GOCE DELCEV UNIVERSITY, STIP, NORTH MACEDONIA

FACULTY OF ELECTRICAL ENGINEERING

ETIMA 2025

THIRD INTERNATIONAL CONFERENCE

24-25 SEPTEMBER, 2025

TECHNICAL SCIENCES APPLIED IN ECONOMY, EDUCATION AND INDUSTRY

УНИВЕРЗИТЕТ „ГОЦЕ ДЕЛЧЕВ“, ШТИП
ЕЛЕКТРОТЕХНИЧКИ ФАКУЛТЕТ

GOCE DELCEV UNIVERSITY, STIP
FACULTY OF ELECTRICAL ENGINEERING

ТРЕТА МЕЃУНАРОДНА КОНФЕРЕНЦИЈА
THIRD INTERNATIONAL CONFERENCE

ЕТИМА / ETIMA 2025

ЗБОРНИК НА ТРУДОВИ
CONFERENCE PROCEEDINGS

24-25 септември 2025 | 24-25 September 2025

ISBN: 978-608-277-128-1
DOI: https://www.doi.org/10.46763/ETIMA2531

Главен и одговорен уредник / Editor in Chief
проф.д-р Сашо Гелев
Prof.d-r Saso Gelev

Јазично уредување / Language Editor
Весна Ристова (македонски) / Vesna Ristova (Macedonian)

Техничко уредување / Technical Editing
Дарко Богатинов / Darko Bogatinov

Издавач / Publisher
Универзитет „Гоце Делчев”, Штип / Goce Delcev University, Stip
Електротехнички факултет / Faculty of Electrical Engineering

Адреса на организационен комитет / Adress of the organizational committee
Универзитет „Гоце Делчев”, Штип / Goce Delcev University, Stip
Електротехнички факултет / Faculty of Electrical Engineering
Адреса: ул. „Крсте Мисирков“ бр. 10А / Adress: Krste Misirkov, 10A
Пош. фах 201, Штип - 2000, С. Македонија / PO BOX 201, Stip 2000, North Macedonia
E-mail: conf.etf@ugd.edu.mk

CIP - Каталогизација во публикација
Национална и универзитетска библиотека "Св. Климент Охридски", Скопје

62-049.8(062)
004-049.8(062)

МЕЃУНАРОДНА конференција ЕТИМА (3 ; 2025 ; Штип)
Зборник на трудови [Електронски извор] / Трета меѓународна конференција ЕТИМА 2025, 24-25 септември 2025 ; [главен и одговорен уредник Сашо Гелев] = Conference proceedings / Third international conference, 24-25 September 2025 ; [editor in chief Saso Gelev]. - Текст во PDF формат, содржи 357 стр., илустр. - Штип : Универзитет "Гоце Делчев", Електротехнички факултет ; Stip : "Goce Delchev" University, Faculty of Electrical engineering, 2025

Начин на пристапување (URL): https://js.ugd.edu.mk/index.php/etima/en. - Наслов преземен од екранот. - Опис на изворот на ден 30.10.2025. - Трудови на мак. и англ. јазик. - Библиографија кон трудовите

ISBN 978-608-277-128-1

а) Електротехника -- Примена -- Собири б) Машинство -- Примена -- Собири
в) Автоматика -- Примена -- Собири г) Инфоматика -- Примена -- Собири

COBISS.MK-ID 67297029

Трета меѓународна конференција ЕТИМА
24-25 Септември 2025
Third International Conference ETIMA
24-25 September 2025

ОРГАНИЗАЦИОНЕН ОДБОР
ORGANIZING COMMITTEE

Драган Миновски / Dragan Minovski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Сашо Гелев / Saso Gelev
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Тодор Чекеровски / Todor Cekerovski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Маја Кукушева Панева / Maja Kukuseva Paneva
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Билјана Читкушева Димитровска / Biljana Citkuseva Dimitrovska
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Дарко Богатинов / Darko Bogatinov
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

ПРОГРАМСКИ И НАУЧЕН ОДБОР
SCIENTIFIC COMMITTEE

Георги Иванов Георгиев / Georgi Ivanov Georgiev
Технички Универзитет во Габрово, Бугарија
Technical University in Gabrovo, Bulgaria

Антон Белан / Anton Beláň
Факултет за електротехника и информациони технологии
Словачки Технички Универзитет во Братислава, Словачка
Faculty of Electrical Engineering and Information Technology
Slovak Technical University in Bratislava, Slovakia

Ивелина Стефанова Балабанова / Ivelina Stefanova Balabanova
Технички Универзитет во Габрово, Бугарија
Technical University in Gabrovo, Bulgaria

Бојан Димитров Карапенев / Boyan Dimitrov Karapenev
Технички Универзитет во Габрово, Бугарија
Technical University in Gabrovo, Bulgaria

Сашо Гелев / Saso Gelev
Електротехнички факултет,
Универзитет „Гоце Делчев", Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Влатко Чингоски / Vlatko Cingoski
Електротехнички факултет,
Универзитет „Гоце Делчев", Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Божо Крстајиќ / Bozo Krstajic
Електротехнички факултет
Универзитет во Црна Гора, Црна Гора
Faculty of Electrical Engineering,
University in Montenegro, Montenegro

Милован Радуловиќ / Milovan Radulovic
Електротехнички факултет
Универзитет во Црна Гора, Црна Гора
Faculty of Electrical Engineering,
University in Montenegro, Montenegro

Гоце Стефанов / Goce Stefanov
Електротехнички факултет,
Универзитет „Гоце Делчев", Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Мирјана Периќ / Mirjana Peric
Електронски факултет
Универзитет во Ниш, Србија
Faculty of Electronic Engineerig,
University of Nis, Serbia

Ана Вучковиќ / Ana Vuckovic
Електронски факултет,
Универзитет во Ниш, Србија
Faculty of Electronic Engineerig,
University of Nis, Serbia

Тодор Чекеровски / Todor Cekerovski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Далибор Серафимовски / Dalibor Serafimovski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Мирослава Фаркаш Смиткова / Miroslava Farkas Smitková
Факултет за електротехника и информациони технологии
Словачки Технички Универзитет во Братислава, Словачка
Faculty of Electrical Engineering and Information Technology
Slovak Technical University in Bratislava, Slovakia

Петер Јанига / Peter Janiga
Факултет за електротехника и информациони технологии
Словачки Технички Универзитет во Братислава, Словачка
Faculty of Electrical Engineering and Information Technology
Slovak Technical University in Bratislava, Slovakia

Јана Радичова / Jana Raditschová
Факултет за електротехника и информациони технологии
Словачки Технички Универзитет во Братислава, Словачка
Faculty of Electrical Engineering and Information Technology
Slovak Technical University in Bratislava, Slovakia

Драган Миновски / Dragan Minovski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Василија Шарац / Vasilija Sarac
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Александар Туџаров / Aleksandar Tudzarov
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Владимир Талевски / Vladimir Talevski
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Владо Гичев / Vlado Gicev
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија;
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia;

Марија Чекеровска / Marija Cekerovska
Машински факултет,
Универзитет „Гоце Делчев “, Штип, Северна Македонија;
Faculty of Mechanical Engineering,
Goce Delcev University, Stip, North Macedonia;

Мишко Џидров / Misko Dzidrov
Машински факултет,
Универзитет „Гоце Делчев “, Штип, Северна Македонија;
Faculty of Mechanical Engineering,
Goce Delcev University, Stip, North Macedonia;

Александар Крстев / Aleksandar Krstev
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија;
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia;

Ванчо Аџиски / Vancho Adziski
Факултет за природни и технички науки,
Универзитет „Гоце Делчев “, Штип, Северна Македонија;
Faculty of Natural and Technical Sciences,
Goce Delcev University, Stip, North Macedonia;

Томе Димовски / Tome Dimovski
Факултет за информатички и комуникациски технологии,
Универзитет „Св. Климент Охридски “, Северна Македонија;
Faculty of Information and Communication Technologies,
University St Climent Ohridski, North Macedonia;

Зоран Котевски / Zoran Kotevski
Факултет за информатички и комуникациски технологии,
Универзитет „Св. Климент Охридски “, Северна Македонија;
Faculty of Information and Communication Technologies,
University St Climent Ohridski, North Macedonia;

Никола Рендевски / Nikola Rendevski
Факултет за информатички и комуникациски технологии,
Универзитет „Св. Климент Охридски “, Северна Македонија;
Faculty of Information and Communication Technologies,
University St Climent Ohridski, North Macedonia;

Илија Христовски / Ilija Hristovski
Економски факултет,
Универзитет „Св. Климент Охридски “, Северна Македонија;
Faculty of Economy,
University St Climent Ohridski, North Macedonia;

Христина Спасовска / Hristina Spasovska
Факултет за електротехника и информациски технологии,
Универзитет „ Св. Кирил и Методиј “, Скопје, Северна Македонија;
Faculty of Electrical Engineering and Information Technologies,
Ss. Cyril and Methodius University, North Macedonia;

Роман Голубовски / Roman Golubovski
Природно-математички факултет,
Универзитет „ Св. Кирил и Методиј “, Скопје, Северна Македонија;
Faculty of Mathematics and Natural Sciences,
Ss. Cyril and Methodius University, North Macedonia;

Маре Србиновска / Mare Srbinovska
Факултет за електротехника и информациски технологии,
Универзитет „Св. Кирил и Методиј “, Скопје, Северна Македонија;
Faculty of Electrical Engineering and Information Technologies,
Ss. Cyril and Methodius University, North Macedonia;

Билјана Златановска / Biljana Zlatanovska
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија;
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia;

Александра Стојанова Илиевска / Aleksandra Stojanova Ilievska
Факултет за информатика,
Универзитет „Гоце Делчев “, Штип, Северна Македонија;
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia;

Мирјана Коцалева Витанова / Mirjana Kocaleva Vitanova
Факултет за информатика,
Универзитет „Гоце Делчев“, Штип, Северна Македонија;
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia;

Ивана Сандева / Ivana Sandeva
Факултет за електротехника и информациски технологии,
Универзитет „ Св. Кирил и Методиј “, Скопје, Северна Македонија;
Faculty of Electrical Engineering and Information Technologies,
Ss. Cyril and Methodius University, North Macedonia;

Билјана Читкушева Димитровска / Biljana Citkuseva Dimitrovska
Електротехнички факултет,
Универзитет „Гоце Делчев”, Штип, Северна Македонија
Faculty of Electrical Engineering,
Goce Delcev University, Stip, North Macedonia

Наташа Стојковиќ / Natasa Stojkovik
Факултет за информатика,
Универзитет „Гоце Делчев“, Штип, Северна Македонија;
Faculty of Computer Science,
Goce Delcev University, Stip, North Macedonia;

PREFACE

The Third International Conference "Electrical Engineering, Technology, Informatics, Mechanical Engineering and Automation – Technical Sciences in the Service of the Economy, Education and Industry" (ETIMA'25), organized by the Faculty of Electrical Engineering at the "Goce Delchev" University – Shtip, represents a significant scientific event that enables interdisciplinary exchange of knowledge and experience among researchers, professors, and experts in the field of technical sciences. The conference was held in an online format and brought together 78 authors from five different countries.

The ETIMA conference aims to establish a forum for scientific communication, encouraging multidisciplinary collaboration and promoting technological innovations with direct impact on modern life. Through the presentation of scientific papers, participants shared the results of their research and development activities, contributing to the advancement of knowledge and practice in relevant fields.
The first ETIMA conference was organized four years ago, featuring 40 scientific papers. The second conference took place in 2023 and included over 30 papers. ETIMA'25 continued this scientific tradition, presenting more than 40 papers that reflect the latest achievements in electrical engineering, technology, informatics, mechanical engineering, and automation.

At ETIMA'25, papers were presented that addressed current topics in technical sciences, with particular emphasis on their application in industry, education, and the economy. The conference facilitated fruitful discussions among participants, encouraging new ideas and initiatives for future research and projects.

ETIMA'25 reaffirmed its role as an important platform for scientific exchange and international cooperation. The organizing committee extends sincere gratitude to all participants for their contribution to the successful realization of the conference and its scientific value.

We extend our sincerest gratitude to all colleagues who, through the presentation of their papers, ideas, and active engagement in discussions, contributed to the success and scientific significance of ETIMA'25.

The Organizing Committee of the Conference

ПРЕДГОВОР

Третата меѓународна конференција „Електротехника, Технологија, Информатика, Машинство и Автоматика – технички науки во служба на економијата, образованието и индустријата“ (ЕТИМА’25), организирана од Електротехничкиот факултет при Универзитетот „Гоце Делчев“ – Штип, претставува значаен научен настан кој овозможува интердисциплинарна размена на знаења и искуства меѓу истражувачи, професори и експерти од техничките науки. Конференцијата се одржа во онлајн формат и обедини 78 автори од пет различни земји.

Конференцијата ЕТИМА има за цел да создаде форум за научна комуникација, поттикнувајќи мултидисциплинарна соработка и промовирајќи технолошки иновации со директно влијание врз современото живеење. Преку презентација на научни трудови, учесниците ги споделуваат резултатите од своите истражувања и развојни активности, придонесувајќи кон унапредување на знаењето и практиката во релевантните области.

Првата конференција ЕТИМА беше организирана пред четири години, при што беа презентирани 40 научни трудови. Втората конференција се одржа во 2023 година и вклучи над 30 трудови. ЕТИМА’25 продолжи со истата научна традиција, презентирајќи повеќе од 40 трудови кои ги отсликуваат најновите достигнувања во областа на електротехниката, технологијата, информатиката, машинството и автоматиката.

На ЕТИМА’25 беа презентирани трудови кои обработуваат актуелни теми од техничките науки, со посебен акцент на нивната примена во индустријата, образованието и економијата. Конференцијата овозможи плодна дискусија меѓу учесниците, поттикнувајќи нови идеи и иницијативи за идни истражувања и проекти.

ЕТИМА’25 ја потврди својата улога како значајна платформа за научна размена и интернационална соработка. Организациониот одбор упатува искрена благодарност до сите учесници за нивниот придонес кон успешната реализација на конференцијата и нејзината научна вредност. Конференцијата се одржа онлајн и обедини седумдесет и осум автори од пет различни земји.

Изразуваме голема благодарност до сите колеги кои со презентирање на своите трудови, идеи и активна вклученост во дискусиите придонесоа за успехот на ЕТИМА’25 и нејзината научна вредност.

Организационен одбор на конференцијата

СОДРЖИНА / TABLE OF CONTENTS:

Трета меѓународна конференција ЕТИМА
Third International Conference ETIMA
UDC: 629.7.014.9:[654.9:004.72.031.43]
https://www.doi.org/10.46763/ETIMA2531157m

BRIDGING TELECOM AND AVIATION: ENABLING SCALABLE BVLOS DRONE OPERATIONS THROUGH AIRSPACE DIGITIZATION

***Gorazd Mirkovski* [1], *Todor Cekerovski* [1], *Marija Cekerovska* [1], *Taulant Berisha* [2], *Sebastian Woblistin* [3]**

,[1] Faculty of Electrical Engineering, Goce Delcev University, Krste Misirkov 10A, 2000 Stip, North Macedonia
email: gorazd.20730@student.ugd.edu.mk;
email: todor.cekerovski@ugd.edu.mk;
email: marija.cekerovska@ugd.edu.mk;

[2] Technische Universität Wien (TU Wien), Austria;
[3] University of Vienna, Austria;

Abstract

The integration between aviation and telecommunication systems is essential for enabling safe and scalable beyond visual line of sight (BVLoS) drone operations. To make BVLOS drone operations scalable, real-time access to dynamic airspace connectivity and dynamic population density data is critical for ensuring operational safety, regulatory compliance, and efficiency. Mobile network operators (MNOs) are uniquely positioned to deliver this data, allowing aviation systems to make informed decisions based on the existing ground risk, as well as extrapolated and real-time network conditions such as throughput, latency, and other key radio network coverage indicators. This paper provides an introduction to the services that mobile network operators (MNOs) are delivering to support the drone ecosystem, with a particular focus on the reliability of information about airspace connectivity.

In Germany, the MNO Vodafone has released a commercially available solution that, uses pre-processed historical radio network data to provide extrapolated insights for the airspace connectivity and population density. In the Netherlands, MNO KPN offering similar capabilities, is collaborating with the Dutch Air Traffic Control to establish a digital drone corridor between hospitals. In Spain, the MNO Telefonica is not only delivering radio network intelligence but is also aiming to become a drone operator itself. In Switzerland, the MNO Swisscom has announced a deployment of 300 "drone-in-a-box" systems, making it the largest drone operator in Europe. In the United Kingdom, MNO BT is not only investing in capabilities to digitise the airspace and deliver dynamic population density data but is also taking a step further by investing in an Unmanned Traffic Management (UTM) system.

These examples demonstrate how MNOs, by leveraging their existing infrastructure and driving airspace digitization, are becoming a critical link in the chain of BVLoS drone operations for the lower airspace. Recognising this role, they are increasingly positioning themselves not just as data providers, but as future aviation system providers. Despite advancements, challenges remain. Regulatory frameworks must evolve to incorporate real-time network intelligence, and standardisation is needed to ensure unified interoperability between telecom and aviation systems. Addressing these gaps will unlock a new era of automated, scalable, and safe BVLOS drone operations. This work aims to contribute to the academic and professional discourse around the convergence of telecommunications and aviation, providing real-world insights into how telecom operators are becoming key enablers of airspace digitization through dynamic connectivity (and population intelligence). The conclusion is clear: to achieve automated and digital airspace management and enable the safe scaling of BVLOS drone operations, mobile network operators must move beyond sim card's provision - becoming an embedded part of aviation systems by bridging telecom infrastructure with the airspace ecosystem. As this white paper will demonstrate, that transformation is already underway.

Key words

BVLOS drone operations, Mobile Network Operators (MNOs), Airspace digitization, Dynamic connectivity, Aviation-telecommunication integration, Real-time network intelligence

Introduction

Drones are transforming industries and reshaping the way we live and work. From delivering vital medical supplies and supporting emergency response operations to enabling infrastructure inspections and environmental monitoring, uncrewed aerial systems (UAS) have become an integral part of the global technological ecosystem. These use cases demonstrate the enormous potential of drone operations to improve safety, efficiency, and quality of life.
However, to unlock this potential at scale, especially for Beyond Visual Line of Sight (BVLOS) drone operations, a paradigm shift is required.
In traditional aviation, a licensed pilot is physically present in the aircraft, directly controlling its movement and bearing full legal responsibility for the safety of the aircraft and its operations. With drones, the situation is fundamentally different: the remote pilot is not on board the aircraft, yet regulators still require proof that the operator maintains full control over the drone throughout the entire planned flight path. For BVLOS operations to scale, aviation authorities must be assured in an automated and unified manner that:

- Command and control (C2) links are reliable,
- Connectivity along the entire flight path is sufficiently robust, and
- Dynamic Ground risk is continuously understood based on dynamic population density data.

This need is further emphasized in the newly released Part 108 draft [166] from the Federal Aviation Administration of USA (FAA) on BVLOS operations, which states:
"Based on current research and operational approvals of BVLOS operations, FAA has seen C2 metrics that include, but are not limited to, link accessibility, latency of link, and operational processes in the event of lost link. FAA expects that work performed by industry consensus standards bodies will refine the key metrics for C2 over time. For BVLOS operations, an operator would need to be aware of the potential for link to their aircraft to not be available due to interferences and other reasons along the predicted flight path. In addition, FAA expects that BVLOS flights could at times experience intermittent lost link. As such, the operator would need to do an assessment of how link latency and intermittent lost link may impact the safety of their operation and produce mitigation protocols in these instances to maintain a low-risk operation. FAA looks to industry and other stakeholders for additional comment on what additional metrics should be considered in a C2 assessment, which are expected to be documented in a to-be-developed industry consensus standard."
This introduces a new requirement: integrating an additional data layer within existing airspace management systems. This data layer provides dynamic insights into airspace connectivity (cellular signal strength, throughput, latency) and dynamic population density intelligence, enabling automated proof of control and enhancing safety assessments for BVLOS flight approvals.

This is where mobile network operators (MNOs) come in. With their nationwide infrastructure beside the connectivity, MNOs have the capabilities to provide:

- Dynamic airspace connectivity information → extrapolated and real-time insights into 4G/5G coverage, throughput, latency, and other key parameters

- Dynamic population density information → essential for ground risk assessment and regulatory compliance
- Integration within UTM systems → enabling automated decision-making and flight approvals

How can the mobile network operators derive extrapolated and real-time insights into the 4G/5G coverage and aviation authorities access this information in practice? The answer lies in one of the few disruptive solutions that many leading MNOs are already using today – AirborneRF [2].

With AirborneRF, the critical question, "is there sufficient connectivity for my planned flight path?", can be answered instantly. The solution delivers predictive and near real-time insights into airspace connectivity using globally unified APIs [3] and a visual user interface (UI) that makes connectivity conditions clear and actionable.

As illustrated in Figure 3, AirborneRF provides a visual representation of connectivity quality across the flightpath, giving both drone operators and aviation authorities the necessary evidence to support BVLOS flight planning, safety cases, and regulatory approvals.

Furthermore, organisations like the Aerial Connectivity Joint Activity [4] (ACJA) are ensuring that this convergence between telecommunications and aviation happens through globally unified interfaces. Since AirborneRF's APIs are fully aligned with ACJA specifications, the solution acts as a practical implementation of this interface, enabling seamless integration between MNOs, UTM systems, and aviation authorities worldwide.

This white paper primarily focuses on airspace connectivity data and aims to demonstrate the predictive capabilities of AirborneRF using statistical indicators. To validate the prediction capabilities, we decided to utilize the real-world measurements as ground truth data and compare them with AirborneRF's predictions. For this reason, a large amount of real-world measurements were gathered in an LTE operational network in Latvia.

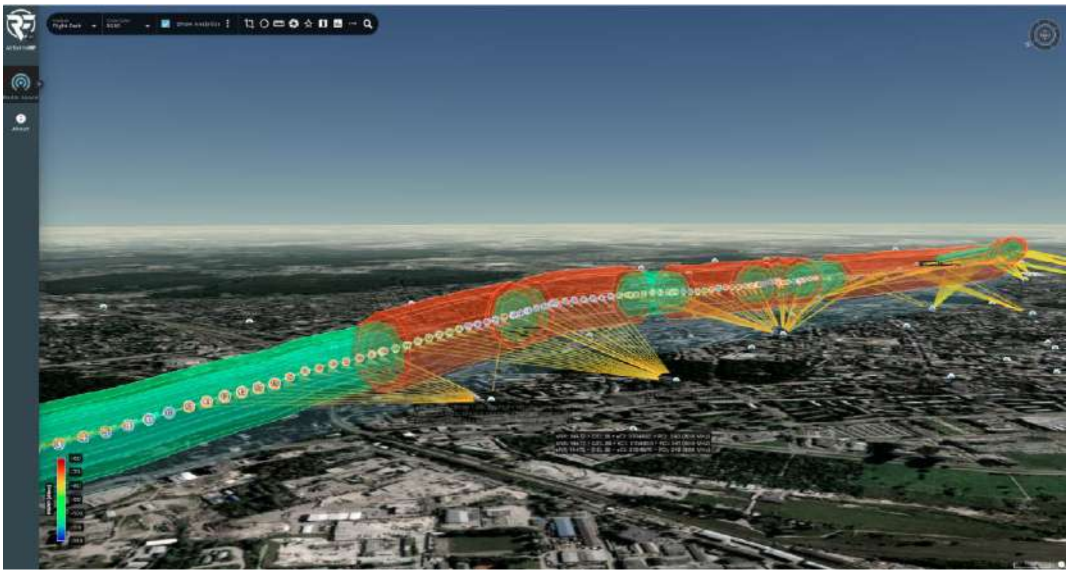

Figure 3. Screenshot taken from a test instance of AirborneRF © [2]. To summarize, green cylinders indicate reliable and safe areas for flying, whereas red

1. Real-World Measurements, Flights and Scenario

A series of RF-measurement campaigns were performed in Latvia during a two-week-period in September 2022 by one of the largest Latvian mobile operators within its operational LTE network. These measurements flights were realized in cooperation with a local UAV contractor using a commercial quadcopter UAV (DJI Matrice 300 RTK) that was equipped with an OnePlus Nord N10 smartphone running the Enhancell measurement software. The smartphone was placed under the UAV and remained in the same position throughout all the flights.

The measurement phone continuously recorded the network KPIs Reference Signal Received Power (RSRP), Reference Signal Received Quality (RSRQ), Signal-to-Noise-and Interference Ratio (SINR) as well as network identifiers. In order to measure latency and throughput, several scripts were run within the measurement software to measure both downlink PHY data rate and latency (i.e. ICMP ping) in specific cycles. The ping script was configured (regarding packet size) in order to correspond to the requirements defined in Global System for Mobile Communications (GSMA) - ACJA [5] regarding round-trip time latency.

Some of the flights were band-locked at 800 MHz, while in others the frequency band selection remained open.

The flights were conducted at various locations in Latvia, covering a range of distances and altitudes. Figure 2 (a) shows the locations of the flights, whereas Figure 2 (b) provides a screenshot captured from AirborneRF representing a flight. The flights were organized to reach heights up to 120 m above ground level, with each flight covering a horizontal distance of approximately 6 km. In total, the flight time amounted to 12 h, covering a total distance of 564 km.

Figure 2. (a) The screenshot captured from Google Earth Pro © illustrates flight areas, which are represented by yellow rectangular shapes;

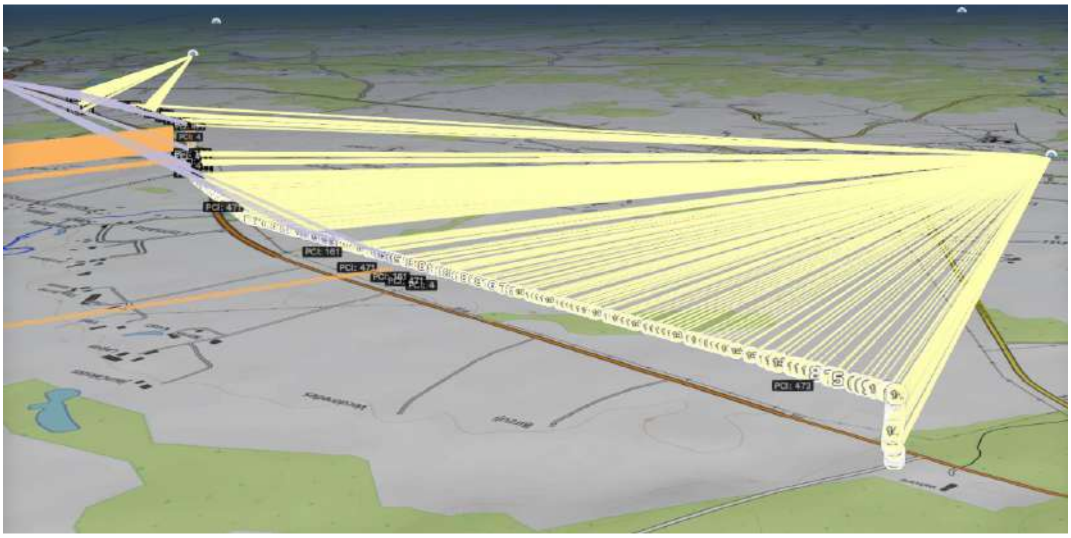

Figure 2. (b) The screenshot captured from AirborneRF © for a measurement flight.

2. Method

The measurement flights were grouped according to their date and location into different flight campaigns, each of which consisting of five to eight flights along comparable routes at the same location at the same time (in a time-frame of around 2h). A total of 86 flights which were grouped into 12 different flight campaigns were available for the evaluation, containing a total of around 70000 individual measurement points (GPS location with RF parameters).

For the validation, to test the calibration and generalization capabilities of the RF prediction algorithms of AirborneRF, k-fold-cross-validation [[6], Chapter 7] was applied. Crossvalidation in Machine Learning (ML) refers to splitting a given dataset into two disjoint subsets: a training set and a test set. The algorithm which is to be evaluated is trained in a first step using only the training set. Then, in order to assert its predictive performance, its predictions for the test scenarios are compared with the measured data for this data set and presented in terms of statistical indicators. See Section 0 for details.

In our case, a data set consists of the flight routes, given in terms of timestamps and GPS points, together with the measured RF KPIs. For the tuning of the algorithms, both the flight route and the measured KPIs are used together with the Mobile Network Operator (MNO)'s static network data (e.g. cell locations, antenna data, etc.) and the MNO's dynamic network data (i.e. cell loads). For the test evaluation only the flight route and static network data was used, whereas the dynamic network data is predicted by the predictive algorithms using only historical data up to a day before the test flight took place. Furthermore, the serving cells were unknown in the test evaluation.

K-fold-cross-validation refers to repeating the cross-validation procedure with different training/test data combinations. In this case, the selection was done on the level of flight campaigns, in order to account also for the level of variation of the individual scenarios. The procedure for generating the individual cross-validation sets was as follows: Select one of the given flight campaigns. For the current cross-validation, this measurement campaign is used as test data set, i.e. with its six to eight flights, while the remaining other flight campaigns were used as training set. This means that the cross-validation procedure was executed nine times, with each campaign appearing exactly once as a test scenario. The predictive errors are collected from each cross-validation and presented in an aggregated manner with both distribution graphs and corresponding indicators presented in Section 0.

3. Results and Discussion

For the evaluation of the performance of AirborneRF's RF prediction algorithms, in this section we present the error distribution along with Mean Error (ME), Root Mean Squared Error (RMSE), Standard Deviation (SD), and 25-th, 50-th, 75- th, 95-th, 99-th quantiles of absolute error for the following KPIs: RSRP, SINR, RSRQ, PHY data rate, round-trip latency, and one-way latency.

3.1 Coverage and Signal Quality

In Figure 3 a, the error distribution of RSRP is depicted. The statistics indicate optimistic results, demonstrating that the predictive algorithms employed in AirborneRF align closely with the actual measurements. It is important to note that, for the purpose of this analysis, the best serving cell selections in AirborneRF's algorithms are simulated rather than using a priori information from the measurement data. Otherwise, even more optimistic overall statistics can be expected in context of predictive algorithms. Moreover, according to 3GPP TS 36.133 [7], measurement errors up to ±6 dB are defined for User Equipments (UEs). Therefore, when it comes to absolute measurement accuracy, it should be understood that such error values can be expected for UEs. Consequently, this small deviation factor can be partly attributed to the measurement uncertainties of the UEs.

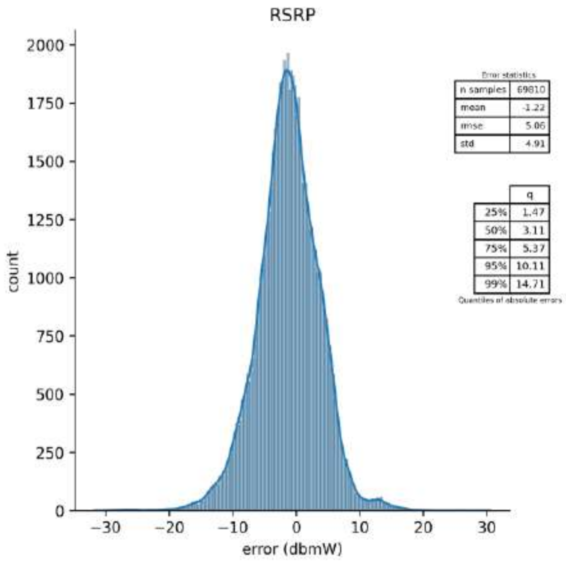

Figure 3 a. Error distribution of RSRP.

Figure 3 b and Figure 3 c represent the error distribution of SINR and RSRQ, respectively. The overall results demonstrate optimistic predictive outcomes for both SINR and RSRQ. In accordance with 3GPP TS 36.133, measurement errors of up to ±3 dB are permissible for RSRQ. It is worth noting that the predictive capabilities of AirborneRF fall within this defined margin. These findings indicate that AirborneRF performs well in predicting both SINR and RSRQ, aligning closely with the actual measurements and complying with the specified measurement error limits.

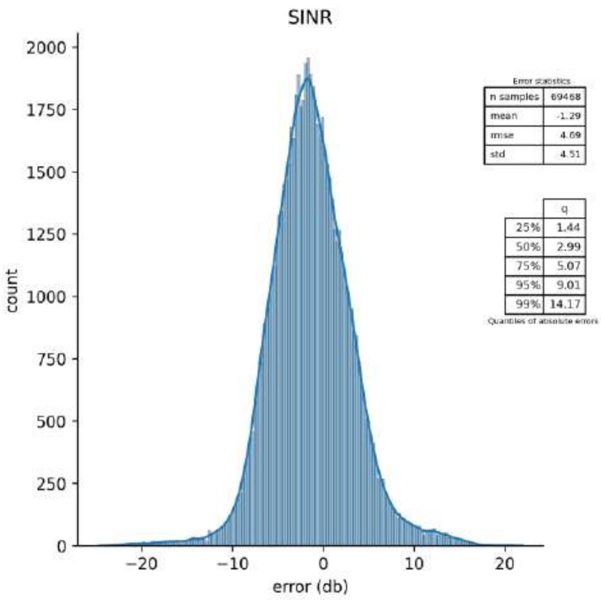

Figure 3 b. Error distribution of SINR

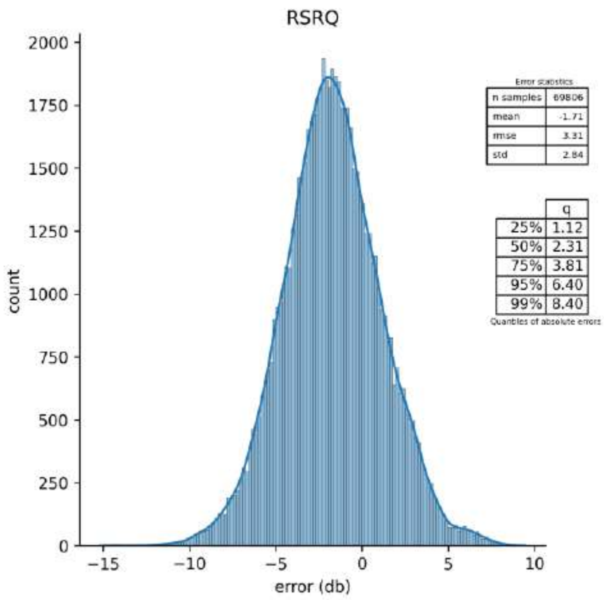

Figure 3 c. Error distribution of RSRQ.

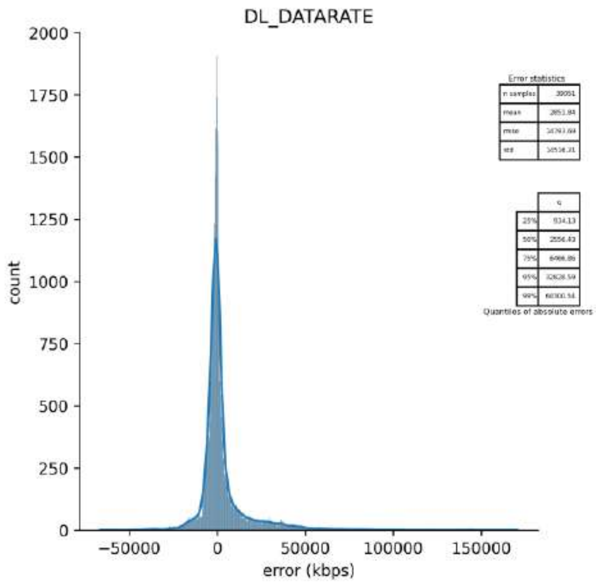

Figure 3.2. (a) Error distribution of downlink PHY data rates: overall

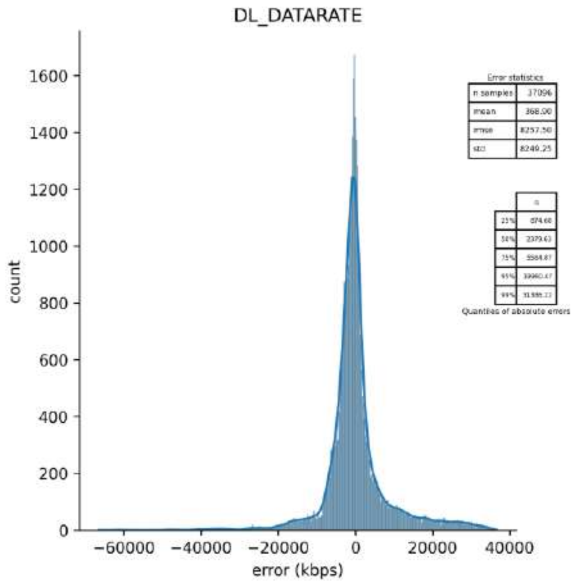

Figure 3.2. (b) Error distribution of downlink PHY data rates: 95-th percentile.

3.2 Data rates

Data rate is an essential aspect of the C2 connectivity service requirements for UAVs, as defined in 3GPP TR 36.777 [8]. Therefore, we aim to discuss the results obtained for predictive capabilities of AirborneRF in this context. It’s widely acknowledged that building robust predictive models for data rates is a complex task due to various factors involved such as SINR levels, spectral efficiency, scheduled bandwidth, appropriately selected Multiple-Input Multiple-Output (MIMO) technique, optimally chosen Carrier Aggregation (CA) functionality, and more. Additionally, as described throughout the paper, AirboreRF's capability to make predictions for the future (e.g. a flight is scheduled to happen in five days) requires predicting highly dynamic parameters, including cell load and other factors. This adds another layer of complexity to the prediction process.

Figure 3.2 presents the error distribution obtained for downlink PHY data rates. Both Figure 3.2 (a) and Figure 3.2 (b) demonstrate reasonable overall results, with 95-th percentile graph (see Figure 3.2 (b)) exhibiting superior performance compared to the overall graph (see Figure 3.2 (a)).

3.3 Latency

Latency is another component of the C2 connectivity service requirements for UAVs, as defined in 3GPP TR 36.777. Let's discuss the obtained results in this regard.

Figure 3.3 (a) presents the error distribution of round-trip latency, considering all the measurement data without any filtering. Despite the complexity introduced by factors such as radio link failures, intermittent network delay peaks, drops in signal quality, transmission delay, re-transmission delay, queuing delay, air-interface delay, node processing delays, and more, optimistic statistical results are obtained. We have observed the presence of frequent extremely high values, with some measurement samples even exceeding 1 s. This behaviour is reflected in the long-tail to the right of the error distribution graph. Modelling such dynamics is highly complex, especially with limited configuration data available. Nonetheless, these extreme values significantly impact the overall statistical evaluation. To minimize their impact, a filter was applied. Figure 3.3 (b) illustrates the error distribution of round-trip latency after applying the filtering process. First, the round-trip latency error was computed, and then the data were filtered based on the 95-th percentile rule. Considering the maximum latency requirement specified in 3GPP TR 36.777 [8] (i.e., one-way maximum latency of 50 ms), the 99-th quantile of the absolute error falls within the acceptable margin. It is worth noting that only half of the obtained value in the graph is reasonably comparable to the maximum latency requirement set by 3GPP.

We define the one-way latency in our measurement samples to be approximately half of the round-trip latency. Typically, in scenarios where there is no pre-scheduling of radio resources occurring at the eNodeB (eNB), it is expected that uplink latency would be higher than downlink latency due to delays associated with scheduling requests and scheduling grants. However, analysing and discussing the specific details of this phenomenon is beyond the scope of this white paper.

Figure 3.3.1 (b) shows the error distribution of one-way latency. The statistics presented in figure 3.3.1 (b) demonstrate that the 99-th quantile of the absolute error falls within the 50 ms margin. Generally speaking, it is plausible to expect one-way latency values higher than 50 ms when considering delay factors falling beyond eNB - UE section, as discussed in [9], [10]. For the sake of completeness, figure 3.3.1 (a) illustrates the overall data.

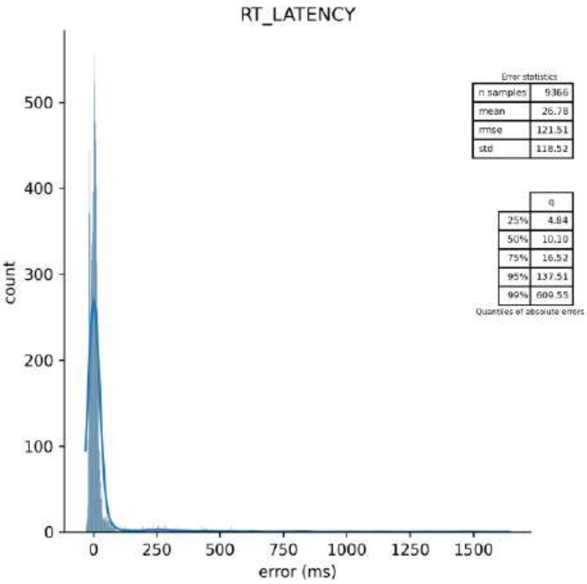

Figure 3.3. (a) Error distribution of round-trip latency: overall

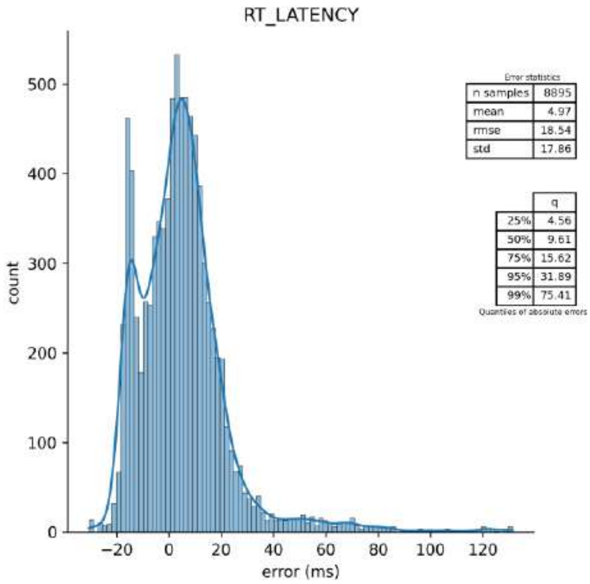

Figure 3.2. (b) Error distribution of round-trip latency: 95-th percentile.

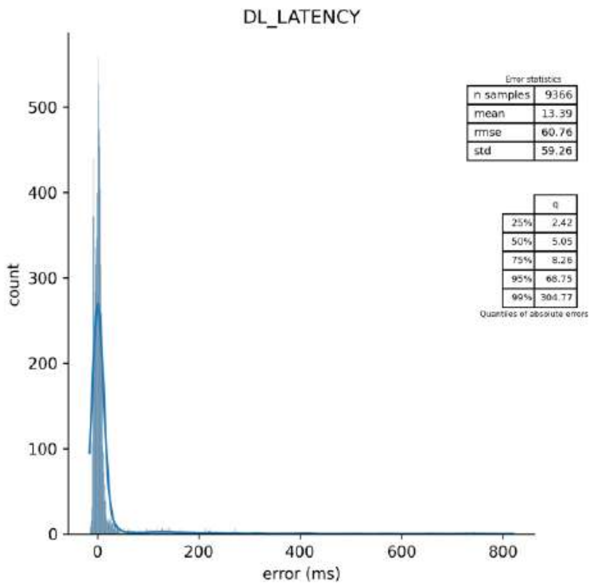

Figure 3.3.1 (a) Error distribution of one-way latency: overall

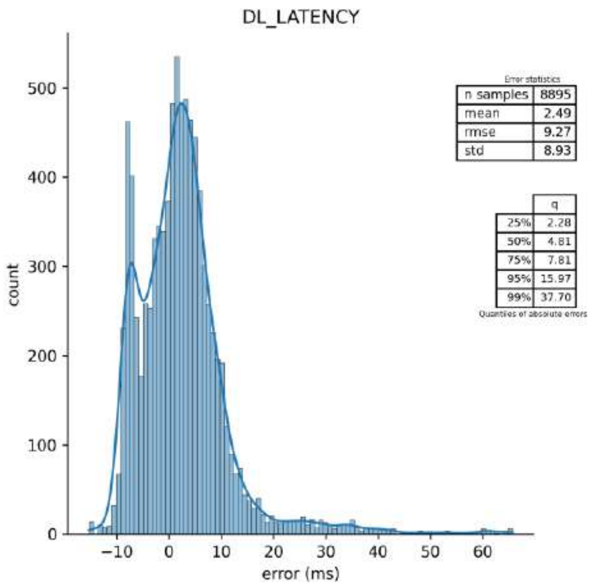

Figure 3.3.1 (b) Error distribution of one-way latency: 95-th percentile.

Conclusion

This white paper provides an introduction to BVLOS drone use cases, explaining how mobile network operators are supporting the drone ecosystem, the interfaces enabling integration between telecommunications and aviation, and the reliability of connectivity intelligence provided by MNOs through one of the key enabling solutions — AirborneRF.

It further presents an overview of the predictive capabilities of AirborneRF. By utilizing statistical indicators and analyzing the evidence gathered, the findings demonstrate a very strong alignment between the predictions and the actual measurements. The results demonstrate that AirborneRF is a sophisticated platform that allows forecasting airspace connectivity with very high accuracy and reliability. On that basis, AirborneRF results are well suited to provide the required evidence of connectivity along a flight path for flight planning, flight clearance and approval processes, as well as for automated risk assessments. Thus, AirborneRF enables the automation and safe scaling of BVLOS drone operations.

References:

[1] FAA part 108, [online available]: https://www.faa.gov/newsroom/BVLOS_NPRM_website_version.pdf

[2] Official website of AirborneRF [online available]: https://www.dimetor.com/solutions/

[3] AirborneRF APIs for drones and airspace industry [online available]: https://apidoc.airbornerf.com/

[4] Aerial Connectivity Joint Activity Network Coverage Service Definition, ACJA Interface for Data Exchange between MNOs and the UTM Ecosystem: NetworkCoverage Service Definition v1.00, 2021., [online available]: https://www.gsma.com/solutions-and-impact/industries/smart-mobility/air-mobility/acja-4-2/

[5] T. Neubauer, M. Williamson, B. O. Neill, S. Dulal, T. Berisha, S. Woblistin, F. Parzysz, S. Homayouni, P. Montowtt, N. Metzner, and A. Prekajski Reference method for assessing cellular C2 link performance and RF environment characterization for UAS, GSMA - Aerial Connectivity Joint Activity (ACJA) - Work Task 2, 2022.

[6] T. Hastie, R. Tibshirani, J. Friedman, The Elements of Statistical Learning, Springer Verlag, 2009.

[7] 3GPP TS 36.133, Evolved Universal Terrestrial Radio Access (E-UTRA); Requirements for support of radio resource management, 2016.

[8] 3GPP TR 36.777, Study on Enhanced LTE Support for Aerial Vehicles, 2017.

[9] S. Homayouni, M. Paier, T. Berisha, S. Woblistin, J. Rehak, 3GPP-based Verification of Latency Measurements in Operational Cellular Networks with Low-altitude Drones, 2022 International Conference on Smart Applications, Communications and Networking (SmartNets): 5G for Industrial Applications, 2022.

[10] S. Homayouni, T. Berisha, M. Paier, S. Woblistin, J. Rehak, T. Neubauer, Verification of Standardized Rel-15 Requirements for Drone’s Command-and-Control Link Reliability, 2023 IEEE 97th Vehicular Technology Conference (VTC)-Spring, 2023.