A Configurable 60GHz Phased Array Platform for Multi-Link mmWave Channel Characterization

Anton Shkel
Facebook
Menlo Park, USA
antonshkel@fb.com

Alireza Mehrabani
Facebook
Menlo Park, USA
tarighat@fb.com

Julius Kusuma
Facebook
Menlo Park, CA
jkusuma@fb.com

***Abstract*— We present the Terragraph Sounder platform, developed to promote and enable research in mmWave propagation, systems, and networks, and is actively employed in research studies in over 13 institutions. Recent advancements to the platform include a suite of tools for performing interference measurements and developing interference mitigation techniques through phased-array-based beamforming. The tool provides 6-bits of phase control for 36 individual antenna elements (azimuth plane), allowing users to synthesize custom beam patterns. Researchers can deploy multiple 802.11ad/ay links and quantify the cross-leakage interference as a function of TX/RX beam configurations, measure degradation in SNR due to interference (SINR), study co-existence between mmWave links in the same frequency, and assess signal quality as a function of beam pattern design. Four software packages were developed that can run on the same hardware, enabling a wide array of research activities, ranging from RF propagation and modelling, phased array beamforming, protocol optimization, and mesh network routing research.**

Keywords*— *mmWave, channel sounding, RF propagation, RF beamforming, channel modeling, interference mitigation

I. Introduction

Terragraph (TG) is a mmWave radio system developed by Facebook as a cost-effective 802.11ad- and 802.11ay-compliant hardware reference platform. Terragraph has been successfully deployed by mobile operators and internet service providers in mesh networks as a backhaul transport for WiFi/Cellular access as well as for fixed wireless access (FWA) in the unlicensed V-band. Facebook has collaborated with the Telecommunication Infra Project (TIP) to develop a low-cost channel sounder kit with the right level of automation, based on the Terragraph radio and a software controller. This suite of software tools, called TG Sounder, has enabled independent research teams to perform indoor and outdoor channel propagation measurements, explore new use-cases, and demonstrate new technology elements.

The TG Sounder program has enabled researchers from 13 different institutions worldwide to conduct channel propagation and channel modelling research studies. Since the launch of the channel sounder program in 2019, the capabilities of the platform have evolved beyond channel sounding and propagation studies to cover a wider range of research areas throughout the communication protocol stack, including measurements related to interference, capabilities to perform custom beam-book design, pattern nulling, and software tools to measure end-to-end network-layer statistics and parameters.

II. System Design and Implementation

The TG Sounder platform includes a suite of tools for performing interference measurements and developing interference mitigation techniques through phased-array-based beamforming. The tool provides 6-bits of phase control for 36 individual antenna elements (azimuth plane), allowing users to synthesize custom beam patterns. Researchers can deploy multiple 802.11ad links and quantify the cross-leakage interference as a function of TX/RX beam configurations, measure degradation in SNR due to interference (SINR), study co-existence between mmWave links in the same frequency, and assess signal quality as a function of beam pattern design. More specifically, four software packages can run on the same TG hardware, enabling a wide range of research activities:

1. **TG-Sounder**: measure and analyze single-link 60GHz propagation's spatial and temporal profiles
2. **TG-Interference**: analyze multi-link propagation and interference, with the ability to design custom beams for nulling
3. **TG-Link**: analyze a beamformed 60GHz link passing TCP/UDP IP traffic with 4Gbps+ application-level throughout at 250m+ range
4. **TG-Mesh**: configure and operate a carrier-grade TG mesh network with cloud-based end-to-end (e2e) and network-management-system (NMS) controllers and to remotely manage, monitor, and upgrade hundreds of 60GHz nodes in the field.

In order to reduce cost, improve flexibility, and increase accessibility to mmWave channel sounder platforms, the TG Sounder project is built upon a low-cost flexible solution based on the Terragraph hardware operating at 60 GHz. The radios have system specifications summarized in Table 1.

TABLE I. HARDWARE SPECIFICATIONS

Parameter	**60 GHz Sounder**
Array Dimensions	8x36
Half-power Beamwidth	2.8°
Waveform Modulation	802.11ad
Center Frequency	60.48GHz
Channel Bandwidth	2.16GHz
Antenna Type	Patch + Waveguide
Antenna Polarization	Linear/Vertical
Antenna Array Dimensions	36 × 8
Antenna Element Spacing	0.55 λ
Phase Shifter Resolution	5.625° (6-bits)

This TG sounder platform provides the following key capabilities and features:

- It utilizes same integrated hardware platform designed and manufactured for field deployments, resulting in low-cost and scalable sounder platforms. This platform has been distributed to, and is currently in use, by more than 13 research institutions.
- Given its compact and portable form-factor (Fig. 1), it can be easily installed in deployment sites to analyze channel characteristics representing actual use cases.
- Enabled by the steerable phased arrays in the equipment, it provides accurate and fast measurement of spatial propagation profiles at transmitter (angle of departure) and receiver (angle of arrival).

A. Power Calibration

Since the intended use of Terragraph is as a communication node rather than a measurement tool, an additional software platform has been developed for automated control and coordination of channel sounding measurements. To enable accurate measurement of physical properties of the electromagnetic channel, a series of additional power calibrations were performed on each unit.

The channel sounder was calibrated through the use of a National Instruments (NI) mmWave transceiver system to accurately report the absolute incident power, absolute effective isotropic radiated power (EIRP), and path loss between the receiver and transmitter. All measurements were performed in channel 2 of the 802.11ad standard (with center frequency of 60.48 GHz). Calibration was performed over a range of ambient temperatures, gain settings, and beam-steering angles.

The BCM20138 chipset used in the Terragraph radio provides a digital Received Signal Strength Indicator (RSSI) metric that is calculated based on post-ADC data samples. Receiver gain settings are programable parameters, as well as reportable by the chipset. A combination of RSSI and Receiver gain settings are used to estimate RSSI at antenna input in dBm units.

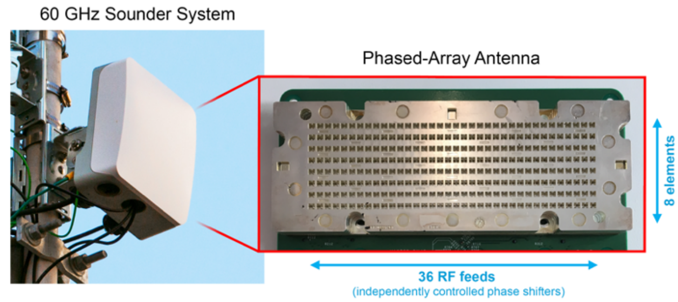

Fig. 1. Dimensions and phased array structures inside the 60GHz sounder equipment, composed of 288 omni antenna elements.

The following equation represents the relationships between measurement parameters (powers in dBm and gains in dB):

$$EIRP - PL + g_{ANT} + g_{RX} = P_{RSSI} \quad (1)$$

where *EIRP* is the transmitter's effective isotopically radiated power, *PL* is the free space path loss, g_{ANT} is the antenna gain of the horn, g_{RX} is the combined receiver RF and IF gain, and P_{RSSI} is the RSSI readout translated into dBm power. The tunable parameters are the *EIRP* and receiver gains. During unit calibration and in the controlled lab environment, Free-space path loss is estimated by the Friis equation for this calibration procedure:

$$PL = -27.55 + 20\,log\,F_c + 20\,log\,D \quad (2)$$

Where F_c is the center frequency in MHz and *D* is distance in meters. Direct calibration in terms of gain indices, RSSI readout, and temperature T requires an explicit derivation of P_{RSSI} mapping and individual receiver gain calibrations. In summary, the true incident received power P_{RX} is given as:

$$P_{RX} = EIRP - PL = f(gain, RSSI, T) \quad (3)$$

The receiver calibration procedure involves characterizing P_{RX} as a function of gain settings, measured digital RSSI, and temperature. The absolute incident power P_{RX}, is calculated as:

$$P_{RX} = P_{TX} + g_{HORN} + 27.55 - 20\,log(F_c) - 20\,log\,D \quad (4)$$

where P_{TX} is the signal generator transmit power and g_{HORN} is the horn antenna gain, used during the lab calibration phase.

A similar calibration procedure was performed for absolute transmit power measurements. Although a self-calibration mechanism for transmit power is implemented and utilized for normal operation of TG links, the accuracy of this built-in transmitter calibration method is not sufficient for the purpose of channel characterization. The accuracy of the built-in calibration further degrades at temperature extremes. Furthermore, this built-in calibration only calibrates the PAs on-chip, without taking into account variations in antenna and PCB characteristics from board to board.

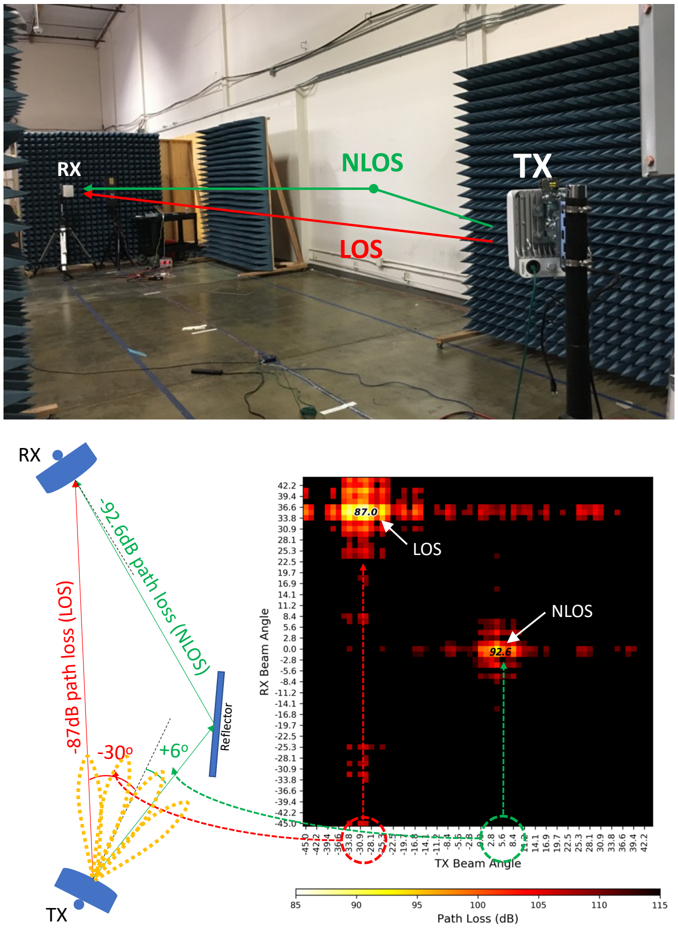

Fig. 2. Spatial profile demonstrating electrical scanning of propagation enginvironment to measure calibrated path loss for both LOS and reflected NLOS paths.

As a result, a comprehensive calibration of transmit power vs temperature and gain settings was required to meet the 60 GHz channel sounder targets. The implemented measurement setup was similar to the RSSI calibration with the roles of transmitter and receiver reversed. During the calibration phase, each unit is placed into a temperature chamber with the calibration procedure repeated for several temperature points within the usage range. The DUT's EIRP is measured with the calibrated 60 GHz receiver equipment, and the measured EIRP is collected over all transmit power configurations and temperature region of interest.

The calibration LUT for the transmitter is populated during the power calibration procedure. The EIRP is calculated as:

$$EIRP = P_{RX} - g_{HORN} + PL \tag{5}$$

$$= P_{RX} - g_{HORN} - 27.55 + 10 \log F_c + 10 \log D$$

For both the receiver and transmitter LUTs, an automated post processing step is used in the channel sounding procedure to interpolate between temperature and measured receiver/transmitter metrics to obtain calibrated values for incident power, EIRP, and path loss.

During field measurements, the sounder platform performs a full scan of TX and RX beam combinations and measures propagation characteristics (e.g., path loss, incident power level, SNR, and channel impulse response) for all combinations of TX and RX directions. This comprehensive measurement of spatial profile of the propagation can be used to analyze feasible use-cases and deployment conditions, such as viable NLOS and reflective paths present in the environment. An example of the spatial profile measurements is shown in Fig. 2.

B. TG-Interference: Multi-Link Interference Characterization

The TG sounder supports the characterization of multiple 60GHz links operating in the same channels, in order to characterize propagation/interference (Fig. 3). This capability is integrated with a tool to design custom beams, for studying the impact of beam design and nulling on multi-link systems.

Signal-to-interference-plus-noise ratio (SINR) is the key performance metric to characterize and validate multi-transmitter deployment topologies. It is characterized and reported on a per-receiver basis. Sweeps of transmitter nodes are preformed sequentially, with receiving nodes sweeping in parallel. That is to say, sounding between TX_1 and RX_1 (primary wanted link) and TX_1 and RX_2 (cross-link interference of secondary receiver) are performed in parallel, followed by sounding between TX_2 and RX_1 (cross-link interference of primary receiver) and TX_2 and RX_2 (secondary link). Given 2 transmitters and 2 receivers, calibrated EIRP (pTX), calibrated RSSI (pRX), and pathloss are computed with the following relationship for each permutation of phased array beam angles:

$$\begin{bmatrix} PL_{1,1} & PL_{1,2} \\ PL_{2,1} & PL_{2,2} \end{bmatrix} = \begin{bmatrix} pTX_1 & pTX_1 \\ pTX_2 & pTX_2 \end{bmatrix} - \begin{bmatrix} pRX_{1,1} & pRX_{1,2} \\ pRX_{2,1} & pRX_{2,2} \end{bmatrix} \tag{6}$$

The SINR can be computed for each link from the calibrated received power:

$$SINR_1[\varphi_{TX1}, \varphi_{TX2}, \varphi_{RX1}] = \frac{pRX_{1,1}[\varphi_{TX1}, \varphi_{RX1}]}{pRX_{2,1}[\varphi_{TX2}, \varphi_{RX1}] + P_{AWGN}} \tag{7}$$

$$SINR_2[\varphi_{TX1}, \varphi_{TX2}, \varphi_{RX2}] = \frac{pRX_{1,2}[\varphi_{TX1}, \varphi_{RX2}]}{pRX_{2,2}[\varphi_{TX2}, \varphi_{RX2}] + P_{AWGN}} \tag{8}$$

Where $\varphi_{TX1}, \varphi_{TX2}, \varphi_{RX1}, \varphi_{RX2}$ are the phased array beam indices for TX_1, TX_2, RX_1, RX_2, respectively, incident powers are in absolute linear units, and the noise power P_{AWGN} is pre-calibrated for each RX gain index using the relationship:

$$P_{AWGN} = pRX - SNR_{STF} \tag{9}$$

SNR_{STF} is the SNR estimated within the chip using the short training field in the preamble of the 802.11ad PHY frame header. SNR_{STF} saturates around 20 dB, requiring calibration of P_{AWGN} through curve fitting in the linear region.

In addition to aiding in the calculation of SINR, the calibrated P_{AWGN} value is used by the sounder to report the effective linearized SNR metric, labelled raw SNR, that is resistant to saturation effects and other impairments present in the chip-reported SNR.

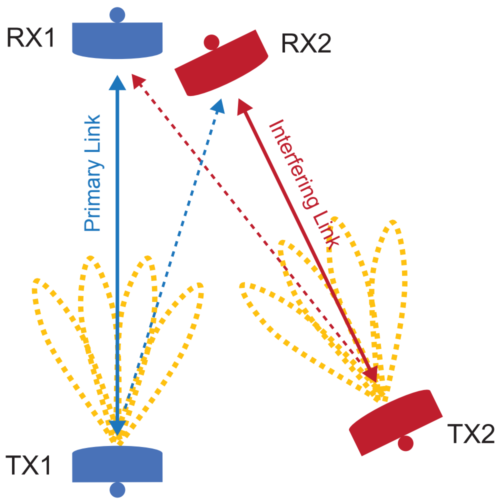

Fig. 3. Spatial profile demonstrating electrical scanning of propagation enginvironment to measure calibrated path loss for both LOS and reflected NLOS paths.

Additionally, spectral efficiency (in bps/Hz) of each link is calculated and reported for each link and combination of beams with the following relationship:

$$SE_1 = \log_2(1 + SINR_1) \quad (10)$$

$$SE_2 = \log_2(1 + SINR_2) \quad (11)$$

The results are displayed in the form of a heatmap, capturing the path loss, link power, cross-link powers, in addition to other uncalibrated metrics for all TX and RX phased array pointing angles for the 4 link path combinations, as shown in Fig. 4. SINR and raw SNR are also shown in the form of a heatmap as a function of the TX_1 and RX_1 pointing angles of the primary link. SINR_1 is dependent on the TX_2 pointing angle of the interferer, and can also be analytically re-estimated for different combinations of TX_1 and TX_2 gains. The tool gives researchers a way to visualize the effect of interference under each of these possible link conditions, as shown in Fig. 5.

C. *TG-Link: High-Frequency Live Link Characterization*

A user-friendly toolkit has been developed to associate nodes and establish a full operational link to collect link quality metrics such as throughput, latency, PER, and PHY statistics such as SNR and LDPC iterations. These metrics are captured at high frequency to study network behavior in dynamic environments. This tool also allows logging of RF parameters such as absolute and spatial profile of path loss. It can be used to optimize performance of MAC protocol algorithms, such as rate adaptation and transmit power control. These tools allow researchers to easily analyze network architecture and study complex deployment scenarios with a fully operational link and/or network.

The high-frequency link capture mode, called TG Link, enables acquisition of both calibrated and uncalibrated metrics at a sampling period of 400 μs (fs = 2.5 kS/s). It expands channel sounder capabilities beyond physical layer metric acquisition in order to validate 802.11ad links from a network

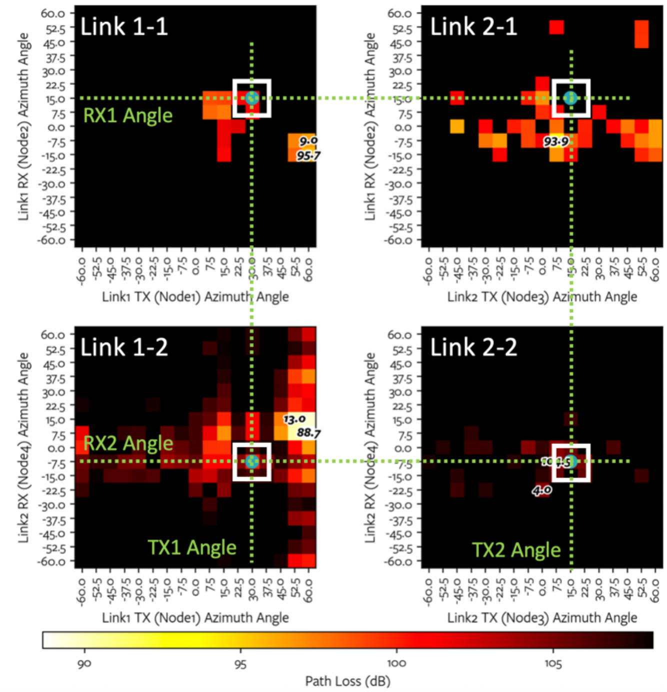

Fig. 4. Propagation metrics shown as a heatmap for each of the 4 link combinations, as a function of the relevant TX and RX beam angles.

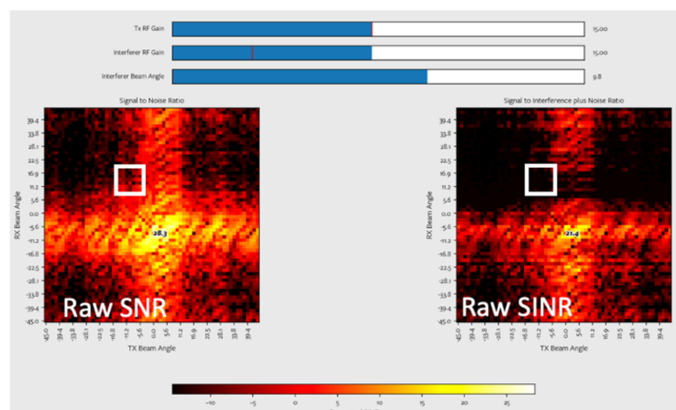

Fig. 5. Screen capture from sounder tool showing Raw SNR heatmap and Raw SINR heatmap as a combination of wanted link TX and RX beam angles.

and MAC protocol perspective. TG Link was developed in order to provide a user-friendly tool to associate nodes and establish an over the air 60GHz link and collect link quality metrics such as throughput, latency, and PHY statistics such as preamble and post-EQ SNR, LDPC iterations, etc. The goal is to create a high-level tool with a minimal but flexible interface. The tool will also allow for configuring/overriding certain link level algorithms, such as rate adaptation, and transmit power control.

The combination of these capabilities add a greater dimension of metrics to improve link assessment and interpretation for static deployments, and provide a tool for high frequency link analysis in dynamic channels and mobility scenarios.

The following protocol features can be selectively enabled or disabled for each test scenario:

- **Transmit power control** (TPC) – allowing user to configure a fixed output power, or allow TPC to dynamically regulate power to maximize SNR.
- **Link Adaptation –** can be left active to dynamically converge to a Modulation and Coding Scheme (MCS) based on channel conditions, or can be overridden to force a fixed MCS.

Traffic generation on the link is implemented with iPerf, and can be customized to pass unidirectional or bidirectional UDP or TCP traffic with any rate. As TG Link runs traffic through a live link with full protocol features active, additional metrics beyond what would normally be available in channel sounder systems. These network-layer and protocol-specific metrics can be correlated at a high frequency with one another, along with existing calibrated propagation metrics available in other sounder modes. Additional metrics include throughput, latency, packet jitter, Packet Error Rate (PER), and LDPC-related statistics (total number of syndromes and LDPC blocks).

III. Ongoing Studies and Results

The use of the channel sounder tool and platform has been employed by 13 research teams from academia, industry, and government labs. These teams have undertaken research studies utilizing the channel sounder tool for characterizing the 60 GHz channel and IEEE 802.11ad/ay protocols across scenarios and focus areas such as outdoor propagation, indoor propagation, beam design, interference, and mobility. A summary of active work through the channel sounder program is outlined in the sections below.

A. Outdoor Propagation

Facebook Connectivity undertook a study evaluating the propagation characteristics of the two preeminent millimeter wave bands centered at 28 GHz (5GNR FR2) and 60 GHz (IEEE 802.11ad/ay) [1]. A series of channel sounding measurements were performed in the two bands side-by-side to compare the reflection, transmission, and diffraction losses of materials typical of urban deployment environments, including wood, foliage, glass, drywall, multiple types of window glass, street utility posts, and concrete walls. The scattering properties found in this comparative study were within range of those reported elsewhere in literature, for both frequency bands. The studies did not conclusively find any advantage in propagation for the 28 GHz band relative to the 60 GHz band, that would be a decisive factor when deploying relatively short links in urban environments.

Siradel and Deutsche Telekom (DT), two research partners in industry co-developing propagation modelling tools, completed an outdoor measurement campaign at DT's Berlin headquarters [2, 4, 5]. The research team used the channel sounder platform and measurement results to validate a 60 GHz raytracing propagation simulation model in residential and urban canyon environments. The results showed close agreement with simulation, within 2db path loss in urban canyon case (which had complex building reflections on each side), and within 10dB of obstructed street furniture and foliage cases, where precise alignment with raytracing model was difficult to guarantee and results are highly sensitive to slight variations in position. The TG channel sounder proved to be a useful tool for validating the raytracing model.

The Athens Information Technology's Smart Wireless Future Technologies (SWIFT) Lab completed both indoor and outdoor propagation studies in an urban office environment [2, 9]. The materials consisted of granite pavement (dry, smooth level), glass windows, glass doors, marble columns and walls and metallic poles. Additionally, the environments characterized included a large water fountain, light pedestrian traffic below the scanning level, and included measurements in a cloudy, highly humid, and drizzled environment. Propagation in these environments was analyzed through the captured path loss values, delay spread, and channel impulse response (CIR).

A team at Blu Wireless, a Bristol, UK-based company developing mmWave equipment and solutions, used the TG sounder to investigate mmWave link variation over time in urban, smart city deployments providing wireless backhaul [2]. The deployment test focused on using existing street fixtures - specifically lampposts. Also taking into account weather conditions over time, the observed performance variations permitted a correlation between topology, weather and rainfall conditions in the tested scenarios.

The Fraunhofer Institute for Telecommunications, Heinrich Hertz Institute (HHI) undertook an outdoor propagation characterization in an urban environment [2]. The environment featured buildings of varying heights along with scattered trees and bushes. The sounder was validated by measuring clear LOS path loss at distinct distances, and at intermediate transition stages from LOS to NLOS.

The Communication Technology Lab at NIST evaluated the Terragraph sounder in both indoor and outdoor environments [2]. To understand system functionality and performance, NIST designed several testing scenarios to compare theoretical and experimental results. Specifically, they measured path loss in free space, loss through common dielectric materials (window glass, and brick), and loss through more complex urban obstructors (cars and foliage). Their measurements validated free space path loss within 2 dB of theoretical values. The object dielectric constants reported by NIST closely agree with ITU-reported values (measured in a lab environment).

Prof. Koksal and his research team at Ohio State University (OSU) used the channel sounder platform to characterize propagation in both indoor and outdoor environments [2]. They characterized long-distance LOS path loss in an outdoor football field, to minimize obstructions and reflections, and found close agreement with theory. Additionally, a set of measurements were completed to estimate the impact of blockage due to passing pedestrians and vehicles. OSU also ran several outdoor experiments in collaboration with the South Central Agricultural Laboratory (SCAL) agricultural fields of the University of Nebraska-Lincoln, aiming to evaluate propagation characteristics in a rural area., including the impact of passing tractors, people, and stationary blockers such as metal silos.

B. Indoor Propagation

Beelde, *et al.* at the research group with imec at Ghent University utilized the channel sounder platform for static characterization of the 60ghz channel in the engine rooms and steering control rooms of bulk shipping vessels [3]. Their experimental work demonstrated improved data rate relative to free space path loss in line-of-sight scenarios, due to constructive interference effects. Furthermore, they demonstrated high data rates in obstructed communication links, benefiting from the highly reflective ship interior to close links through secondary scattering effects. While their research did not find a clear relationship due to the naturally complex nature of the multipath reflective channel, it provides a statistical understanding of propagation in complex indoor environments.

A research group at Technische Universität Berlin (TUB) validated 60 GHz wireless propagation in indoor office environments [2]. They analyzed penetration losses through materials common in office settings as a function of thickness. They also studied the effects of beamwidth in multipath environments on SNR and packet error rate (PER), and demonstrated that the channel impulse response can be effectively used to accurately characterize reflected paths in a reverberant environment.

C. Mobility Scenarios

The studies conducted by the Wireless Internet of Things at Northeastern University targeted several aspects of mmWave UAV-based communication, using the TG Sounder to analyze beam alignment in different mobility scenarios [2, 6, 7, 8]. Their research looks at developing a beam management solution for air-to-ground and air-to-air UAV communication, assisted by integrating sensor localization data. Overall, their studies showed a 66% reduction in link establishment overhead with minimal link loss, as compared to the state of the art blind beam management scheme. The channel sounder platform was further utilized for analyzing the impact of beam misalignment, link quality variability due to hovering, and overall link budget implications for the UAV deployment case.

These and similar mobility studies could be further improved by taking advantage of the high-frequency acquisition features in the sounder, which can provide a high temporal resolution profile of performance variability in both mobility and dynamic blockage scenarios.

D. Interference

Researchers at the Berkeley Wireless Research Center (BWRC) primarily focused on studies to understand the impact of interference on mmWave mesh network capacity [2]. Channel sounder accuracy was extended by developing a post-processing method to extract calibrated SNR, which was used as primary performance indicator. They studied interference in an open outdoor environment with minimized presence of reflectors, and observed interesting and unexpected phenomena in their measurements, demonstrating conditions where active link performance was improved in some cases with an interferer present. Ongoing interference studies at BWRC are focusing on urban outdoor environments rich in reflectors and scatters.

The Cognitive Reconfigurable Embedded Systems Lab at the University of California, Los Angeles (UCLA) developed a neural network assisted beam alignment algorithm that uses noncoherent received signal strength measured by a small number of sounding beams to infer the optimal beam steering direction [10]. Their algorithm was demonstrated using the TG channel sounder's beam design capability and showed an order of magnitude overhead savings with marginal post-alignment beamforming gain loss, as compared to an exhaustive beam sweep. Ongoing studies utilize the channel sounder platform to assess the algorithm for prediction of multiple steering directions in multi-path environments, and to complete a comparative study of different sounding codebooks in a joint design with the beam alignment algorithm.

IV. Closing Comments

The TG channel sounder tool has been developed and improved beyond its original capabilities as a physical channel measurement tool. Researchers from over 13 institutions have found creative ways to employ the TG sounder in their own research, and have contributed significant findings to further the understanding of propagation in 60 GHz, and mmWave generally. New TG Sounder tool developments further extend the potential usage scenarios for the tool, enabling collaborators to conduct a wide variety of studies with deployment-grade equipment, with results and characterizations that are directly applicable to commercial mmWave deployments.

References

[1] Telecom Infra Project, "Analysis of 28GHz and 60GHz Channel Measurements in an Indoor Environment," Telecom Infra Project, White Paper, 2019. [Online]. https://telecominfraproject.com/mmwave/

[2] Telecom Infra Project, " TIP Channel Sounder Program Results Summary Report", Telecom Infra Project, White Paper, 2019. [Online]. Available: https://telecominfraproject.com/mmwave/

[3] De Beelde, Brecht, et al. "60 GHz Path Loss Modelling Inside Ships." 2020 14th European Conference on Antennas and Propagation (EuCAP). IEEE, 2020.

[4] Aslam, Mohammed Zahid, et al. "Analysis of 60-GHz In-street Backhaul Channel Measurements and LiDAR Ray-based Simulations." 2020 14th European Conference on Antennas and Propagation (EuCAP). IEEE, 2020.

[5] Aslam, Mohammed Zahid, and Yoann Corre. "Simulated Propagation Properties for Future Outdoor sub-THz Networks." 2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications. IEEE.

[6] Bertizzolo, Lorenzo, et al. "mmBAC: Location-aided mmWave backhaul management for UAV-based aerial cells." Proceedings of the 3rd ACM Workshop on Millimeter-wave Networks and Sensing Systems. 2019.

[7] Sanchez, Sara Garcia, et al. "Millimeter-wave Base Stations in the Sky: An Experimental Study of UAV-to-Ground Communications." IEEE Transactions on Mobile Computing (2020).

[8] Polese, Michele, et al. "An Experimental mmWave Channel Model for UAV-to-UAV Communications." Proceedings of the 4th ACM Workshop on Millimeter-Wave Networks and Sensing Systems. 2020.

[9] Tariq, Muhammad Haroon, et al. "mmWave Massive MIMO Channel Measurements for Fixed Wireless and Smart City Applications." 2020 IEEE 31st Annual International Symposium on Personal, Indoor and Mobile Radio Communications. IEEE.

[10] Yan, Han, Benjamin W. Domae, and Danijela Cabric. "mmRAPID: Machine Learning assisted Noncoherent Compressive Millimeter-Wave Beam Alignment." Proceedings of the 4th ACM Workshop on Millimeter-Wave Networks and Sensing Systems (2020).