descent.

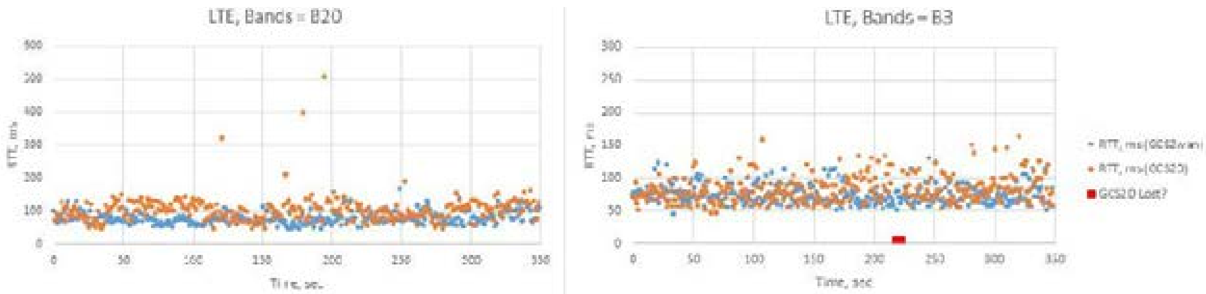


Fig. 3.3. RTT of ground station to drone (GSC2D) and ground station to google free DNS server (GCS2WAN) in LTE B3 and B20 bands.

In 2019, the opportunity arose to study in more detail the coverage of 3G and LTE networks using a drone. In this research the Huawei ME909s-120 module was used as a measurement equipment. The advantages of this module are that, firstly, it allows to search not only 3G but also LTE cells, secondly, it was equipped with an external omnidirectional antenna, which greatly simplified its spatial orientation compared to a PIFA antenna, and, thirdly, its receiver diversity antenna was not connected.

Due to the limited battery capacity, measurements were taken in increments of 25 meters in altitude. At each height, two measurements were made. It should be noted that the base stations do not always respond to the search request, and also because of the side wind it was not possible to keep the antenna in a strictly vertical position, therefore, the measurement results start to fluctuate. Measurements were made only in the LTE network. Base stations of all operators were found, but to save space, only base stations of the Tele2-LV operator of B3 band (as an example) will be shown in Fig. 3.4. The *X* axis shows the height above ground level (AGL, m); along the *Y* axis, levels of received signals, dBm, are shown; CIDs are shown in color and indicated in the legend of the graph.

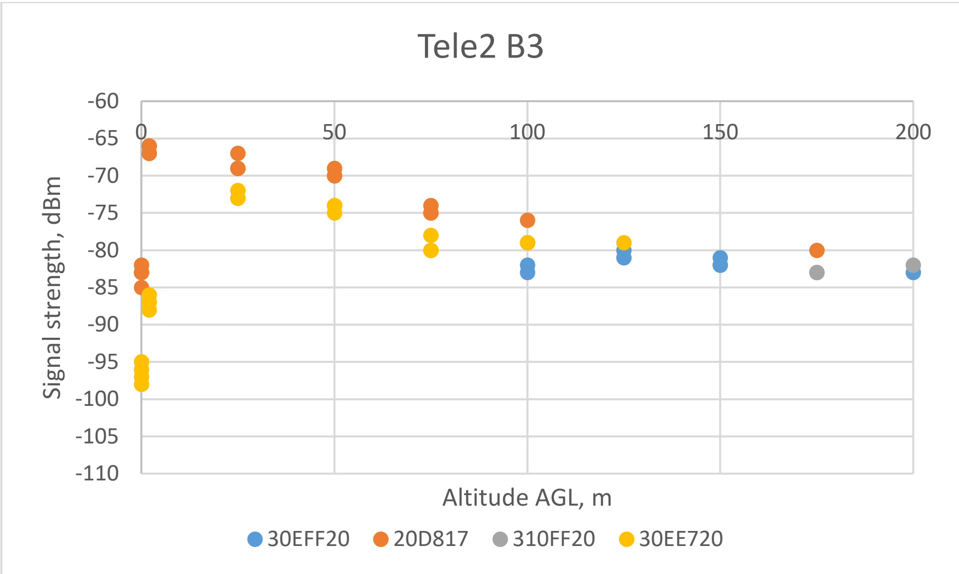


Fig. 3.4. Example: Vertical LTE network coverage in the B3 band of the Tele2-LV cellular operator.

The experimental results show that the coverage of LTE networks is more than sufficient (–105 dBm is considered as “good” signal strength [13]), which promises possibility to operate up to 200 meters. However, in order to ensure that the LTE UE can operate efficiently, not only the signal strength, but also the signal quality should be evaluated.

For this, the drone was first climbed, where at an altitude of 130 m the LTE service was lost. LTE service was restored at an altitude of 90 m. The illustrations in Figs. 3.5 and 3.6 a is a record of the descent process.

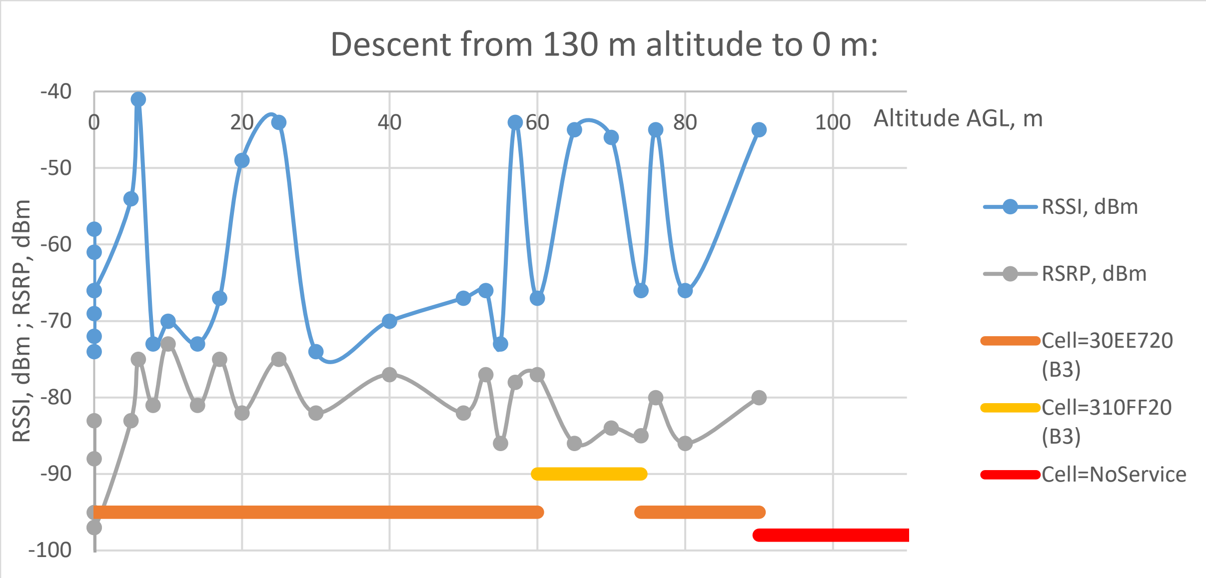


Fig. 3.5. RSSI, RSRP in dBm vs altitude, LTE service of the Tele2-LV cellular operator.

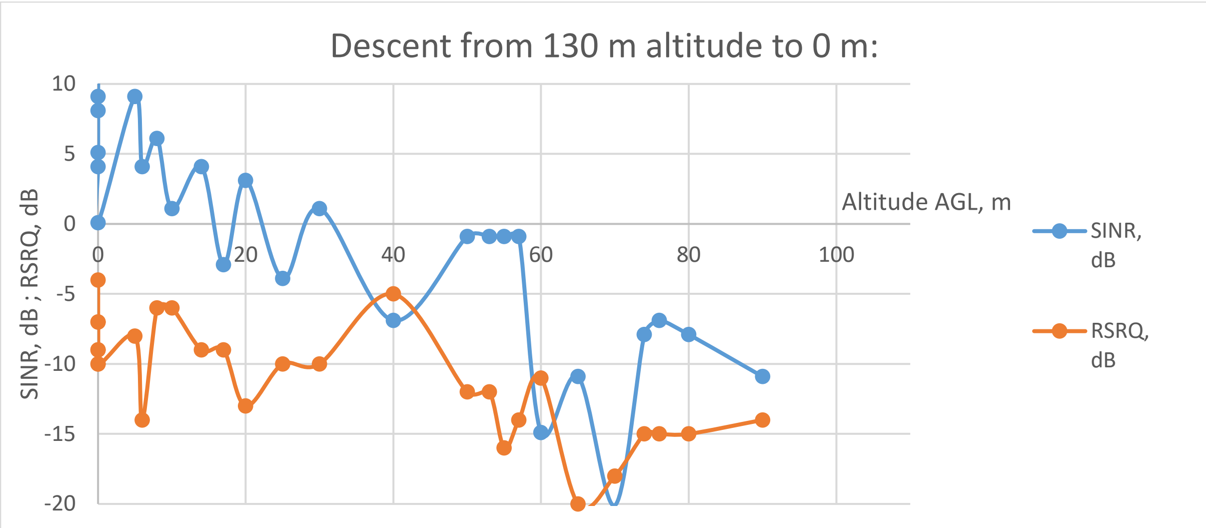


Fig. 3.6. SINR, RSRQ in dB vs altitude, LTE service of the Tele2-LV cellular operator.

Thus, preliminary it is possible to conclude that the LTE service is more stable at high altitudes than the 3G HSPA+ service. Based on the analysis of the network delays, the AMC mechanism of LTE service can efficiently select a coding and modulation scheme, adapting to changing interference. However, when interference exceeds a certain threshold, the LTE service fails (in the literature, the minimum value of SIRN is –6 dB, but in our experiment, the operation was maintained down to –10 dB).

It is interesting to consider the difference between 3G and LTE networks. Both suffer from an increase in interference at higher altitudes, but the performance of 3G networks with increasing altitude almost immediately begins to fail. According to the author ‘opinion, this can be explained by two factors. Firstly, during experiments with the car it was experimentally shown that sharp changes in the position of the antenna lead to increased delays in 3G networks, whereas this was not been observed in LTE networks (the experimental results were published in [28]). Secondly, there is an assumption that with the soft handover used in 3G networks, packet reordering also leads to increased delays, since with increasing height the network coverage becomes heterogeneous and the coverage areas of base stations mix and give almost similar signal levels, which causes the constant involvement of the soft handover mechanism. In LTE networks, the use of soft handover is not possible due to the use of OFDMA, which does not allow working with several base stations simultaneously. The hard handover used in LTE networks has a small hysteresis between switching, which in this case partially helps to avoid the problems described above. It is worth noting that the analysis of preliminary experimental data suggests that the value of the hysteresis between switching between BSs should be increased for users in the air. It should also be noted that a full study of this problem has not been conducted. Existing fragmentary studies were generalized in [29], but the studies presented there cannot be called comprehensive.

Thus, it should be recognized that at the moment 3G / LTE networks deployed in Latvia are not ready to become a reliable means for implementing C2 Link.

4. METHODS TO MINIMIZE THE IMPACT OF UNSTABLE DATA TRANSFER QUALITY OVER A CELLULAR MOBILE NETWORK

The effect of unstable operation of 3G/LTE networks for users in the air can be minimized by using parallel redundancy of data transmission channels.

In the Thesis two studies of the operability of two parallel redundant solutions were performed. These solutions were not previously used in mobile communication networks, which are characterized by a large number of lost packets and intermittently changing delays.

Let us assume that the GCS will be connected to the wired Ethernet. An IEEE Std 802.3 defines that for the 100 Mbit Ethernet, BER should not be more than 1e-10, and for the 1000 Mbit Ethernet, BER should not be more than 10^{-12} [30]. This makes wired Ethernet extremely safe compared to cellular data transmission service with BER of 10^{-4} [12].

To implement a parallel redundant link, the node must be connected to two different networks with same protocols. Such node is called dual attached node (DAN). Both networks can be still accessible by other equipment, called single attached nodes (SANs). Simplified network structure is represented in Fig. 4.1.

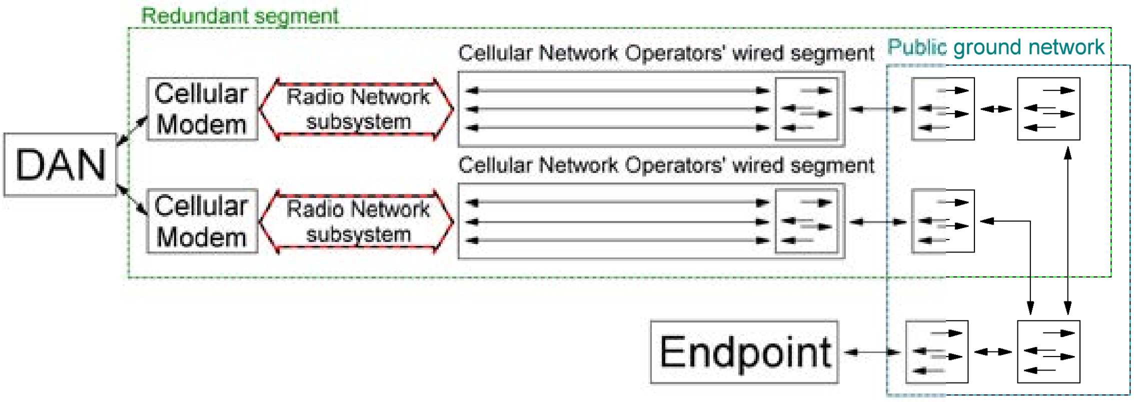


Fig. 4.1. Structure of a redundant network implemented on two different cellular operators' networks.

In the Thesis, two software solutions were tested. Both have not been previously implemented in cellular networks, therefore their performance in cellular networks of the solutions was evaluated experimentally.

The first one was the Parallel Redundancy Protocol (PRP) [31], which is an IEC standard that is used to build redundant industrial ethernet solutions for the critical applications that cannot tolerate packet losses and require hitless network. The key benefits of PRP are the ability to use paths with identical protocol but with different topology, as well as transparent operation for the network equipment. As PRP operation is transparent for both paths, its traffic usually is not blocked by the network equipment [32]. Such solution will protect any kind of packets, e.g. TCP, UDP, ICMP, etc. In the experiments, ZHAW university implementation of the Parallel Redundancy Protocol (PRP according to IEC 62439-3 / 2012) as a VHDL IP core [33] was used. Detailed description of the experimental setup as well as the experimental results can be found in [34].

The second solution was the MultiPath TCP (MPTCP) kernel implementation [35]. This solution can protect only TCP traffic, whereas UDP traffic remains on a single node. This solution can operate under the control of one of three schedulers. All schedulers' operations were experimentally investigated. The reaction on single node failure was investigated too. Detailed description of the experimental setup as well as the experimental results can be found in [36].

The choice of the combinations of cellular network services has been evaluated and motivated in [37]. The flexible software platform for a prototype development is described in [38].

It can be concluded that ZHAW's PRP-1 software implementation can be used as efficient redundant solution for all kind of traffic, however its implementation with a single endpoint of GCS is problematic. MPTCP kernel implementation with enabled "redundant" scheduler can be used as efficient redundant solution for TCP traffic, can be easily implemented with a single endpoint, but its implementation is useless in Telemetry and FPV video transmissions due to the use of UDP packets.

A study was also conducted regarding the recommendations for choosing service combinations for constructing a parallel redundant communication channel [37]. Today, it is possible to conclude that the most recommended solution is to combine LTE services from two different operators. If only one operator is available, then the use of one high-frequency band (usually B3) and a one long-range band B20 can be recommended. The use of 3G networks can only be recommended if local overloads of LTE cells are observed, which was not observed in Latvia during the 2018 experiments.

The question of what improvement can be obtained if parallel redundancy is used is usually solved either by simulating the network topology (e.g. OPNET [39], [40]; OMNet ++ [41], etc.) or using ITU recommendations where Markov chains are used [42]. The use of modeling with software such as OPNET in mobile networks can be recommended only if later the user remains stationary or moves in a limited space of coverage. In turn, for applying Markov chains, it is necessary to know the probabilities of transitions from one state to another, which are unknown to a typical user.

In this Thesis another method is proposed. The method allows to predict network latencies for a parallel redundant network using only statistics from the "ping" utility. To do this, we assume that the lost packets are eliminated, and the remaining real values of the delays *z* of each channel are described by the conditional probability function $F_Z(z)$. We also denote the probability of packet loss in each of the q_n channels. If all data transmission channels are independent, then in the general case, the resulting conditional (without lost packets) probability function for *n* parallel channels will be described by the following equation:

$$F_Z(z) = P(Z^* < z | Z^* < \infty) = \frac{P(Z^*<z)}{1-P(T_1^*=\infty)\cdot P(T_2^*=\infty)} = \frac{P(Z^*<z)}{1-q_1 q_2}\,. \tag{4.1}$$

The probability of Z^*, when $Z^* < \infty$, can be expressed by finding a minimum, as follows:

$$F_Z(z) = 1 - P(Z > z | Z < \infty) = P(Z^* < z | Z^* < \infty) = \frac{P(Z^*<z)}{1-P(Z_1^*<z)\cdot P(Z_2^*<z)\cdot\ldots\cdot P(Z_n^*<z)} = \frac{P(Z^*<z)}{1-\prod_{i=1}^{n} q_i}\,. \tag{4.2}$$

In real life a parallel redundancy of *n* = 2 parallel channels are usually used. In this case, the expression for conditional probability will have the form

$$F_Z(z) = 1 - P(Z > z|Z < \infty) = \frac{1-\left(\left(1-F_1(z)\right)\cdot(1-q_1)+q_1\right)\cdot\left(\left(1-F_2(z)\right)\cdot(1-q_2)+q_2\right)}{(1-q_1 q_2)}. \quad (4.3)$$

Further, accepting the hypothesis that the delays in LTE networks obey the log-normal distribution law, we can replace the CDF function $F_Z(z)$ built from experimental data with a CDF function built for the log-normal distribution. Further, the parameters of the log-normal distributions can be found using the known values of the minimum and average delays, which can be obtained from the “ping” utility program report (see Subsection 2.1.2 for more details). Further calculations are not complicated.

According to the author, the suggested approach in parallel redundant networks with simple architecture is faster and more convenient than applying the unified approach described in the ITU recommendations [42].

CONCLUSIONS

The purpose of the Thesis is to evaluate the possibility to implement wireless command and control link of low-flying UAVs via existing mobile data transfer services. According to the obtained experimental data, it can be concluded that, in general, the existing LTE network allows to create an RC and FPV channels, suitable for experienced pilots, considering sufficient quality of a radio signal. Since the coverage of existing cellular mobile networks is optimized for terrestrial users, special attention is payed to evaluation methods and experimental results, associated with the high maneuverability and flight altitude of UAVs. The results presented are intended to supplement the theory and practice of remote control of UAVs using cellular networks. The research results of independent significance are the following:

1. The performance requirements for the wireless "Command and Control Link" of lightweight UAVs has been developed based on the review of available scientific papers. An experimental evaluation of the defined KPIs has not been performed.
    a. It was found that the recommended value of the two-way delay in the RC channel for a typical pilot should be ≤ 150 ms, with a limit of 200 ms; for an experienced pilot the recommended value of the two-way delay should be ≤ 310 ms, with a limit of 400 ms.
    b. It was found that the one-way delay in the FPV video channel should be ≤ 150 ms.
2. The type of distribution law of delay values of LTE cells has been defined. The applicability of the log-normal distribution law and quick estimation method were experimentally proved. It should be highly noted that since delays in different cells generally differ, the analysis should be carried out for each cell separately.
    a. It was proved that the delays of a real-working LTE cell mostly fit to log-normal distribution (compared to gamma, normal and Weibull). In order to obtain the average delay and delay jitter with satisfactory accuracy, it is possible to accept that the delays in LTE cells obey the logarithmically normal distribution law.
    b. In addition, a quick estimation method for the parameters of log-normal distribution has been provided. The method is based on known minimum and average RTT values that are available from the “ping” utility report.
    c. The recommendations of the required number of RTT measurements to be used in the quick estimation method are also provided.
3. The delay values in the LTE network of the Tele2-LV cellular operator have been experimentally estimated. In contrast to the available scientific papers, delays of LTE cells were estimated separately for each specific cell. This allows to build the CDF of the delays in a cell without using weighting factors (considering the time spent in each specific cell), as well as with a given probability to predict delays in those cells that were not evaluated during the experimental study.
    a. Assuming that the delays of an LTE cell obey the log-normal distribution law, the delays in each LTE cell can be described by estimates of two parameters $\acute{\theta}_0 = \hat{\mu}$ and $\acute{\theta}_1 = \hat{\sigma}$ of logarithmically normal distribution.
    b. It has been experimentally confirmed that the cells of a cellular operator have different delays due to differences in terrestrial backhaul of BSs. Therefore, when

evaluating the delays of overall LTE network, the delays of each LTE cell should be evaluated separately.

c. Considering the above mentioned, the delays of the LTE network of a particular cellular operator can be described using a system of two random variables – *parameter* $\hat{\mu}$ and *parameter* $\hat{\sigma}$ of logarithmically normal distribution of each LTE cell. To exclude the influence of a weak signal due to lack of the coverage of the cellular network on the delay values, only those data were processed that were obtained at the signal level RSSI ≥ –80 dBm (for the given UE it has been experimentally proved that there is no impact on the delays of small packets if the RSSI ≥ –80 dBm).

d. Approximating the above system of two random variables $\hat{\mu}$ and $\hat{\sigma}$ according to the normal distribution law and taking into account that the values of variables $\hat{\mu}$ and $\hat{\sigma}$ are independent, it is possible to obtain unbiased estimates of mathematical expectation $\hat{m}_{\hat{\mu}}$ and $\hat{m}_{\hat{\sigma}}$, standard deviation $\hat{\sigma}_{\hat{\mu}}$ and $\hat{\sigma}_{\hat{\sigma}}$ and correlation coefficient $\hat{r}_{\hat{\mu}\hat{\sigma}}$. The numerical values of these parameters for the D2D and D2WAN connections are provided in Subsection 2.3.1.

4. The analysis of the compliance of the delays of LTE network to the requirements of a "Command and Control Link" of low-flying, lightweight UAVs has been performed. In contrast to the averaged experimental results provided in the available scientific papers, the proposed conclusions are based on the delays analysis of individual LTE cells. The experimental results were obtained from LTE B20 band of the Tele2-LV cellular operator. The RTT of LTE cells was expressed as the 0.999 fractals (with the aim to show that the RTT in 99.9 % will not be greater). Note that the proposed results assume "good" signal quality specified in the recommendation [13]).
   a. It was found that only 25 % of LTE cells guarantee that at least 99.9 % of RTT will be below 150 ms and only 53 % of LTE cells guarantee that at least 99.9 % of RTT will be below 200 ms. Therefore, the delays of LTE networks are not suitable for the RC operations for a typical pilot.
   b. It was found that 88 % of LTE cells guarantee that at least 99.9 % of RTT will be below 310 ms and 97 % of LTE cells guarantee that at least 99.9 % of RTT will be below 400 ms. Therefore, an experienced pilot can perform RC operations via the LTE network (note that sometimes an experienced pilot will have to provide more mental effort, as RTT will be greater than 310 ms).
   c. If was found that in the video channel, the constant size de-jittering buffer of 310 ms will be sufficient in 99.9 % of times (thus providing 0.1 % packet loss in LTE cells with worth performance); 230 ms buffer will be sufficient in 99 % of times (thus providing 1 % loss in LTE cells with worth performance).
   d. Taking into account previously stated, the LTE data transfer service does not satisfy the requirements for the FPV of 150 ms latency if a constant size de-jittering buffer is used.
   e. It was found that in the video channel, if the size of de-jittering buffer is adaptive and is equal to the IPDV, only 86 % of LTE cells will satisfy the requirements for the FPV of 150 ms latency. Since modern video codecs can accept packet loss up to

1 %, the upped bound for the IPDV can be set to 0.99. In this case 98 % of LTE cells will provide satisfactory latencies for the FPV.

5. Experimental evaluation of the impact of terrestrial user mobility on the delays of mobile data transfer services has been performed. It was found that in 3G (HSPA+ and above) delays become increased if UE PIFA antennas have angular rotations, as well as that spikes in latency may occur during sharp turns or ground altitude changes. These phenomena have not been previously mentioned in the available scientific papers. However, such behavior in LTE was not observed. Therefore, it can be concluded, that the performance of LTE (LTE-A was not tested) network does not depend on the travelling speed (proved up to 100 km/h), as well as on acceleration / deceleration and other attitude changes at the reasonable rate (typical car acceleration / deceleration rates).
6. Experimental evaluation of the impact of flying altitude on the performance of mobile data transfer services has been performed. The following has been found:
   a. The interference increases with the increase of altitude because the UE gets direct visibility with many BS. Strong interference leads to the selection of slower modulation and coding scheme or even to blocked service of 3G/LTE networks at higher altitudes. However, this conclusion has no scientific novelty because a lot of research papers in this field were published in 2018.
   b. The effect of rapid angular position variations of PIFA antennas is aggravated at higher altitude due to stronger interference. In this case, the 3G data transfer service can be partially interrupted even if the wireless signal parameters are not below their acceptable limits.
   c. A lot of handovers are observed due to complex aerial coverage of cells. In this situation the use of soft handovers (like in 3G HSPA+ and above) leads to high amount of delayed packets / reordered packets even if the wireless signal parameters are not below their acceptable limits. This finding has not been previously published in the scientific papers.
   d. The LTE technology utilizes hard handovers only, therefore, there are no lost / reordered packets due to soft handover in the complex aerial coverage. However, massive handovers were observed in LTE too. Therefore, it is advisable to pay more attention to the operation of handover mechanism if the cellular network is planned to be used for aerial users.
7. The approach of detailed evaluation of the aerial coverage has been proposed. It allows to measure signal levels from all surrounding BSs of all cellular operators simultaneously. The proposed method is based on the legacy search function and does not require expensive equipment. Such method has not been previously published in scientific papers.
8. The parallel redundant communication solutions to increase the reliability and performance of a "Command and Control Link" were applied and tested.
   a. Two redundant solution implementations (PRP and MPTCP) that previously had not been used in cellular mobile data transfer services, were experimentally evaluated. It can be concluded that it is possible to utilize the PRP and MPTCP (with the “redundant” scheduler) solutions in LTE networks.
   b. The Thesis contains the method of calculations, which helps to foresee the delays of the redundant network solution based on the available delays and packet loss rates

of the proposed redundant networks. The proposed method has not been published previously and, in contrast to existing ITU methodology, is less complicated and requires fewer initial data. However, it is not suitable for very complex redundant solutions.

REFERENCES

[1] International Civil Aviation Organization (ICAO), “Remotely Piloted Aircraft System (RPAS) Concept of Operations (CONOPS) for International IFR,” p. 22, 2014.

[2] ITU, “ITU-T Y.1541 - Network performance objectives for IP-based services,” 2011.

[3] N. Santos, A. Raimundo, D. Peres, P. Sebastião, and N. Souto, “Development of a software platform to control squads of unmanned vehicles in real-time,” in *2017 International Conference on Unmanned Aircraft Systems, ICUAS 2017*, 2017, pp. 1–5.

[4] Ardupilot, “APSync.” [Online]. Available: http://firmware.ap.ardupilot.org/Companion/apsync/. [Accessed: 08-Jun-2018].

[5] Minla-RC, “Minla HDW.” [Online]. Available: http://minlarc.com/. [Accessed: 08-Jun-2018].

[6] Virt2real-ltd, “Virt2Real.” [Online]. Available: http://virt2real.com/. [Accessed: 08-Jun-2018].

[7] Emlid, “Navio2.” [Online]. Available: https://emlid.com/navio/. [Accessed: 08-Jun-2018].

[8] Y. Paramonov, M. Kleinhofs, and A. Kuznetsov, *Reliability of fatigue prone airframes and composite materials*. Riga: RTU Publishing House, 2011.

[9] V. Paxson, J. Mahdavi, M. Mathis, and G. Almes, “RFC 2330: Framework for IP Performance Metrics.”

[10] G. Almes, S. Kalidindi, and M. Zekauskas, “RFC 7679: A One-way Delay Metric for IPPM,” *Internet Eng. Task Force*, Sep. 1999.

[11] IETF, “Request for Comments RFC3550 - RTP: A Transport Protocol for Real-Time Applications,” 2003.

[12] R. Stuhlfauth, *High Speed Packet Access*, First Edit. Munchen: Rohde&Schwarz GmbH&Co. KG2012, 2012.

[13] Cisco and/or its affiliates, “LTE Antenna Guide. Cisco Integrated Services Router (ISR G2) and Connected Grid Router,” pp. 1–23, 2016.

[14] D. Brodnevs and A. Kutins, “An Approach to Constructing a Model of Delays in Cells of a Cellular Network Based on Experimentally Obtained Data,” in *Proc. IEEE Microwave Theory and Techniques in Wireless Communications (MTTW)*, 2020, pp. 206–211.

[15] ITU, “ITU-T G.114 General Recomendations on the transmission quality for an entire international telephone connection,” 2003.

[16] ITU, “ITU-T G.1010 - End-user multimedia QoS categories,” 2001.

[17] M. Dusi, S. Napolitano, S. Niccolini, and S. Longo, “A closer look at thin-client connections: Statistical application identification for QoE detection,” *IEEE Commun. Mag.*, 2012.

[18] E. Vinogradov, H. Sallouha, S. De Bast, M. M. Azari, and S. Pollin, “Tutorial on UAV: A Blue Sky View on Wireless Communication,” pp. 1–43, 2019.

[19] M. Claypool and K. Claypool, “Latency and player actions in online games,” *Commun. ACM*, 2006.

[20] M. Ries, P. Svoboda, and M. Rupp, “Empirical study of subjective quality for massive multiplayer games,” in *Proceedings of IWSSIP 2008 – 15th International Conference on Systems, Signals and Image Processing*, 2008.

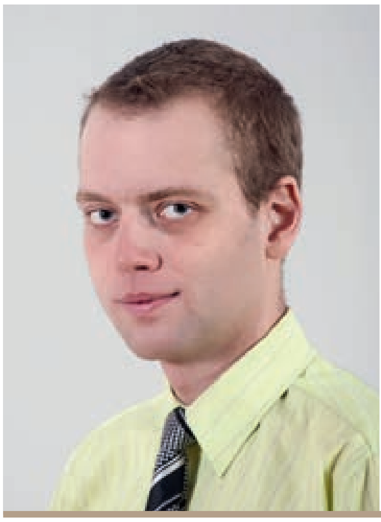
[21] F. Wang, S. Qi, and L. Jing, “An Analysis of Time-delay for Remote Piloted Vehicle,” 2017, pp. 1–6.

[22] V. Casas and A. Mitschele-thiel, “On the impact of communication delays on UAVs flocking behavior,” in *2018 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, 2018, pp. 67–72.

[23] M. Kottkamp, “HSPA+ Technology Introduction,” *Rohde Schwarz White Pap.*, 2012.

[24] N. Goddemeier, K. Daniel, and C. Wietfeld, “Coverage evaluation of wireless

networks for unmanned aerial systems," in *2010 IEEE Globecom Workshops, GC'10*, 2010, pp. 1760–1765.
[25] J. A. Romo, G. Aranguren, J. Bilbao, I. Odriozola, J. Gómez, and L. Serrano, "GSM / GPRS Signal Strength Measurements in aircraft flights under 3,000 meters of altitude," *WSEAS Trans. Signal Process.*, vol. 5, no. 6, pp. 219–228, 2009.
[26] X. Lin *et al.*, "The Sky is Not the Limit: LTE for Unmanned Aerial Vehicles," *IEEE Commun. Mag.*, vol. 56, no. 4, pp. 204–210, 2018.
[27] DOCOMO and Ericsson, "RP-170779: Study on Enhanced LTE support for Aerial Vehicles," 2017. [Online]. Available: http://www.3gpp.org/ftp/tsg_ran/tsg_ran/TSGR_75/Docs/.
[28] D. Brodnevs and A. Kutins, "Deterioration Causes Evaluation of Third Generation Cellular LTE Services for Moving Unmanned Terrestrial and Aerial Systems," *Electr. Control Commun. Eng.*, vol. 14, no. 2, pp. 141–148, 2018.
[29] S. D. Muruganathan, X. Lin, H.-L. Maattanen, Z. Zou, W. A. Hapsari, and S. Yasukawa, "An Overview of 3GPP Release-15 Study on Enhanced LTE Support for Connected Drones," pp. 1–7, 2018.
[30] IEEE Computer Society, "IEEE Standard for Ethernet 802.3," in *IEEE Standard for Ethernet*, vol. 2012, no. December, 2012, pp. 1–400.
[31] IEC, "International Standart 62439-3:2016 Industrial communication networks – High availability automation networks," 2016.
[32] M. Rentschler and H. Heine, "The Parallel Redundancy Protocol for industrial IP networks," in *Proceedings of the IEEE International Conference on Industrial Technology*, 2013, pp. 1404–1409.
[33] ZHAW Institute of Embedded Systems InES, "PRP-1 Software Stack." [Online]. Available: https://www.zhaw.ch/en/engineering/institutes-centres/ines/products-and-services/high-availability/prp-1-software-stack/#%2Fc46689. [Accessed: 15-Jan-2017].
[34] D. Brodnevs and A. Bezdel, "High - Reliability low - Latency cellular network communication solution for static or moving ground equipment control," in *Proc. IEEE 58th Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, 2017, pp. 1–6.
[35] C. Paasch and S. Barre, "Multipath TCP in the Linux Kernel," 2018. [Online]. Available: multipath-tcp.org. [Accessed: 02-Apr-2018].
[36] D. Brodnevs and A. Kutins, "Reliable data communication link implementation via cellular LTE services for static or moving ground equipment control," in *Proc. IEEE 59th Annual International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON)*, 2018, pp. 1–6.
[37] D. Brodnevs and A. Kutins, "Cellular networks selection for the remote control vehicles' control channel setup with parallel redundancy," *J. Mod. Technol. Eng.*, vol. 3, no. 1, pp. 63–74, 2018.
[38] D. Brodnevs, "Development of a Flexible Software Solution for Controlling Unmanned Air Vehicles via the Internet," *Transp. Aerosp. Eng.*, vol. 6, no. 1, pp. 37–43, 2018.
[39] M. Rentschler *et al.*, "Simulation of parallel redundant WLAN with OPNET," *IEEE Int. Conf. Emerg. Technol. Fact. Autom. ETFA*, pp. 1–8, 2013.
[40] M. Hendawy *et al.*, "Application of parallel redundancy in a Wi-Fi-based WNCS using OPNET," *Can. Conf. Electr. Comput. Eng.*, vol. 1, pp. 1–6, 2014.
[41] M. Rentschler *et al.*, "Simulative comparison of parallel redundant wireless systems with OMNet++," in *IEEE International Symposium on Industrial Electronics*, 2014.
[42] ITU, "ITU-T G.911 Parameters and calculation methodologies for reliability and availability of fibre optic systems," *ITU Telecommun. Stand. Sect.*, 1997.



Deniss Brodņevs was born in 1987 in Riga. He obtained a Bachelor's degree in Engineering in Aviation Transport in 2011 and a Master's degree in Aviation Transport in 2013 from Riga Technical University. Since 2011, he has been a lecturer and research assistant with the Institute of Aeronautics of Riga Technical University. His research interests are in the field of electrical power and radio communication systems for aircraft and remotely piloted aerial vehicles with particular attention to the use of mobile cellular networks for the needs of piloted aerial vehicles, as well as to the development of airborne electrical generators.