5G over Terahertz Using OpenAirInterface

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***Abstract*—This work demonstrates the first-of-a-kind real-time end-to-end 5G connectivity between a user (UE) and the base station (gNB) at terahertz (THz) frequencies. While the gNB's 5G solution is based on OpenAirInterface (OAI), the UE can either be an off-the-shelf commercial 5G mobile terminal or an OAI-based solution. In both nodes, analog THz frontend modules are used to up-convert the intermediate frequency signal into THz frequencies. Implementation details and early experimental results indicating the feasibility of sending 5G waveform at THz frequencies are presented. Such prototypes will facilitate the development of integrated access and backhaul (IAB) solutions using THz links beyond 5G and 6G networks.**

I. Introduction

To satisfy the high data rate and low latency demands arising from AR/VR, digital twins and x-haul links in disaggregated open radio access networks (O-RAN), it has become necessary to tap into the huge bandwidths available in terahertz (THz) frequency bands (100 GHz-10 THz). With this in mind, the Federal Communications Commission (FCC) has created experimental licenses that span 21.2 GHz of spectrum in frequencies between 95 GHz and 3 THz. Particularly, multiple bands in the 110–160 GHz and 200–260 GHz have been allocated to fixed/mobile usage [1].

While the initial days of THz communication research is limited to channel modeling and numerical studies, recent advances in radio and photonic devices in THz frequencies have led to several experimental platforms demonstrating gigabit wireless links operating in the sub-terahertz and terahertz bands [2], [3]. To further advance the THz communication research and standardization activities there is an urgent need to develop software-defined radio (SDR) based platforms and protocol stacks that can showcase real-time communication technologies at THz frequencies.

The majority of the current experimental platforms operating over 100 GHz have been either channel sounders or physical layer testbeds that rely on offline processing [3]. Recently the work in [4], has demonstrated a real-time programmable SDR platform that can support Orthogonal Frequency Division Multiplexing (OFDM) based physical layer with bandwidth on the order of several GHz, and operating at carrier frequencies 120-140 GHz. However, the platform is limited to the link level and no communication protocol stack that includes higher layers runs on the transmitter (TX) or the receiver (RX).

On the other hand, when it comes to 5G and beyond systems, open-source projects that implement 3GPP cellular standards on general-purpose computing hardware and off-the-shelf SDR cards are making a huge contribution to the experimental research, standardization, and testing of multi-vendor networks in O-RAN [5]. For example, the OpenAirInterface (OAI) [6] project is widely known for providing an end-to-end 3GPP standard-compliant 5G NR protocol stack that can run on various SDR platforms. It is possible to quickly build a 5G network using OAI with a combination of low cost with COTS SDRs and general-purpose x86 computers. Recently, it has been shown that OAI can operate in millimeter wave (mmWave) FR2 bands [7].

In this work, to facilitate the 6G communication system architecture and reproducible experimental research, we demonstrate an OAI-based real-time end-to-end 5G communication at THz frequencies. To the best of the authors' knowledge, no such platform exists as of today.

II. System Design and Implementation

We leverage on the OpenAirInterface (OAI) 5G NR protocol stack [6], USRP software-defined radio (SDR) cards, and TeraNova testbed [8] to build the OAI-THz platform. This platform is capable of delivering end-to-end real-time 5G over THz. The system architecture is depicted in Fig 1. The OAI stack, along with the USRP, is used at the base station (gNB) to generate the 5G NR signals at an intermediate carrier frequency (IF) of 3.39GHz, while a Quectel module (commercial 5G module) serves as a UE operating at the same intermediate frequency. Further, THz frontend modules from TeraNova testbed [8] are utilized to upconvert the IF signals into THz frequencies and downconvert the THz signals to IF frequencies.

As shown in Fig. 2, the gNB antenna ports from the USRP and the antenna ports of the UE are connected to the THz frontend modules that upconvert IF to THz frequencies and downconvert back to IF. Circulators, isolators, and attenuators are added, ensuring that the operating power levels do not exceed the damage limits of the transmitter intermediate frequency (IF) port and prevent the reverse power/leakage into the receiver IF port.

We will first describe the OAI 5G architecture, and the description of THz frontend modules follows in Section IV.

III. OpenAirInterface 5G NR

OpenAirInterface (OAI) is an open-source initiative that provides a reference implementation of a 5G base station (gNB), User Equipment (UE), and 5G Core Network (5GC) which is standard compliant with 3GPP Release-15 (and above). OAI has software-based network functionalities that

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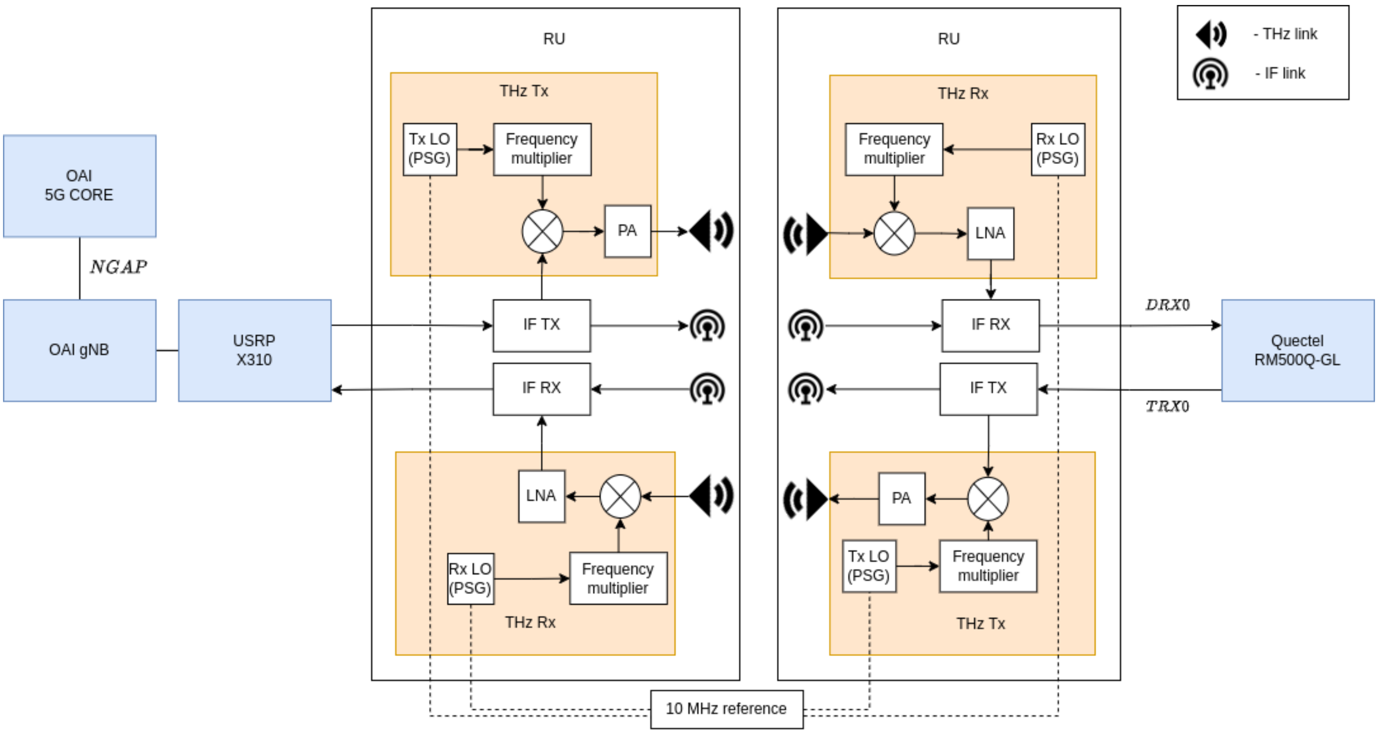

Fig. 1. A block diagram depicting the OAI-THz system architecture.

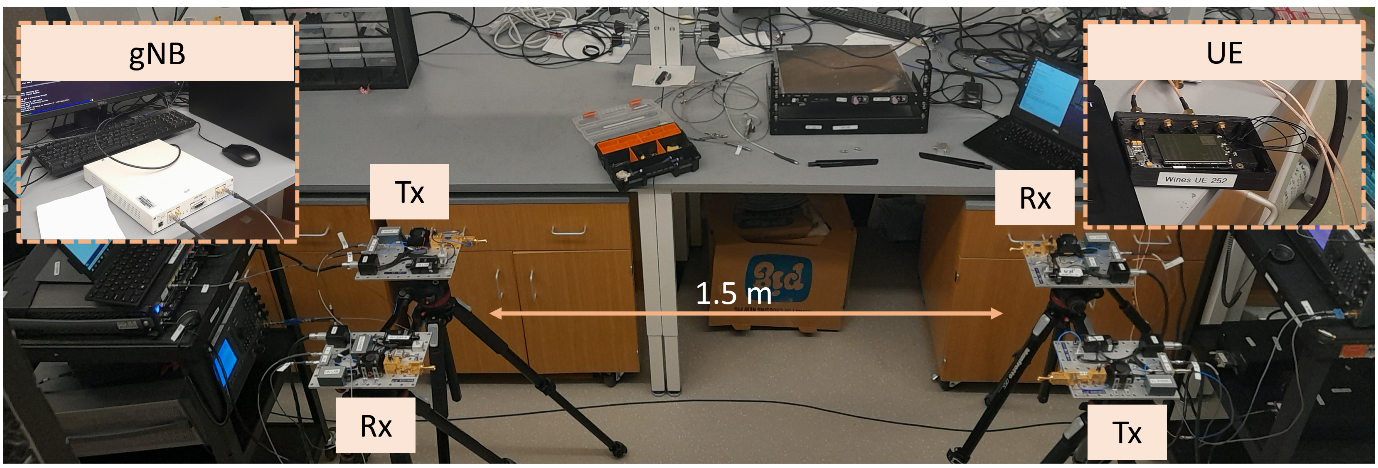

Fig. 2. A picture of the OAI-THz experimental setup in the lab.

reduce the implementation cost and increase the flexibility of the deployment. Detailed functionalities of each of the components in the OAI 5G stack are described as follows,

A. 5G Core Network

The 5G Core Network (5GC) manages and controls the various functions and services provided by the 5G network, including enhanced mobile broadband (eMBB), massive machine-type communications (mMTC), and ultra-reliable and low-latency communications (URLLC). The 5GC performs several essential functions such as authentication, mobility management, network slicing, and service orchestration. The OAI-THz setup uses the basic deployment version of 5GC based on OAI [9].

B. Radio Access Network

The OAI 5G-NR RAN can either be deployed as a monolithic gNB or split in centralized unit (CU) and distributed unit (DU) connected over the F1 interface. The CU can further be split into a control plane (CU-CP) and a user plane (CU-UP) functions that are connected over the E1 interface. The DU implements RLC, MAC, and PHY layers and supports fronthaul split option 8 with Off-The-Shelf (COTS) Software Defined Radio (SDR) cards like the ETTUS Universal Software Radio

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Peripheral (USRP) as well as O-RAN split 7.2 which has been tested with different O-RAN compatible radio units. OAI also supports the O-RAN E2 interface to the near real-time RAN intelligent controller (RIC) and the O1 interface to the Service Management and Orchestration (SMO) Framework. The interfaces supported by OAI 5G RAN is shown in Fig. 3.

The OAI 5G NR PHY supports all physical channels and signals according to the 3GPP Release-15. However, it is limited to subcarrier spacing of 15 kHz, 30 kHz in FR1, and 120 kHz in FR2. The supported bandwidths in FR1 are 10, 20, 40, 50, 60, 80, and 100 MHz. Furthermore, there is a Channel State Information Reference Signal (CSI-RS) sequence generation in the downlink and a Sounding Reference Signal (SRS) in the uplink for channel sounding.

In this work we use a simple deployment as a monolithic gNB using the USRP as a radio frontend. The USRP consists of a transmit path and a receive path. In the transmit path, the baseband signal is converted from digital to analog, upconverted, amplified, and transmitted over the air at an intermediate frequency (IF). In the receive path, the signal at the intermediate frequency is filtered, downconverted, and sampled by an analog-to-digital converter, resulting in a baseband signal. The IF signal is up/downconverted to/from THz for over-the-transmission using the THz radio frontends. The system parameters of the RAN are shown in Table I.

TABLE I
SYSTEM PARAMETERS

Parameters	Values
Bandwidth	80 MHz
Subcarrier Spacing	30 kHz
Intermediate Frequency (IF)	3.39 GHz
Centre Frequency	130 GHz
Sampling Rate	92.16 MHz
FFT Size	3072

C. User Equipment

In the OAI-THz setup, the Quectel RM500Q-GL module is used as UE, a commercial 5G modem with a Qualcomm chipset that supports 5G SA mode in real time. The module has four antenna ports operating at 3.39 GHz frequency. Two of these ports are transmit/receive (TRX) antenna ports, while the other two are diversity receive antennas (DRX) antennas. ANT0 and ANT3 correspond to TRX1 and TRX0 antennas on the module, respectively, and ANT1 and ANT2 correspond to DRX0 and DRX1 antennas. The TRX0 antenna port is used as a transmitter, which is connected to the THz transmitter frontend, and DRX0 as a receiver connected to the frontend of the THz receiver. OAI-softUE, which can emulate the behavior of a real-time 5G UE using a programmable radio like USRP, has also been validated in the platform. However, only the results of the Quectel module are presented in this paper.

IV. TERAHERTZ COMMUNICATION

The THz frontend modules used in the OAI-THz platform are a part of TeraNova testbed [10]. The TeraNova transmitter consists of an analog programmable signal generator (PSG) from Keysight Technologies and upconverter frontends, along with directional high-gain antennas encompassing frequency ranges in the terahertz band (0.095–1.05 THz) [11]. The PSG is used to generate the local oscillator (LO) signal and is capable of producing frequencies up to 50 GHz. The upconverter takes an IF signal, mixes it with the LO signal, and upconverts it to a higher radio frequency (RF) signal. The upconverters manufactured by Virginia Diodes, Inc. (VDI) operate in the frequency range of 120–140 GHz. They consist of a frequency multiplier chain of $\times 4$, a frequency mixer with a double sideband (DSB) conversion loss of about 7 dB, and an RF power amplifier (PA) with a gain of 20 dB. The transmit power before feeding the antenna is about 13 dBm (20 mW).

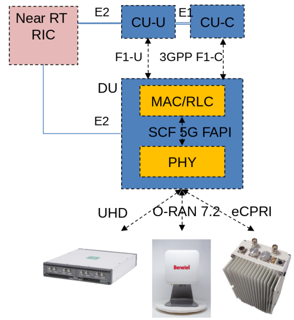

Fig. 3. OAI 5G-NR Radio Access Network.

The TeraNova receiver consists of a PSG of the same model as the transmitter, and downconverter frontends, along with similar high-gain antennas as the upconverters. The receiver PSG is used to generate the LO signal at the receiver side. The VDI downconverter frontends operate in the same frequency range of 120–140 GHz and have the same architecture as the upconverter frontends, but instead of an RF PA, an IF low-noise amplifier (LNA) is used to provide the required amplification. Fig. 1 depicts how the different transmitter and receiver components of the TeraNova testbed are interconnected. A 10 MHz reference cable is used to synchronize the transmitter and receiver PSGs and compensate for the carrier frequency and phase offsets. The testbed has multiple sets of broadband antennas with directivity gains ranging from 21 dBi to up to 40 dBi at the aforementioned frequencies.

V. EXPERIMENTAL RESULTS

This section analyzes the channel state information and throughput results at THz frequencies and compares them with those at the IF. The channel state information, depicted in Fig. 4 and Fig. 5, is obtained in the uplink using wideband pilots known as SRS. The channel frequency response (CFR) in the wideband (80 MHz) is obtained using the least square estimates of the SRS, as shown in Fig. 4. Moreover, the channel impulse response (CIR) is obtained by taking the IFFT of the channel frequency response, as shown in Fig. 5.

From Fig. 4 and Fig. 5, we can infer that the CFR at THz frequencies is almost flat, whereas, at IF, it is frequency-selective and has a multi-path channel, as seen in Fig. 4. The

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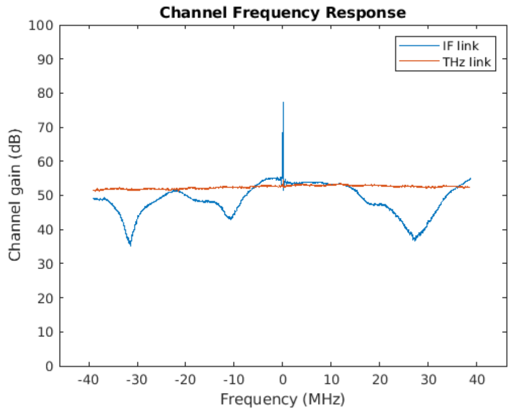


Fig. 4. Channel frequency response at both IF and THz frequencies.

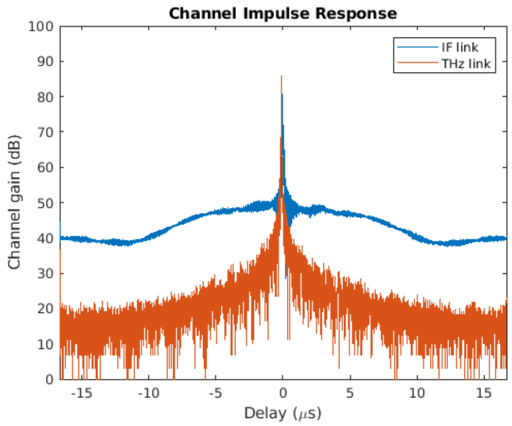


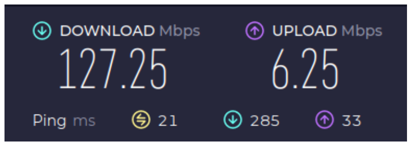
Fig. 5. Channel impulse response at both IF and THz frequencies.

peak at the center of the CFR at IF frequency is due to the DC leakage of the TX path into the RX path in the un-calibrated USRP X310 due to the usage of two individual dipole antennas for TX and RX (this could be avoided by using an external switch or circulator). This leakage is not present in the THz link is due to separation of UL and DL paths and the use of highly directive antennas. This DC leakage in the frequency domain is also the reason for the higher floor in the CIR of the IF link in Fig. 5.

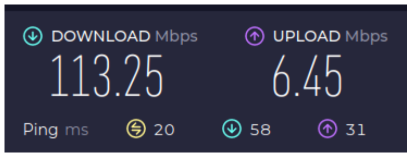
The throughput results, as depicted in Fig. 6, are obtained using a speed test web application by OOKLA [12] on the laptop connected to the internet via the Quectel module. The throughput results obtained at the THz frequencies are comparable to those obtained at the IF.

VI. Conclusion

In this paper, we have successfully demonstrated a first-of-a-kind real-time end-to-end 5G connectivity over THz frequencies using commercial user equipment with throughput results comparable to the throughput results of a 5G base station operating at 3.39 GHz. The use of open-source software for the 5G stack and a THz platform allows researchers in academia and industry to facilitate the development of integrated access and backhaul (IAB) solutions using THz links beyond 5G and 6G networks.



(a) Speed test at IF



(b) Speed test at THz

Fig. 6. Speed test at different frequencies.

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