Field Trial of a 5G Non-Terrestrial Network Using OpenAirInterface

Florian Völk © (Student Member, IEEE), Thomas Schlichter, Florian Kaltenberger © (Member, IEEE), Thomas Heyn, Guido Casati ©, Robert T. Schwarz © (Member, IEEE), and Andreas Knopp © (Senior Member, IEEE)

Satellites enable the provision of global 5G coverage utilizing a customized protocol stack for direct access of 5G devices. This paper reports the results of a field trial based on an Open Source Software (OSS) 5G protocol stack modified for Satellite Communications. 5G New Radio (NR) functions have been adapted to support 3GPP Non-Terrestrial Networks (NTN) standardization for Release 17. Some of the currently discussed enhancements for 5G NR direct access for NTNs were evaluated in this study utilizing a geosynchronous satellite system. NTN devices and base station were software-defined solutions communicating via satellite through a standardized 5G NR waveform. The results show that OSS implementations running on general purpose platforms greatly support the research and standardization process for 5G-Beyond NTNs. New functions related to NTNs can be evaluated at an early stage over channel emulators or real world satellites to highlight the capabilities of space based 5G-Beyond networks. Therefore, OSS can be a starting point to turn the vision of 6G protocols on-board the satellite into reality.

Index Terms—Satellite communication, Satellite ground stations, 5G mobile communication, Radio access networks, Space communications

I. INTRODUCTION

The Fifth Generation Mobile Networks (5G), is set to revolutionize the world of mobile communications. Satellites will play an essential role in the development of 5G-Beyond networks and in this field major satellite operators see future market potential. In this context, the current 3rd Generation Partnership Program (3GPP) work programme for Release 17 of the 5G New Radio (NR) standardization defines new features to support transparent (non-regenerative) satellites. In this architecture the satellite acts as a amplify-and-forward relay. This step towards standardizing satellite links in the 5G network represents only the first phase of the seamless integration of non-terrestrial systems in future 5G-Beyond architectures.

The standardization efforts on Satellite Communication (SatCom) in 3GPP is commonly known as Non-Terrestrial Networks (NTNs). The ambition is to achieve initial integration of NTNs into 5G by evolving the protocols and functions of the 5G Core Network (5GC) and Radio Access Network (RAN), including the NR radio interface, to support NTNs. As part of the standardization process on 5G (3GPP Release 15 to 17), this is the first time that satellites are being studied in detail outside of the transport network to provide value to a direct end user. Here, the terminal no longer communicates with a base station via a terrestrial mobile radio channel, but via a satellite channel to a distant base station as part of the satellite ground components. This NTN is intended to enable the integration of Geostationary Earth Orbit (GEO) and upcoming Non-Geosynchronous Orbit (NGSO) satellites (e.g. [1], [2]) in both transport and access networks. Within the first two phases of the 5G standardization in 2017 to 2019, two fundamental studies (see [3] and [4], respectively) were conducted to investigate in which network architectures GEO satellites (Fig. 1) can play a role in the future 5G/6G infrastructure [5].

The current focus of Release 17 3GPP standardization is on satellites and High-Altitude Platform System (HAPS) with transparent (non-regenerative) payloads. Release 17 features taking care of NTN aspects and issues were frozen in March 2022. The extensions on standardization provide a specifica-tion how 5G NR can be used for direct access via satellite between Low Earth Orbit (LEO) and GEO.

Previous studies have identified two main types of service links between satellites and earth stations: First, direct connectivity with handheld devices transmitting at a maximum power of 23 dBm and omnidirectional antenna. Second, broadband connectivity utilizing Very Small Aperture Terminals (VSAT) with directional antennas. Furthermore, the standardization distinguishes between direct and indirect access as shown in Fig. 2. The direct access allows an end user terminal to directly utilize a satellite link whereas the indirect access and backhauling is required to use a relay or base station on earth. This study considers the novel direct access architecture where the 5G NR waveform is employed for the first time on a satellite link.

However, this convergence is expected to be realized in 10 years as part of the 6G standard. Until then, a truly “intelligent” network will be set up in space that makes optimum use of the capacities of satellites in different orbits. These efforts in standardization can pave the way for an even more significant role of NTNs in the 6G standards. First definitions of the 6G network at a scientific level have been recently established initial research and development goals for the next 10 years. Recent work has already shown first efforts in terms of deriving first concepts and exploration of new technologies [6], [7], [8]. It is expected that NTNs will be

This paper was submitted for review on Feb 11th, 2022. The work presented is part of the European Space Agency (ESA) ARTES Advanced Technology project 5G METEORS - MakerSpace for 5G and satellite communication, ESA Contract No. 4000125926. The views expressed herein can in no way be taken to reflect the official opinion of the ESA.

F. V., R. S., and A. K. are with the Institute of Information Technology, University of the Bundeswehr Munich, Neubiberg, Germany (e-mail: papers.sp@unibw.de).
T. S., T. H., and G. C. are with the Fraunhofer IIS, Erlangen, Germany (e-mail: firstname.lastname@iis.fraunhofer.de)
F. K. is with Eurecom, Sophia-Antipolis, France, (e-mail: flo-rian.kaltenberger@eurecom.fr)
a main service provider in the overall 6G ecosystem. Early prototypes of the NTN technology are important for the 6G community and the Release 18 standardization process.

Open Source Software (OSS) can make an important contribution to new NTN innovations, since New Space companies, can rely on a basic framework for their future software development. Porting the 5G/6G protocol stack on-board will be an unprecedented innovation. The integration becomes even more important, in the light of satellites connecting with each other via inter-satellite links. Implementing base station functions on-board the satellite is therefore only logical in future 6G networks.

In addition to the commercial implementations of the 3GPP based standards by the major network equipment suppliers, there is a small group of OSS projects implementing 3GPP RAN components. Several projects have been implemented the Fourth Generation Mobile Networks (4G) Long Term Evolution (LTE) standard. GNU’s Not Unix (GNU) Radio provides an LTE User Equipment (UE), Evolved Node B (eNB) and Evolved Packet Core (EPC) implementation [9]. There are currently no activities with respect to 5G NR, and even the development on the LTE components have not been continued. Software Radio Systems (SRS) provides an OSS implementation of several LTE features for UE, eNB and EPC [10]. In April 2021, SRS renamed the OSS project from srsLTE to srsRAN, as 5G Non-Standalone Access (NSA) support was released for the srsUE. In May 2022, srsRAN brought 5G Standalone Access (SA) support to both Next Generation Node B (gNB) and UE. At the moment, the OpenAirInterface™ (OAI) project [11] seems to provide the most advanced implementation of 5G NR gNB and 5G NR UE. On the contrary to the other OSS projects, the OAI gNB is already reaching a downlink throughput higher than 250 Mbps with a single layer 80 MHz configuration utilizing a Commercial Off-The-Shelf (COTS) device.

The contribution of this article is to demonstrate the feasibility of the 5G NR protocol stack via a NTN. We developed a prototype based on the OAI OSS and off-the-shelf radio hardware which has partly been published in [12]. The results from an Over-The-Air (OTA) field trial over a transparent GEO satellite are reported in detail in this article.

The paper is organized as follows: In Section II, the current status of the 5G OSS protocol stack OAI is described. Section III presents the NTN adaptions of the 5G protocol stack, which were the baseline for our study. The field trial is reported in Section IV. An outlook on future work is given in Section V. Conclusions are drawn in Section VI.

II. OpenAirInterface 5G Development Status

To bring the 5G/6G protocol stack on-board the satellite, an inter-operable, modular and open network architecture including a strong OSS ecosystem is necessary. OAI implements 4G and 5G RAN and Core Network (CN) as specified by the 3GPP on general purpose x86 computing hardware and COTS Software Defined Radio (SDR) cards such as the Universal Software Radio Peripheral (USRP). Real-time operation requires specific hardware and operating system constraints for different hardware targets. An SDR system performs most of the signal processing using a general purpose computer, combined with dedicated hardware such as signal processors and/or Field Programmable Gate Arrays (FPGAs). Receiver bandwidths of a few 10 MHz can be realized with general purpose computers. This allows the deployment of 4G LTE as well as 5G NR networks at a very low cost [11].

Most terrestrial 5G NR deployments today use the NSA mode, which requires an existing 4G LTE network. In the NSA option all the control plane traffic is exchanged with the UE through the 4G eNB. Once the UE is attached to the EPC and connected to the cell, the end-to-end user-plane traffic between the UE and the 5GC is delivered through the gNB. For any new network deployment the SA mode is much more interesting compared to NSA mode. The 5G SA mode requires a new 5GC and does not use legacy LTE radio access. For future NTNs the 5G SA mode seems to be the most attractive architecture as well. Fig. 3 shows the OAI 5G RAN architectures discussed in the following subsections.

A. 5G Non-Standalone Access

Initial terrestrial deployments of 5G NR will use the NSA option. In the NSA mode all Control Plane (CP) traffic is exchanged between the UE and the 4G eNB. The eNB communicates with the gNB over X2-C interface. This allows
the exchange of all required NR configuration to and from the UE. The S1-C interface is required for the communication between the eNB and the EPC to successfully attach the UE. Once the UE is attached to the EPC and connected to the 5G cell, the end-to-end user-plane traffic between the UE and the CN (S1-U interface to the SGW) is delivered exclusively through the gNB.

B. 5G Standalone Access

For 5G NTN, as well as other applications of 5G (in, e.g., Industry 4.0), the 5G network will need to operate in SA mode which does not depend on legacy 4G LTE, but requires a new 5GC. The 5GC Service-Based Architecture (SBA) is fully cloud-aligned and supports control plane function interaction, re-usability, flexible connections and service discovery [14]. A high level representation of the 5G SA system is illustrated in Fig. 4. The main 5GC functions have all been implemented in the OAI 5GC and can easily be deployed using docker-compose:

- Access and Mobility Management Function (AMF)
- Session Management Function (SMF)
- Network Repository Function (NRF)
- User Plane Function (UPF)
- SPGW-U-tiny

Compared to NSA, in SA the gNB needs to also implement the complete Radio Resource Control (RRC) layer and handling of all the associated messages as well as the NG Application Protocol (NGAP) to interface with AMF (N2 interface) and UPF (N3 interface). A support of multiple Bandwidth Parts (BWP) at the gNB is needed for the SA mode. The BWP feature has been included into 5G NR to support various UE categories in terms of bandwidth. In addition, a more advanced UE can use a small bandwidth if less data is transmitted and open the full cell bandwidth when a large amount of data is needed. The initial access of a UE happens only on the initial BWP. Support for contention based access is needed as well. In addition, support for common and dedicated control channels is required. Only after the initial connection and authentication with the AMF, the full BWP is configured and used for user-plane traffic.

C. noS1 mode

With the noS1 mode no eNB or CN is needed to establish a connection between an OAI UE to an OAI gNB. This mode is a mixture of the NSA and SA mode. The noS1 mode only supports user-plane traffic. Control-plane traffic is injected and received via Ethernet. One exception is the Random Access (RA) procedure that is also happening in noS1 mode. The UE knows the parameter configuration in advance by means of a configuration file. We chose the noS1 mode because the OAI 5GC development had not been completed. All user traffic terminates at the OAI gNB and is not forwarded to another data network.

III. Non-terrestrial networks adaptations

The basic framework for the NTN standardization is the terrestrial 5G NR standard. An overview and summary of the 5G NR RAN system is given in [15]. The current 3GPP focus is on transparent communication payload satellite systems, meaning all the enhancements are added to the UE and the gNB on earth. UEs and gNBs are required to handle a very large propagation delay compared to terrestrial systems. The 3GPP studies assume a Frequency Division Duplex (FDD) system, earth fixed tracking area, and UEs with Global Navigation Satellite System (GNSS) capability. Typical SatCom effects and their impact on the NR standard are shown in Table I. The following enhancements are included into the 3GPP Rel. 17 specification [4]:

- Timing-relationship
- Uplink (UL) time and synchronization
- Hybrid Automatic Repeat Request (HARQ) operation (adaptation of the number of HARQ processes and disabling of HARQ feedback)
- RA procedure
- Value range extension of Radio Link Control (RLC) and Packet Data Convergence Protocol (PDCP) parameters
- Cell selection/reselection
- UL scheduling
- Handover
- Service continuity to move between terrestrial and non-terrestrial service

A. 5G OAI Extensions to support NTN

The basic configuration for terrestrial networks implemented in OAI supports 30 kHz Sub-Carrier Spacing (SCS) and a
**TABLE I**

<table>
<thead>
<tr>
<th>Effect</th>
<th>Impact on NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long latency</td>
<td>HARQ</td>
</tr>
<tr>
<td>Long latency</td>
<td>PHY procedures (ACM, power control)</td>
</tr>
<tr>
<td>Long latency</td>
<td>MAC/RLC Procedures</td>
</tr>
<tr>
<td>Differential delay</td>
<td>RACH</td>
</tr>
<tr>
<td>Differential delay</td>
<td>TA adjustment</td>
</tr>
<tr>
<td>SatCom channel impairments</td>
<td>Demodulation Reference Signal (DMRS) frequency density</td>
</tr>
<tr>
<td>SatCom channel impairments</td>
<td>Cyclic prefix</td>
</tr>
<tr>
<td>SatCom regulatory constraints</td>
<td>FDD access</td>
</tr>
<tr>
<td>Doppler effect</td>
<td>Initial synchronization DL</td>
</tr>
<tr>
<td>Doppler effect</td>
<td>DMRS time density</td>
</tr>
<tr>
<td>Delay variation due to large cell size</td>
<td>TA adjustment</td>
</tr>
<tr>
<td>Moving cell pattern for NGSO</td>
<td>Hand-over/paging</td>
</tr>
<tr>
<td>Phase noise impairment</td>
<td>Peak to Average Power Ratio (PAPR) reduction techniques</td>
</tr>
<tr>
<td>High-power amplifier back-off</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 5.** 5G NTN architecture for direct access including UEs, a transparent satellite link, a gNB and the 5GC.

bandwidth of 40 MHz. Within a 10 ms frame, 20 slots (each 0.5 ms) are transmitted. A Time Division Duplex (TDD) period of 10 slots includes 7 Downlink (DL) slots, 1 mixed slot and 2 UL slots. However, since most of the NTN scenarios operate in FDD mode, the implementation of OAI 5G features to support FDD operation with configurable intermediate frequencies at Physical Layer (PHY) was required. Our FDD implementation was limited to the PHY and was still relying on the TDD scheduling procedures at the Medium Access Control (MAC) layer, i.e. the scheduler was allocating resources according to a TDD DL and UL time domain allocation pattern. Our implementation provides UL and DL transmissions which is separated in frequency and time. This half-duplex mode does not use the spectrum efficiently compared to a true TDD and FDD mode. This mode will be replaced in our future implementations by a true FDD mode.

To enable this field trial, 10 MHz bandwidth with 30 kHz SCS, including the necessary changes for Physical Random Access Channel (PRACH) have been implemented as well. In addition, Phase-Tracking Reference Symbols (PTRS) in Physical Downlink Shared Channel (PDSCH) and Physical Uplink Shared Channel (PUSCH) were added to our OAI repository.

**B. 5G OAI pre-standard extensions for NTN Rel-17**

The main degradation of the 5G signal over the satellite channel is due to the large propagation delay, which can be hundreds of times the average terrestrial delay. For geostationary spacecrafts at 35 786 km altitude, the delay in one direction is approximately 250 ms, with a Round Trip Time (RTT) of around 0.5 s.

In order to account for the large GEO satellite propagation delay, the features listed in Table II were implemented in our OAI repository, thus, enabling the final NTN field trial.

**TABLE II**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial timing advance at UE side based on the target channel propagation delay</td>
<td>The computation of the initial timing advance for the reception of the initial DL synchronization signals and the transmission of the RA preamble shall take into account the characteristic propagation delay of the satellite channel.</td>
</tr>
<tr>
<td>Extension of time domain allocation (k₂) for PUSCH scheduled by Random Access Response (RAR) UL grant (clause 6.2.1.1 of [4])</td>
<td>In case of PUSCH transmission initiated by the RA procedure, the UE receives an UL grant via RAR. The UL scheduling is given by n + k₂ + Δ (clause 8.3 of [16]), where n is the slot in which the RAR was received. To take into account the longer propagation delay the k₂ is extended with by means of k₂_{f, PUSCH}.</td>
</tr>
<tr>
<td>Extension of time domain allocation (k₂) for DCI (clause 8.3 of [16])</td>
<td>In case of PUSCH transmission initiated by Physical Downlink Control Channel (PDCCH), the UE receives an UL grant via Downlink Control Information (DCI). The UL scheduling is given by n - k₂_{PDCCH} + k₂ (clause 6.1.2.1 of [17]), where n is the slot in which the DCI was received and µ is the numerology. To take into account the longer propagation delay the k₂ is extended with by means of k₂_{f, PUSCH}.</td>
</tr>
<tr>
<td>Extension of RAR window (clause 7.2.1.1.2 of [4])</td>
<td>The RAR window, during which the UE monitors the PDCCH for a RAR message, is designed for terrestrial communications and covers only up to a few milliseconds after the transmission of the preamble. Therefore, size is extended by means of a slot offset UE_{k₂} to delay the start of the RAR window.</td>
</tr>
<tr>
<td>Disabling of HARQ (clause 7.2.1.4 of [4])</td>
<td>UL HARQ retransmission and feedback for DL transmission are disabled by means of changes to the OAI gNB scheduler. The number of the HARQ processes is also increased.</td>
</tr>
</tbody>
</table>

**IV. 5G-NTN TRIALS OVER GEO SATELLITE**

**A. Test Setup**

The reference architecture for the demo is depicted in Fig. 6 and consists of a 5G NR link between OAI UE and OAI gNB, both located on ground at the Earth station in Neubiberg, Germany. This research facility enabled a real OTA test of our NTN platform over a GEO satellite located at 13.2° East and casting a single NTN cell for our European service zone. Table III shows the most relevant configuration parameters of the demo platform. The GEO satellite itself operated as an OAI repository, thus, enabling the final NTN field trial.

Both gNB and UE as shown in Fig. 8 were running on consumer computers with ETTUS X310 USRP operating in L-band below 2 GHz. We used a Block Upconverter (BUC).
Fig. 6. 5G NTN architecture (noS1 mode) for the field trial. Our demonstrator includes adapted PHY, MAC, and RLC layer for OAI.

### TABLE III

**Configuration Parameters of the NTN Demo.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>10 MHz (DL and UL)</td>
</tr>
<tr>
<td>Frequency band</td>
<td>7.0 GHz to 11.0 GHz (X-band)</td>
</tr>
<tr>
<td>Satellite position</td>
<td>13.2° East</td>
</tr>
<tr>
<td>Antenna</td>
<td>4.9 m parabolic (50 dBi receive gain, Fig. 7)</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK and 16-QAM modulation scheme</td>
</tr>
</tbody>
</table>

in our UL transmission to convert a frequency band from the lower USRP frequency to the higher satellite transmission frequencies. Our Low-Noise Block Downconverter (LNB) converted the received satellite signals to the lower USRP frequencies. During our field test, all traffic was terminated at our OAI base station (noS1 mode), so no transport and CN was needed to send Internet Protocol (IP) user traffic between the UE and gNB.

### B. Results

The OTA test consisted of the following steps: (i) verify the proper functionality of the RA adaptations by performing a successful initial connection setup between UE and gNB; (ii) verify the proper functionality of the time-domain adaptations by successfully decoding the 5G DL transmission signal; (iii) verify the proper functionality of the implemented 5G Timing Advance (TA) procedure by successfully decoding the 5G UL transmission signal, thus, achieving UL synchronization.

After receiving the initial synchronization sequences we observed a successful four-step RA procedure with our NTN network prototype: The UE transmitted the RA preamble which was received by the gNB. A RA response sent by the gNB indicated the preamble reception and provided a timing-alignment command to adjust the transmission timing of the UE. Afterwards UE and gNB exchanged *Message 3* in the UL and *Message 4* in the DL to resolve collisions with potential other UEs. In addition, the RA procedure was also used to re-
establish UL synchronization if the UE lost synchronization due to a too long period without any UL transmission.

Over the course of the tests, the satellite drift of the GEO spacecraft in its orbital station-keeping box was also compensated by the NTN TA procedure. By means of a Linux ping command, we measured a RTT between gNB (IP address: 10.1.10.1) and UE (IP address: 10.1.10.2) ranging between 530 and 570 milliseconds. The RTT measurements with our prototype, shown in Fig. 11, are comparable with COTS satellite modems. The Quadrature Phase Shift Keying (QPSK) constellation diagrams in the IQ domain, of the Physical Broadcast Channel (PBCH), PDSCH and PUSCH shown in Fig. 10 and 9 visually confirm the successful reception of the PHY signals with negligible phase rotation of the constellation points. No 5G PTRS was utilized due to the high Signal-to-Noise Ratio (SNR). Please note that all the control information was transmitted via Ethernet between UE and gNB.

Fig. 12 shows the spectrum of the received signals from the GEO satellite at the 4.9 m satellite antenna. The two carriers\(^1\) in the red box and the blue box belong to the gNB and the UE, respectively. The maximum received power is highlighted with a spectral mask (black line). Furthermore, the satellite transponder was also used by other satellite modems during our field trial. Fig. 12 (left) shows spectrum occupied by COTS modems. However, utilizing large guard bands between the modem carriers and the 5G NR carriers we tried to avoid in-band interference.

V. FUTURE WORK

The evolution of this NTN platform is being continued in the European Space Agency (ESA) funded 5G-GOA project [18]. Aim of the project is to produce a standard compliant 5G NTN network, consisting of an adapted UE and gNB. The intention is to verify a bidirectional end-to-end communication between two user terminals and the 5GC. Therefore, additional changes in the protocol stack are needed. The OAI PHY will be adapted to support: (i) 5 MHz bandwidth with 15 kHz SCS; (ii) multiple BWPs; (iii) full FDD scheduling at the MAC layer, by enabling continuous DL and UL transmission/reception; (iv) multiple carriers on the uplink, implemented in the 5G NR uplink multiple input multiple output (MIMO) mode.

\(^1\)The Local Oscillator (LO) for both gNB and UE was clearly visible. There seems to be a problem or driver issue with the daughter boards for ETTUS X310 USRPs. Calibration did not resolve it. We will apply filtering to mitigate the LO for future tests.
multi-UE support with the necessary enhancements of the simultaneous RA; (v) enhancement of the feature disable HARQ for a better collaboration with the upper layers (especially RLC and PDCP), as we observed issues in the data transmission with our implementation during this field trial.

Furthermore, the OAI Graphical User Interface (GUI) will be extended within the project to show Key Performance Indicators (KPIs) of the 5G communication link such as the Block Error Rate (BLER) of the transmissions, achievable throughput per UE and experienced delay of the link, including effects of retransmissions on IP layer. 5G-GOA will merge the developed extensions and improvements into the main development branch of OAI in September 2022. The ultimate goal of the OAI protocol stack for NTNs is to support in orbit 5G NR NTN experimentation and validation on-board the satellite.

In addition to customizing the protocol stack for GEO satellites, the next step is to conduct initial tests of 5G NR over NGSO channel emulators. Many issues regarding the realization of a 5G satellite system for NGSO constellations are still unresolved and raise a variety of technical and scientific problems. An example of a known difficulty is that low-flying satellites move around the Earth at high speeds. In such a scenario, a 5G end user will be within the footprint of the satellite for a few minutes only. Therefore, the connection from one satellite to a subsequent one, has to be handed over without any interruption of the 5G NTN link. This issue is even more challenging with high UE mobility like in high-speed train and airplane use cases which have been analyzed in [19], [20], [21].

VI. CONCLUSION

In this paper, we reported the results of our 5G non-terrestrial field trial. A dynamic investigation and prototyping of the 5G protocol stack via GEO satellite, as currently discussed in the 3GPP NTN RAN meetings, was performed. We showed that the OSS OAI, compliant with 5G Release 15, can be adapted in such a way that the protocol stack is able to achieve bidirectional IP traffic transmission via a GEO satellite. Our test results illustrate the importance of OSS for the 5G-Beyond research & development phase and satellite integration into 6G networks. OSS could be a starting point to bring the 5G/6G protocol stack on-board the satellite. The development of an OSS 5G/6G ecosystem will be an innovation driver for SatCom in the next few years.

ACKNOWLEDGMENT

We would like to thank the Fraunhofer IIS OAI team for implementing the OAI software customization for NTNs. In addition, we would like to thank the OAI Software Alliance for developing the 5G OSS ecosystem. Special gratitude goes to the Bundeswehr Cyber and Information Domain Service for providing satellite capacity.

REFERENCES

Florian Völkl is a Research Fellow and Ph.D. candidate at the SPACE Research Center of the University of the Bundeswehr Munich. He studied Electrical Engineering and Information Technology in Nuremberg and Melbourne and focused on communications engineering during his studies. He received the master’s degree in 2016.

Since 2016, he has been a Research Fellow with the University of the Bundeswehr Munich. His research interests include physical layer techniques, system design and architecture optimization for hybrid satellite-terrestrial networks. He has strong interest in prototyping, experimental work, and testbeds.

Thomas Schlichter received his degree in Computer Engineering (Dipl.-Inf.) from the University of Mannheim, Germany, in December 2003. From 2004 to 2009 he worked as a research assistant in the Department of Hardware-Software-Co-Design at the University of Erlangen-Nuremberg, Germany.

In 2009, he joined Fraunhofer Institute for Integrated Circuits IIS as a hardware-software engineer. Here, he was responsible for the design and implementation of hardware-software-interfaces and high-speed FPGA hardware designs in ESA and EU projects as well as supervising student works on different topics, e.g., software defined radio and high-level synthesis. In 2012 he was promoted to Senior Engineer. Besides contributing software to the Open Air Interface project, he is also member of the Open Air Interface Software Alliance Technical Committee.

Florian Kaltenberger is an Assistant Professor in the Communication Systems department at EURECOM (France). He received his Diploma degree (Dipl.-Ing.) and his PhD both in Technical Mathematics from the Vienna University of Technology 2002 and 2007 respectively.

He is part of the management team for the real-time open-source 5G platform OpenAirInterface.org and for the general secretary of the OAISoftware alliance. He is coordinating the developments of the OAI radio access network project group, which delivered support for 5G non-standalone access in 2020 and for 5G standalone access in 2021. He also manages several research projects (industrial and academic) around the platform and teaches a course on radio engineering. His research interests include 5G and MIMO systems at large, software defined radio, signal processing for wireless communications, as well as channel modeling and simulation.

Prof. Kaltenberger received the Neal Shepherd Best propagation Award for the Journal article “Experimental characterization and modeling of outdoor-to-indoor and indoor-to-indoor distributed channels” (IEEE Transactions on Vehicular Technology, Vol.59, N°5, June 2010) in 2013. In 2016 Prof. Kaltenberger received the best demo award for the project ADEL at the European Conference on Networks and Communications.

Thomas Heyn received his degree in electrical engineering (Dipl.-Ing.) from Friedrich-Alexander-University in Erlangen in 1996 and joined Fraunhofer IIS shortly after.

He has been working in national and international projects in the area of telecommunication and digital broadcasting systems for contracting authorities as well as industrial partners for more than two decades. He is head of the Connectivity Group within the Broadband and Broadcast Department. His current research interests include future mobile networks, investigating evolutions of 4G and 5G technologies like virtual-MIMO concepts, convergence of satellite and terrestrial networks in 5G, industrial communications and connectivity of cars and UAVs. As a 3GPP delegate for Fraunhofer IIS, his work at first largely revolved around NTN and URLLC. He was one of the first within 3GPP to integrate Non-Terrestrial-Networks and satellite into the new mobile communications standard. Currently Mr. Heyn and his team are pursuing this target in the 3GPP RAN working groups.

Guido Casati received his M.Sc degree in Telecommunications Engineering from the University of Roma Tor Vergata, Italy, in December 2013. He completed his master’s thesis at the European Space Research and Technology Centre (ESTEC) in Noordwijk, Netherlands. He joined Fraunhofer IIS in June 2018 as a research associate. His main research and development topics focus on 5G NR features for terrestrial and NTN applications.

Robert T. Schwarz received the Ph.D. degree (Hons.) in satellite communications from the University of the Bundeswehr Munich, in 2019.

From 2006 to 2012, he was with the Federal Office, Bundeswehr for Information Management and Information Technology, where he was involved in the German Program for satellite communications of the Bundeswehr (SATCOMBw). Since 2012, he has been a Research Fellow with the University of the Bundeswehr Munich. His research interests include digital signal processing, waveform design, and MIMO for satellite and other non-terrestrial networks.

Dr. Schwarz is a member of the German Engineers’ Association VDE/ITG and the AFCEA.

Andreas Knopp received the Ph.D. degree (Hons.) in radio communications from University of the Bundeswehr Munich, in 2008.

Since 2014, he has been a Full Professor of signal processing, coordinating in addition Germany’s largest SpaceCom Laboratory and experimental satellite ground station, the Munich Center for Space Communications. Prior to taking up the faculty position, he gained expertise as a Communications Engineer and the Satellite Program Manager. His current research interests include satellite network integration and waveform design for 5G, digital satellite payloads, secure/antijam communications, and low-power mTC.

Prof. Knopp is an Advisor to the German MoD, a member of the Expert Group on radio systems in the German Engineers’ Association VDE/ITG, and a member of AFCEA.