

Empirical Study of Sensor-Aided Beam Management for 5G-and-Beyond Systems

Berk Açıkgoz

Master's Thesis

November 12, 2025

Examiners

Prof. Dr.-Ing. Marina Petrova
Dr. Ljiljana Simić

Supervisors

Prof. Dr.-Ing. Marina Petrova
Dr. Ljiljana Simić
Aron Schott, M.Sc.

Mobile Communications and Computing
RWTH Aachen University



communicated by Prof. Dr.-Ing. Marina Petrova

The present work was submitted to Mobile Communications and Computing

Empirical Study of Sensor-Aided Beam Management for 5G-and-Beyond Systems

Master's Thesis

presented by
Berk Açıkgoz

Prof. Dr.-Ing. Marina Petrova
Dr. Ljiljana Simić

Aachen, November 12, 2025

(Berk Açıkgoz)

Acknowledgements

I would like to start by expressing my gratitude to Prof. Dr.-Ing. Marina Petrova and Dr. Ljiljana Simić for placing their trust in me throughout my time at iNETS/MCC, culminating in this master's thesis. This experience has been invaluable for my academic development, and I am truly thankful for it. I especially appreciate my supervisor, Aron Schott, M.Sc., for guiding me through the thesis, providing direction, patiently answering my every question, and taking the time out for fruitful and enlightening discussions. Furthermore, I would like to thank Dr.-Ing. Aleksandar Ichkov for his tutelage on the subject during my early days at iNETS and role in conceptualizing the thesis topic. I would also like to thank Xianglong Wang, M.Sc. for his assistance with the measurements. I appreciate the entire iNETS/MCC team for their camaraderie and the welcoming environment they create, which facilitates a good learning and working experience, and wish every one of them the best in their professional and personal future. Last but not the least, I would like to thank my family and friends for everything they have done for me up to this point. It would not have been possible without them.

Contents

Acknowledgements	II
Contents	III
Abstract	V
1 Introduction	1
2 Background	3
2.1 5G-NR and Beyond-5G	3
2.2 Propagation Characteristics at mm-Wave Frequencies	4
2.2.1 Free-Space Path Loss	4
2.2.2 Atmospheric Losses	5
2.2.3 Non-Line-of-Sight Propagation	5
2.2.4 Shadow Fading and Blockages	7
2.3 Directional Communication & Beamforming	8
2.3.1 Phased Antenna Arrays	8
2.3.2 Beamforming Architectures	9
2.4 RF-based Beam Management at mm-Wave Frequencies	10
2.5 Sensor-Aided Beam Management for 5G-and-Beyond	11
2.6 Related Work	14
3 Design and Implementation of Two Testbeds	17
3.1 Overview	17
3.2 Hardware Components	18
3.2.1 USRP X410 Software Defined Radio	18
3.2.2 EVK02001 Antenna Array Transceiver	18
3.2.3 OS-1 LiDAR Sensor	20
3.2.4 ZED 2i Stereo Camera	20
3.2.5 Raspberry Pi 4 Model B, SparkFun GNSS Receiver Breakout - MAX-M10S and u-blox ANN-MB5 GNSS Antenna	21
3.2.6 Host PCs	21
3.2.7 Hunter 2.0 Robot	22
3.3 Software Components	22
3.3.1 UHD	22

Contents	IV
3.3.2 ROS 2	22
3.3.3 OpenAirInterface	23
3.3.4 GNU Radio	24
3.4 Implementation of Testbed 1: OAI-based 5G-Compliant Testbed with Environmental Awareness	24
3.4.1 SPI/GPIO Control for EVK02001	25
3.4.2 Beam Management for 5G-NR	27
3.4.3 Sensor Integration with OAI	28
3.5 Implementation of Testbed 2: Fast-Sweeping Measurement Platform with Multiple Sensor Modalities	29
3.5.1 Implementation of Fast Beam Sweeps	30
3.5.2 Multi-Antenna Support over SPI	32
3.5.3 Time Synchronization Between Transmitter (TX) and Receiver (RX) Host PCs	33
3.5.4 Sensor Modalities	36
4 Measurement Setup	38
4.1 Testbed 1: OAI-based 5G-Compliant Testbed with Environmental Awareness	38
4.2 Testbed 2: Fast-Sweeping Measurement Platform with Multiple Sensor Modalities	39
5 Measurement Results and Analysis	43
5.1 Demonstration of Sensor-Aided Beam Management in OpenAirInterface (OAI)	43
5.2 Sensor-Aided Propagation Analysis for Static Positions	45
6 Conclusion and Future Work	58
A Beam ID to Azimuth Angle for EVK02001	60
B Including the Standalone UHD Library and Enforcing the Correct UHD Version for a GNU Radio Out-of-Tree Module	61
C Radiation Patterns for EVK02001 Antenna Array	62
D Correspondence Between RX Channel ID, RX Beam ID and RX Direction	66
E Abbreviations	69
List of Tables	73
List of Figures	74
Bibliography	76
Declaration	89

Abstract

Millimeter-wave (mm-wave) frequencies are crucial for addressing the growing demand for capacity in fifth generation (5G) mobile networks and beyond. However, they are impacted by unique challenges such as high path loss and susceptibility to blockages. To overcome these challenges, directional communication is implemented with phased antenna arrays. Directional communication requires operations collectively known as beam management, which traditionally incur high overhead and delays. Environmental awareness via sensors has emerged as a candidate to decrease the overhead and delay associated with beam management.

In this thesis, two mm-wave testbeds that integrate multiple sensor modalities for the design of novel sensor-aided beam management schemes have been implemented. The first testbed is based on the OpenAirInterface 5G project and enables the development and evaluation of novel sensor-aided beam management protocols in full-stack end-to-end 5G networks. The second testbed serves as a measurement platform to gather multi-modal sensor and mm-wave radio frequency data, facilitating the creation of datasets for the development and evaluation of sensor- and machine learning-aided beam management protocols.

This thesis provides the details of the implementation of both testbeds, demonstrates their capabilities in example scenarios and measurement campaigns, and discusses the findings from these. The usage of sensors is shown to be highly beneficial for beam management and the analysis of the site-specific propagation characteristics of mm-waves. These testbeds enable the creation of datasets to be used for the development of machine learning/deep learning algorithms for sensor-aided beam management.

Keywords: Millimeter-wave, OpenAirInterface, environmental awareness, beam management, sensors

Introduction

Mobile communication technologies go through substantial transformations every ten years in order to keep up with the changing requirements and growing capacity demands, recently brought forth primarily by video streaming [1]. The monthly mobile network data traffic was reported as 172 EB¹ for the first quarter of 2025, indicating a 900% increase in seven years, and is expected to grow to 430 EB by 2030 [2]. Sub-6 GHz frequencies, already used in a variety of radio access technologies (RAT), are becoming increasingly congested in correlation with the growth in mobile network data traffic, thus being unable to answer the growing demand for capacity. In order to answer this demand, the millimeter-wave (mm-wave) frequencies between 24.25 and 71 GHz have been standardized for use in 5G New Radio (5G-NR), the newest standard for mobile radio access [3]. However, communication at mm-wave frequencies is impacted by remarkable challenges, such as high free-space path loss (FSPL), susceptibility to blockages, and a strong dependency on its surroundings [4]. In order to alleviate these challenges, directional communication via phased array antennas is deployed to seize the optimal link opportunities. However, establishing and maintaining the optimal beam alignment in dynamic environments under user mobility is an open challenge, with various approaches being considered by the research community [5]. Leveraging environmental awareness via sensors such as global navigation satellite systems (GNSSs), light detection and ranging (LiDAR), and cameras has been receiving considerable attention from the research community [6–8]. The information obtained from these sensors can be leveraged to acquire a better understanding of the propagation environment, then infer viable link opportunities based on available propagation paths and blockages.

This thesis aims to empirically demonstrate the performance of sensor-aided beam management techniques for mm-wave communications in 5G-and-Beyond systems. Two testbeds have been developed for this purpose: (1) a testbed that is based on the OpenAirInterface (OAI) 5G project [9] and integrates sensor modalities in a full-stack end-to-end 5G-NR communication, and (2) a testbed that integrates sensor modalities into a mm-wave measurement platform. Thus, the platform in (1) can be used to evaluate the real-world performance of novel sensor-aided beam management protocols in standard-compliant deployments, and (2) enables the gathering of datasets that combine multi-modal sensor and mm-wave radio frequency (RF) data towards the design and training of machine learning (ML)-based environment-aware beam management approaches. The capabilities of these testbeds have been demonstrated in multiple sessions, the most extensive of these being an outdoor measurement campaign in the medium-sized German city of Aachen. The results demonstrate how sensor input can be leveraged to maintain link stability in the presence of mobile obstacles that may block the

¹One exabyte (EB) is one billion gigabytes (GB).

communication link. Furthermore, the findings from the measurement campaign illustrate the strong dependence of communication at mm-wave frequencies on line-of-sight (LoS) or strong non-line-of-sight (NLoS) propagation paths and the susceptibility to blockage in highly urbanized environments.

The thesis is structured as follows: Chapter 2 provides a theoretical and conceptual background in mm-wave communications, beamforming, and sensor-aided beam management. The body of work related to this thesis is discussed, and gaps in the literature are assessed. The details regarding the design and implementation of the testbeds are explained in Chapter 3. Chapter 4 describes the testbed configurations and the conditions of the measurement sessions, including the demonstration of the indoor full-stack environment-aware 5G-compliant network deployment and the outdoor measurement campaign. The results obtained from the measurement sessions are evaluated and discussed in Chapter 5. Finally, Chapter 6 concludes the thesis by highlighting key findings and providing direction for future research efforts in this area.

2

Background

In this chapter, a brief overview of technologies and concepts that are crucial for the understanding of this thesis is given. In Section 2.1, 5G-NR and the outlook on Beyond-5G technologies are introduced. In Section 2.2, the propagation characteristics at mm-wave frequencies, and the associated benefits and challenges are addressed. In Section 2.3, the concept of directional communication, which is required for mm-wave networks, is introduced, and the associated beamforming architectures are outlined. In Section 2.4, traditional RF-based beam management methods at mm-wave frequencies are discussed. In Section 2.5, the idea of using non-RF sensors to develop beam management is introduced. Finally, the body of related work concerning sensor-aided beam management at mm-wave frequencies is discussed in Section 2.6.

2.1 5G-NR and Beyond-5G

5G-NR is the standardized radio access technology for the fifth generation (5G) of mobile cellular networks. It was developed to address shortcomings of its predecessors in the face of swiftly changing internet usage habits that result in the growth in the overall data volume. However, it was not solely envisioned for mobile broadband for everyday users but rather for a variety of use cases under three main categories:

- **Enhanced mobile broadband (eMBB):** Enhancement of mobile broadband services in terms of data rate, traffic capacity, user mobility, and user density for a more seamless user experience within various deployment and coverage scenarios [1, 3, 10].
- **Ultra-reliable and low-latency communications (URLLC):** Applications that require highly reliable, low-latency, and highly available communication networks, such as tactile internet applications, remote medical surgery, vehicle-to-everything (V2X), transportation safety, and wireless control of industrial manufacturing. [1, 3, 10]
- **Massive machine type communications (mMTC)**¹: Applications that combine a large number of Internet of Things (IoT) devices that intermittently produce small amounts of traffic at low data rates, requiring high reliability, with the constraint that the devices must have very long battery lives. [1, 10]

5G-NR started utilizing previously unused bands among the sub-6 GHz frequencies, most prominently the frequencies between 3.4 and 3.8 GHz [11]. The sub-6 GHz frequencies are designated as Frequency Range 1 (FR1) by 3rd Generation Partnership Project (3GPP) for 5G-NR, span from 410 MHz to 7.125 GHz, and support downlink bandwidths of up to

¹Named massive Internet of Things (mIoT) in 3rd Generation Partnership Project (3GPP) Release 15 [3].

100 MHz [12]. However, to be able to answer the aforementioned demands regarding the growing data volume, more bandwidth is needed, which is available at mm-wave frequencies, i.e. frequencies between 24 and 300 GHz². The lower range of mm-wave frequencies is designated as Frequency Range 2 (FR2) by the 3GPP for 5G-NR, spanning from 24.25 GHz to 71 GHz and supporting downlink bandwidths of up to 400 MHz or optionally 2 GHz [14]. In recent years, interest in Frequency Range 3 (FR3), spanning from 7.125 GHz to 24.25 GHz, has been growing within academia [15–17] and industry [18], with portions of it being considered as candidate frequencies for sixth generation (6G) mobile cellular networks [19].

Although mm-wave frequencies have been designated for use in 5G-NR networks, there are very few providers globally that offer a 5G mobile broadband service at mm-wave frequencies. Initial deployments of Verizon's 5G-NR mm-wave network in the United States were marred by underwhelming throughput and stability issues, despite showing improvements over the long-term evolution (LTE) infrastructure [20]. The 60 GHz band has been designated for use in WiGig[®] [21] by the Institute of Electrical and Electronics Engineers (IEEE) in the standard IEEE 802.11ad [22] and its follow-up, IEEE 802.11ay [23]. Other use cases like last-mile/fixed wireless access (FWA) [24], small-cell backhaul [24,25], and V2X [26,27] have also been envisioned for 5G mm-wave networks. FWA as a technology in general has been experiencing growth in recent years, and 5G FWA is projected to account for more than a third of new fixed broadband connections by 2030 [2].

2.2 Propagation Characteristics at mm-Wave Frequencies

mm-wave frequencies have the advantage of having large unused sections that allow for wide carrier bandwidths (up to 1 GHz) that enable data rates of 1 Gbps and more for lower spectral efficiency, which in turn simplifies the implementation and decreases the effects of hardware impairments on network performance [28]. However, the characteristics of propagation at mm-wave frequencies differ significantly from those at sub-6 GHz frequencies, which are used more commonly in cellular communication. This section provides an overview of the propagation characteristics of mm-waves and the associated potential and challenges.

2.2.1 Free-Space Path Loss

The relationship between transmitted and received power of an electromagnetic wave in free space, under line-of-sight conditions and perfect antenna alignment [29], is given by Friis' equation [30,31]:

$$P_r(d) = P_t \frac{G_t G_r \lambda^2}{(4\pi d)^2 L} \quad (2.1)$$

where P_t is the transmitted power, $P_r(d)$ is the received power for distance d between transmitter and receiver in meters, G_t is the transmitter antenna gain (unitless), G_r is the receiver antenna gain (unitless), λ is the wavelength in meters, and L is the system loss

²mm-wave frequencies are generally regarded to fall between 30 and 300 GHz, corresponding to wavelengths of 10 to 1 mm, as the name suggests. Since the propagation characteristics of the frequencies between 24 and 30 GHz are similar to those between 30 and 300 GHz [13], the term "mm-wave" will refer to frequencies between 24 and 300 GHz for the rest of this thesis, fully encompassing Frequency Range 2 (FR2).

factor due to hardware artifacts, not related to propagation ($L \geq 1$). The wavelength is related to the frequency and speed of light as follows:

$$\lambda = \frac{c}{f} \quad (2.2)$$

where λ is the wavelength in meters, f is the frequency in Hertz, and c is the speed of light in meters/second. The antenna gain is related to the directivity of the antenna (2.3) and the antenna aperture, the fixed effective antenna area (2.4), as follows [29]:

$$G = e_r D \quad (2.3)$$

$$= \frac{4\pi}{\lambda^2} A_e \quad (2.4)$$

where e_r is the radiation efficiency, D is the directivity, A_e is the (effective) antenna aperture, and λ is the wavelength. When the antennas are assumed to have unity gain³ and the hardware losses are excluded, the FSPL is given by the following formula [31]:

$$FSPL = \left(\frac{4\pi d}{\lambda} \right)^2 = \left(\frac{4\pi d f}{c} \right)^2 \quad (2.5)$$

The formula indicates that FSPL increases with the frequency, hence the higher FSPL at mm-wave compared to sub-6 GHz frequencies⁴.

2.2.2 Atmospheric Losses

Atmospheric attenuation is another phenomenon that affects the propagation characteristics at mm-wave frequencies. Water (H_2O) and oxygen (O_2) molecules cause the most attenuation through absorption [34]. Figure 2.1 shows the attenuation level over distance (dB/km) versus frequency (GHz) for water and oxygen molecules and rain. For FR2, an attenuation of 0.18 dB/km is observed at 23 GHz due to water molecules, while an attenuation of 15 dB/km is observed at 60 GHz due to oxygen molecules, which is also referred to as the 60 GHz oxygen absorption band [28]. Communication at mm-wave frequencies is also affected more severely by rainfall, as rain droplets, which typically have dimensions of a few millimeters, are of comparable size with mm-waves, increasing the likelihood of blockages from rainfall compared to sub-6 GHz frequencies [34].

2.2.3 Non-Line-of-Sight Propagation

In urban deployments of mobile cellular networks, there is generally no clear LoS path between the transmitter and receiver, which noticeably impacts the performance of the communication link [31]. In this subsection, three NLoS propagation mechanisms are introduced, and their effects on mm-waves are described.

mm-waves typically experience **reflection** upon striking an object with dimensions much larger than their wavelength, 1-10 mm. This applies to a variety of objects and structures, such as furniture, walls, and buildings. The mm-wave could also partly get *refracted*, i.e. pass through the struck object at an altered angle, depending on a variety of parameters

³Isotropic, radiating with the same power density in all directions, i.e. unity directivity [29]

⁴Under the aforementioned assumptions.

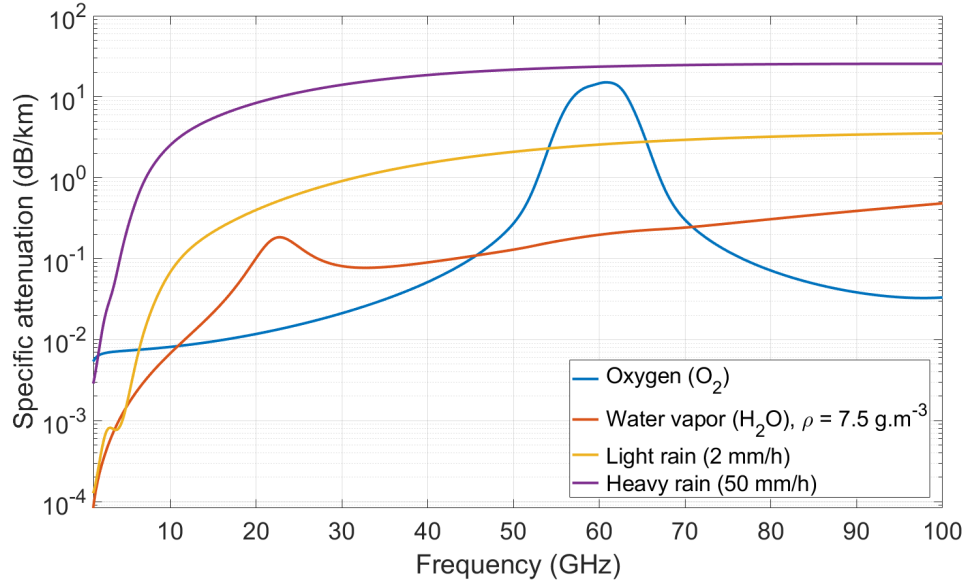


Figure 2.1: Specific attenuation curves of O_2 , H_2O and rain at sea level, drawn with [32,33].

Table 2.1: Reflection losses in dB for various materials at 9.6, 28.8, and 57.6 GHz [36].

Surface	9.6 GHz	28.8 GHz	57.6 GHz
Metal	< 6	< 8	< 9
Brick (solid)	2 - 6	7 - 14	7 - 8
Concrete (ribbed)	5 - 6	7 - 11	18 - 19
Brick (windows, doorway)	9 - 12	14 - 15	15 - 18
Concrete aggregate	6 - 12	10 - 12	17 - 20

such as the electrical properties of the struck object, the frequency and polarization of the wave, and the angle of incidence [31,35]. The ability of mm-waves to pass through objects is characterized by their *penetration losses*, which are measured as the difference in power between the unobstructed and obstructed paths.

Several studies (e.g. [36–38]) have been carried out to characterize reflection and penetration losses at mm-wave frequencies. The authors in [36] have demonstrated a trend of reflection losses increasing with frequency, as seen in Table 2.1. Metal is shown to be a good reflector, with reflection losses up to 8 dB at 28.8 GHz, whereas rougher materials such as brick and concrete incur higher reflection losses. The authors in [38] analyzed the reflection and penetration behavior at 28 GHz for various building materials found indoors and outdoors. Table 2.2 shows the reflection coefficients, the ratio indicating the portion of the wave that got reflected, and penetration losses for different building materials obtained in [38]. It is observed that a smaller portion of the signal gets reflected as the incident angle increases. The penetration loss for tinted glass, often found in urban environments, was found to reach 40 dB, making indoor-to-outdoor and outdoor-to-indoor penetration infeasible.

Table 2.2: Reflection coefficients for incident angles of 10° and 45° , and penetration losses at indicated thicknesses for different building materials at 28 GHz [38].

Environment	Material	Reflection Coefficient at 10°	Reflection Coefficient at 45°	Thickness (cm)	Penetration Loss (dB)
Outdoor	Tinted glass	0.896	-	3.8	40.1
	Brick	-	-	185.4	28.3
	Concrete	0.815	0.623	-	-
Indoor	Clear glass	0.740	-	<1.3	3.6 - 3.9
	Tinted glass	-	-	<1.3	24.5
	Drywall	0.704	0.628	38.1	6.8

mm-waves experience **diffraction** when there are obstacles with sharp edges on the propagation path, resulting in the mm-wave bending around the obstacle [31]. Diffraction is dependent on carrier frequency and therefore more prominent at sub-6 GHz frequencies compared to mm-wave frequencies [39]. The authors in [40], who measured diffraction patterns at 28 GHz in an urban environment and presented a diffraction model, identified a small dependence on building material and negligible dependence on polarization for diffraction loss. Reflection is found to generally dominate diffraction at mm-wave frequencies [35, 41, 42].

mm-waves experience **scattering** upon contact with objects in the propagation environment that are smaller in size compared to their wavelength or exhibit other irregularities such as rough surfaces, causing the reflected energy to spread out in different directions [31]. As scattering depends on the size of objects and irregularities in relation to the wavelength, its effects are more pronounced at mm-wave frequencies compared to sub-6 GHz frequencies. The authors in [43] measured scattering from limestone and brick walls at 28 GHz and found that the effects of scattering are more pronounced for the rough limestone walls compared to the smoother brick walls.

2.2.4 Shadow Fading and Blockages

Obstacles in the propagation environment may cause **shadowing**/shadow fading, which is the phenomenon of electromagnetic waves getting attenuated while going through or around obstacles [44]. This may result in the **blockage** of LoS or NLoS components. The authors in [45] distinguish between three types of shadow fading, and claim that the effects of shadowing are more pronounced at mm-wave frequencies compared to sub-6 GHz frequencies:

- **Environmental shadowing**, which occurs due to user equipment (UE) mobility and manifests itself as fluctuations in power as the UE moves in and out of regions that are covered by the base station (BS).

- **Shadowing induced by obstacles**, which manifests itself as an attenuation in power upon the blockage of a LoS or NLoS component.
- **Self-shadowing** induced by the person holding the UE, which is dependent on the rotation of the UE and the position and type of hold, such as holding the UE to the ear during a call or in front of the torso looking at the screen.

mm-waves have been shown to get blocked by metal-coated or tinted glass and brick pillars, which hinders outdoor-to-indoor penetration [36–38]. Vegetation/foilage losses, due to tree leaves, branches, and trunks, are an important impairment in mm-wave propagation. Conversely, foliage can also act as a reflector to establish NLoS paths [35].

Studies [46, 47] have shown that hand blockages can cause up to 20 dB blockage loss depending on antenna positions and the tightness of the grip. Another study that measured human blockages at 15, 28, and 60 GHz [48] has shown that the blockage loss ranges from 10 to 25 dB, depending on the body orientation and transmitter height.

2.3 Directional Communication & Beamforming

Cellular mobile networks that use sub-6 GHz carrier frequencies transmit either in an omnidirectional manner, i.e. dissipating equal power in all directions, or within wide sectors. While this is a feasible solution for sub-6 GHz frequencies, the propagation characteristics of mm-waves, such as high path loss and susceptibility to blockages, render this approach unfeasible for communication at mm-wave frequencies, especially over larger distances. These challenges can be alleviated by decreasing the cell size to mitigate path losses [34] and deploying directional communication via phased antenna arrays that perform beamforming. The authors in [49] found that directional transmission or reception with phased antenna arrays can increase the received power by 15 to 29 dB at mm-wave frequencies.

2.3.1 Phased Antenna Arrays

A phased antenna array is a system comprised of multiple antenna elements. It is used to focus energy in one direction by forming a specific radiation pattern, often referred to as a *beam*. The utilization of multiple antenna elements increases the overall gain and, equivalently, directivity (*cf.* Section 2.2). As indicated in Equation 2.4, the antenna elements are smaller for mm-waves, which enables such antenna arrays. In turn, antenna arrays enable communication at higher frequencies, and are crucial in FR2 and high FR3. The width of beams, which indicates the directivity of communication, is in inverse proportion to the number of antenna elements. Antenna elements are placed in intervals of $\lambda/2$ to avoid fading and aliasing [50].

The formation of beams, referred to as *beamforming*, is achieved by electronically adjusting the phases of antenna elements. While it is possible to select any phase shift for any antenna element, *codebooks*, structures that hold the phase shifts for each antenna element, are often used. In contrast to mechanically steering an aperture antenna, which used to be the traditional method of scanning directionally, phased antenna arrays change the direction electronically via beams, eliminating the need for mechanical rotation [29].

2.3.2 Beamforming Architectures

The following three approaches have been established to realize beamforming via phased antenna arrays [51]:

- **Analog beamforming:** As the name suggests, the phase shifts are applied in the analog domain. In other words, all antenna elements receive a phase-shifted version of the same analog signal. Therefore, a single RF chain, thus a single digital-to-analog converter (DAC)/analog-to-digital converter (ADC)⁵, is utilized, resulting in lower circuit complexity and power consumption. This approach is preferred in power-limited and low-cost applications, like handheld UEs. The antenna weights can either be applied by using time delay elements, which adjust the line length, or by phase shifting the signal [29]. Two varieties of analog beamforming, with respect to when the phase shift occurs, exist. In *analog baseband beamforming*, the phase shift is performed before frequency up/downconversion, whereas in *analog RF beamforming*, it is performed after frequency up/downconversion. Analog baseband beamforming requires frequency up/downconverters for each antenna element, whereas analog RF beamforming requires a single frequency up/downconverter for all antenna elements [51].
- **Digital beamforming:** The processing for beamforming, including phase shifting, is done in the digital domain separately for each antenna element, each of which thus requires one RF chain. This enables features such as multiple simultaneous beams on a single antenna array, which is useful for multiple-input multiple-output (MIMO) applications, and interference canceling [29]. However, due to the need for one RF chain per antenna element, the architecture complexity and power consumption are increased [51].
- **Hybrid beamforming:** Hybrid beamforming combines aspects of analog and digital beamforming. Instead of using one RF chain for each antenna element or all antenna elements, antenna elements form subgroups that use one RF chain. The signal streams are digitally precoded and forwarded to M RF chains. Then, analog beamforming is applied, and the signal streams are output to N antenna elements, with $M < N$. Each of the M signal streams can be fed either to analog beamformers that output the signal to only a subgroup of the antenna elements (*sub-array configuration*) or to a single, common analog beamformer that outputs combinations of these signal streams to all N antenna elements (*full-array configuration*) [51]. While digital beamforming enables MIMO applications thanks to its capacity to digitally process a data stream for each antenna element, it is not necessary to have one data stream for each antenna element since the optimal number of data streams is generally smaller than the number of antenna elements due to the physical properties of the mm-wave channel. Therefore, hybrid beamforming could be used to reduce the number of RF chains, in turn reducing the cost and energy consumption [28].

⁵In a typical RF chain, the power consumption is dominated by mixed signal components, such as the ADC and DAC [51].

2.4 RF-based Beam Management at mm-Wave Frequencies

Directional communication at mm-wave frequencies using phased antenna arrays requires a multitude of beam management procedures for the alignment of transmitter (TX) and receiver (RX) and to maintain beam alignment during rapidly changing environmental conditions, including mobility and blockage [52,53]. The procedure for idle users to connect to a base station is referred to as *initial access (IA)* and requires the identification of viable beam pairs for communication. Continuously updating the beam pair to maintain connectivity is referred to as *beam tracking*.

Beam management in 5G cellular networks encompasses a number of operations for initial access and beam tracking, which are defined in 3GPP Release 14 [54]:

- **Beam sweeping:** The operation of covering a spatial area by transmitting/receiving data over beams with predetermined time intervals and directions [52,53].
- **Beam measurement:** The evaluation of the quality of received beamformed signals either at the BS, which is called Next Generation NodeB (gNB) in 5G networks, or the user equipment (UE) [52,53]. Used metrics include received signal strength (RSS), reference signal received power (RSRP), and signal-to-noise ratio (SNR).
- **Beam determination:** The selection of the suitable TX/RX beam(s) based on the beam measurements at the gNB or UE [52,54].
- **Beam reporting:** The operation of the UE reporting findings from beam measurement, such as beam quality based on RSRP readings and best beam⁶ decision [52,53].
- **Beam maintenance:** A set of operations, including beam tracking and refinement, to maintain a selection of candidate beams at the gNB or UE to be used to adapt to changes in the channel. *Beam tracking* is the operation of handling beam misalignment caused by unexpected UE mobility by selecting new beams to prevent the reduction of the data rate or outage [55], whereas *beam refinement* is the operation of selecting a narrower beam [53].
- **Beam recovery:** The operation of the UE identifying new candidate beams after it detects beam failure, ultimately sending a beam recovery request to the gNB with information on the new candidate beams [53].

Exhaustive search has emerged as a primary technique to identify viable beam pairs between the UE and gNB during IA in 5G mm-wave networks. This is a brute-force technique that can be implemented with the following steps [56]:

1. The gNB transmits a signal on one of its beams, while the UE receives the signal on all of its beams sequentially.
2. The UE decides its best beam based on the metric it uses, such as maximum SNR or RSRP.

⁶As in the beam for which the highest RSRP was measured.

3. The UE reports its best beam back to the gNB using the best beam.
4. The first three steps are repeated for all the beams available at the gNB.
5. When all beams have been scanned by the gNB, both the gNB and UE select the best beams to communicate with each other and start using them.

Due to its brute-force nature, exhaustive search is associated with large overhead and delay, which can reach hundreds of milliseconds based on the antenna array size [56]. Several alternatives to exhaustive search have been proposed by the research community (e.g. [57–62]). **Iterative search**, a multiple-stage technique, has been proposed by the authors in [56], consisting of two phases:

1. The *first phase* concerns wide sectors at the gNB, with the following steps:
 - The gNB transmits a signal on one of its sectors, while the UE receives the signal on all of its beams sequentially.
 - The gNB repeats the previous step for all of its sectors.
 - The UE chooses its best beam, the beam on which it has received with the maximum SNR.
 - The UE transmits the received SNR information for all gNB sectors on its best beam. The gNB stores the information in a table.
2. The *second phase* concerns beam refinement at the gNB, i.e. choosing a narrow beam instead of a wide sector to communicate with the UE. The steps are as follows:
 - The gNB transmits a signal on one of the beams within its best sector, i.e. the gNB sector over which the UE received with the maximum SNR. The UE receives with its best beam, which it selected in the first phase.
 - The UE transmits its received SNR information on its best beam, which the gNB receives on the beam it used in the previous step and stores the information in a table.
 - The gNB repeats the previous steps for all beams within its best sector.

Although iterative search might incur a smaller overhead and delay compared to exhaustive search, the misdetection and outage probabilities associated with iterative search are higher due to the lower beamforming gain of wide sectors [63]. Another disadvantage of iterative search is that one error in an earlier stage, such as the selection of a suboptimal sector, renders the outcome of all the following steps inaccurate [55].

2.5 Sensor-Aided Beam Management for 5G-and-Beyond

As the mm-wave channel is highly site-specific, exploiting context information (CI) from out-of-band RF or non-RF information sources during IA and beam tracking to develop agile beam management techniques has been explored. Such context information includes, but is not limited to [6]:

- Out-of-band channel information, i.e. channel information obtained from frequency bands other than the one used for communication
- User location and movement
- Information about the environment, including street layout, building facades and surfaces, mobility patterns, and static & mobile obstacles
- Information about device orientation and position
- Knowledge of the location of base stations
- Prediction of traffic patterns

RF-based out-of-band approaches, such as the one suggested in [64], envision leveraging information obtained via frequency bands other than mm-wave (such as sub-6 GHz). The authors in [64] utilize information such as angle of arrival (AoA) and angle of departure (AoD), which are found to be similar between mm-wave and sub-6 GHz frequencies. Such information can be obtained either via the existing sub-6 GHz infrastructure or, alternatively, via radars mounted on the mm-wave infrastructure [65]. However, RF-based out-of-band approaches are associated with multiple challenges, including, but not limited to, the following [6]:

- Out-of-band RF measurements must be taken simultaneously with mm-wave communication. This requires an integrated protocol for multi-band coexistence, which might incur additional overhead on the communication system and increase the complexity of mm-wave transceivers.
- An optimal mapping between mm-wave and out-of-band measurements is required for out-of-band channels that have different propagation characteristics, such as sub-6 GHz frequencies. The number of viable reflections in the mm-wave band is less than in sub-6 GHz frequencies. Furthermore, some paths might be LoS at sub-6 GHz frequencies but NLoS at mm-wave frequencies [64].
- A considerable amount of RF-based out-of-band beam management schemes have been suggested for sub-6 GHz frequencies (see [6] and references therein). However, resources are already limited in this band, which might make it more difficult to deploy such systems in dense networks.

Non-RF-based out-of-band approaches, in contrast, envision leveraging **sensors** to obtain CI to develop agile beam management schemes, collectively known as *sensor-aided beam management*. The deployment of sensor-aided beam management becomes more viable as sensors are envisioned to be mounted on next-generation, autonomously driving vehicles, which would be capable of communicating with each other (vehicle-to-vehicle (V2V)), with the road infrastructure (vehicle-to-infrastructure (V2I)), or even the rest of their surroundings (vehicle-to-everything (V2X)) [26]. Data collected by these sensors can be distributed to other UEs or gNB, where they can be utilized to facilitate IA and beam tracking. Commonly used sensors and proposed sensor-aided beam management schemes utilizing these sensors include the following:

- **GNSS/GPS**⁷, to obtain the location, velocity, direction of travel, and orientation of the user. The location information can be used to estimate beam directions by exploiting the highly directional and site-specific nature of the mm-wave channel. Similarly, the direction of travel information can be used for beam tracking by inferring the user movement and updating the ideal beam pair accordingly. Such applications narrow the beam search space, thus reducing the overhead and delay associated with IA and beam tracking. The location information mainly facilitates LoS communication, since NLoS depends on the site geometry. Therefore, it is less valuable for scenarios where NLoS communication is needed [67]. The reliability of GNSS data significantly decreases in indoor environments due to attenuation of GNSS signals through walls and other building structures [6]. Furthermore, the location and orientation information often suffer from errors [8], which are addressed by techniques such as radio environment maps (REMs) [68, 69].
- **Image data** captured by RGB cameras. Thanks to recent developments in computer vision and deep learning, images can be processed in real time with powerful algorithms [6]. Several applications that utilize image data to facilitate beam management have been proposed, such as beam prediction based on past images and beam indices (e.g. [70–72]), beam prediction based on gNB and/or UE location inferred from image data (e.g. [73, 74]), and blockage prediction (e.g. [75]). However, using image data is not viable in low-light scenarios and foggy/rainy weather [76]. Furthermore, cameras are also associated with privacy concerns [77].
- **LiDAR**, a type of sensor that emits a laser and measures the time delay of the reflections to estimate the distance to the target. The data is transformed into 3D *point clouds* that indicate the relative position and intensity. These point clouds can then be used to construct 3D models of the environment, on which ray tracing can be deployed to identify propagation paths (e.g. [78]). Alternatively, the environment model could be used to complement GNSS-based location error models and augment REMs [6]. Several methods have been proposed to assess if the user is in LoS (e.g. [79, 80]), to predict current or future beams (e.g. [77, 79]), and to predict blockages (e.g. [81, 82]). LiDAR for beam management has been envisioned for deployment both on autonomously driving vehicles and base stations [77, 79]. The mounting angle of the LiDAR has been observed to affect the prediction performance, i.e. the models produce more accurate predictions when the LiDAR is angled towards the base station [80]. LiDARs generally have a narrow field of view (FoV) in the elevation domain. The quality of LiDAR data suffers under poor weather conditions such as rain, snow, and fog, resulting in inaccurate distance measurements [76, 77]. Similarly, they cannot penetrate through clutter such as foliage. Furthermore, LiDARs tend to be more expensive than cameras [6], and the cost scales up in direct proportion to the number of channels, which directly impacts the resolution of the point cloud.

Sensor fusion is the combination of information from two or more sensors to obtain a better understanding of the environment. Sensor fusion is associated with advantages such as increasing confidence, resolving ambiguity, and compensating for missing data [83].

⁷While Global Positioning System (GPS) is the colloquially used term for GNSSs in general, it is only one of the four GNSS services that are currently active worldwide [66].

These advantages can be applied to sensor-aided beam management in the form of retrieving BS/UE coordinates missing in LiDAR point clouds and camera images from GNSS, compensating for LiDARs and cameras in rainy and foggy weather conditions, and increasing the possibility of availability of at least one sensor type for inference [6]. In line with these benefits, some research groups have carried out measurements and/or simulations with multiple sensor modalities (e.g. [76, 79, 84, 85]).

2.6 Related Work

Table 2.3 shows a selection of mm-wave experimental platforms throughout the years, highlighting their strengths and limitations. The authors in [86] conducted some of the earliest measurement campaigns in urban environments at 28 GHz and 38 GHz with mechanically steered horn antennas, when phased antenna arrays for mm-wave frequencies were not yet widely available. The authors in [87] developed one of the earliest mm-wave testbeds that utilized phased antenna arrays, measuring at 60 GHz and using a field-programmable gate array (FPGA)-based baseband architecture. [88] presents a measurement campaign in the medium-sized German town of Langenfeld with a horn antenna and the EVK06002, which is an evaluation kit for a 60 GHz phased array antenna by Sivers IMA, and the Universal Software Radio Peripheral (USRP) X310 software-defined radio (SDR). The authors in [89] developed a mm-wave testbed with IEEE 802.11ad-compliant building blocks, using a USRP X310, a 60 GHz horn antenna, and the RF Network-on-Chip (RFNoC) development framework. The COSMOS platform [90, 91] consists of open-access programmable testbeds in different form factors, envisioned for mobile communications, mm-wave, optical networking, and edge cloud research. It utilizes USRPs and phased antenna arrays for 28 GHz and 60 GHz, including a 60 GHz front-end by Sivers IMA. mMobile [92] is a custom-developed 5G-NR-compliant mm-wave testbed with a 28 GHz phased antenna array and FPGA- and USRP-based baseband architectures. The authors implemented a beam tracking algorithm based on Synchronization Signal Blocks (SSBs) for beam refinement and demonstrated it within the operation of mMobile. Furthermore, they released the data collected with mMobile to the public [99]. mm-FLEX [93] is an open-source real-time full-duplex signal processing mm-wave testbed with an FPGA-based baseband architecture and the EVK06002 as the 60 GHz RF front-end, primarily intended for IEEE 802.11ad. The authors demonstrated fast beam alignment by exploiting the ns-level beam switching capabilities of the testbed. MIMORPH [94] is an open-source wireless platform based on reasonably cheap components such as a single FPGA board using the RF System-on-Chip (RFSoc) development platform and the EVK06002 as the 60 GHz RF front-end. It is a multi-band platform, operating both at sub-6 GHz and mm-wave frequencies, and supports up to 5 GHz of bandwidth at mm-wave frequencies. mm-O-RAN [95] is a 5G-compliant full-stack mm-wave testbed based on the open-source OAI 5G project.

Raymobtime [80, 96] is a collection of open-access datasets for ray tracing, consisting of RF data at 60 GHz synthesized by a traffic simulator and a ray tracer, and LiDAR data synthesized with a sensor simulator. The authors in [73] developed one of the earliest testbeds for sensor-aided beam management, applying machine learning algorithms on camera images to predict the optimal beam pair based on the locations of the TX and RX. The authors in [97] collected data to be used for federated learning from multiple sensor

Table 2.3: A selection of mm-wave experimental platforms and datasets.

Platform	Frequency Bands	Baseband Architecture	RF Front-End	Sensors
[86]	28 GHz, 38 GHz	Custom	Horn + mechanical rotation	None
OpenMili [87]	60 GHz	FPGA + PC	Phased array	None
[88]	60 GHz	USRP + PC	Horn, phased array + mechanical rotation	None
[89]	60 GHz	USRP + PC	Horn	None
COSMOS [90, 91]	sub-6 GHz, 28 GHz, 60 GHz	USRP + PC, RFSoc	Phased array	None
mMobile [92]	28 GHz	USRP/FPGA + PC	Phased array	None
mm-FLEX [93]	60 GHz	FPGA + processor card	Phased array	None
MIMORPH [94]	sub-6 GHz, 60 GHz	FPGA	Phased array	None
mm-O-RAN [95]	28 GHz	USRP + PC	Phased array	None
Raymobtime [80, 96]	60 GHz	- (synthetic)	- (synthetic)	LiDAR (synthetic)
[73]	60 GHz	FPGA + PC	Phased array	Camera
FLASH [97]	60 GHz	COTS	Phased array (COTS)	Camera, LiDAR, GNSS
DeepSense 6G [76]	60 GHz	USRP + PC	Omnidirectional, horn, phased array	Camera, GNSS, 2D/3D LiDAR, radar
[84]	28 GHz, 60 GHz	USRP + PC	Phased array	LiDAR, camera, GNSS
[98]	28 GHz	USRP + PC, COTS	Phased array	Camera

modalities, namely camera, LiDAR, and GNSS, and simultaneous RF data with commercial off-the-shelf (COTS) 60 GHz IEEE 802.11ad-compliant transceivers. DeepSense 6G [76] is a multi-modal open access dataset consisting of RF measurements at 60 GHz, coupled with sensor data from cameras, LiDARs, radars, and GNSS, taken in various weather and lighting conditions. The authors in [84] developed an open-access multi-band multi-modal measurement platform, using USRP X410s for the baseband architecture and the EVK02001 and EVK06003 phased antenna arrays by Siivers Semiconductors as the 28 GHz and 60 GHz RF front-ends. Furthermore, they deployed an ML-based object recognition model that runs on LiDAR point clouds to demonstrate sensor-aided beam management and collect data from cameras, LiDARs, and GNSS, in addition to multi-band RF measurement data. The authors in [98] demonstrated sensor-aided beam management using a camera at the gNB of the OAI 5G full-stack network.

The OpenAirInterface (OAI) 5G project [9] has emerged as an important candidate for a full-stack cellular network research platform, thanks to its open-source core network (CN) and 3GPP-compliant 4G and 5G-NR radio access network (RAN) implementations. Research using the OAI software stack has been carried out on a variety of topics, such as LTE [100,101], 5G non-terrestrial networks [102–104], 5G-NR positioning [105], sub-6 GHz networking studies [106–108], mm-wave testbed development and full-stack network demonstration [95,109,110] and THz applications [111]. In particular, the platform in [109], which is currently the only setup to couple the OAI 5G RAN with a mm-wave antenna array that is available for purchase, has attracted interest from the research community. However, the antenna array used is an order of magnitude more expensive than other antenna arrays, such as the EVK02001. The work presented in [98] builds upon the platform in [109], demonstrating camera-aided beam management. However, it executed beam switches via an external application instead of executing the beam switch directly from the OAI 5G RAN, which we implement in this thesis.

Despite the considerable body of work on mm-wave testbeds and sensor-aided beam management, none of these studies address important aspects of mm-wave testbeds and sensor-aided beam management by themselves. [73,76,87,89,93,94,97] lack measurements in the 28 GHz band, which is more important for 5G-and-Beyond networks compared to the 60 GHz oxygen absorption band. Furthermore, [73,87,93,94] rely solely on FPGA-based implementations, which are costly and not easily reconfigurable. [76,92,97] have directional antennas only on either the receiver or transmitter, thus lacking insight about directional-to-directional communication links. Out of all the aforementioned testbeds, except for those based on OAI, the source code for the communication framework is available to the public only for [84,90,91,93,94]. None of the multi-modal datasets include real-world RF measurements for scenarios where both the TX and RX are operating directionally, a gap that we address with this thesis.

This thesis aims to further the understanding of sensor-aided beam management at mm-wave frequencies by developing two testbeds that utilize multiple sensor modalities accompanying communication at mm-wave frequencies. These testbeds are envisioned to further our understanding of sensor-aided beam management at mm-wave frequencies by demonstrating sensor-aided beam management for different sensor modalities within a full-stack end-to-end 5G-compliant network and collecting multi-modal sensor and RF data to create datasets, which will be used to develop novel machine learning/deep learning-based beam management methods. The functionality of these testbeds is verified with extensive tests and a measurement campaign in the medium-sized German city of Aachen.

3

Design and Implementation of Two Testbeds

This chapter explains the building blocks and implementation details of the testbeds developed throughout this thesis. Section 3.1 provides a general overview of the testbeds. Section 3.2 introduces the hardware components, and Section 3.3 introduces the software frameworks. Finally, Sections 3.4 and 3.5 detail how these building blocks are integrated and the software implementations needed to make the testbeds work.

3.1 Overview

In the scope of this thesis, two testbeds have been developed for (1) the demonstration of a 5G-compliant end-to-end communication system with integrated sensors for sensor-aided beam management and (2) capturing RF and multi-modal sensor measurements. The testbed for (1) has been demonstrated in an example scenario at the Berlin 6G Conference 2025, as seen in Figure 3.1. The testbed for (2) has been deployed to conduct an outdoor measurement campaign in Aachen in fall 2025, as seen in Figure 3.2, to get a better understanding of a variety of blockages and their effects on the radio link in an outdoor environment and facilitate the creation of multi-modal datasets to be used for machine learning/deep learning applications and the development of ray tracing models.

The reason for developing two different testbeds instead of combining the functionalities in one mainly stems from the stability issues observed with OAI. Thus, a more stable and easily modifiable testbed has been developed for (2), taking the work in [84] as a starting



Figure 3.1: The testbed for (1) being demonstrated at the Berlin 6G Conference 2025, with the gNB and UE indicated.



(a) RX



(b) TX

Figure 3.2: The receiver (RX) and transmitter (TX) from the testbed for (2), deployed in an outdoor measurement campaign.

point and implementing the software for mm-wave communications from scratch to meet our performance requirements.

3.2 Hardware Components

In this section, the hardware components used in our testbeds are introduced. The majority of them are common among the testbeds. Testbed-specific details are provided in Sections 3.4 and 3.5.

3.2.1 USRP X410 Software Defined Radio

The USRP X410, seen in Figure 3.3, is an SDR developed by National Instruments [112]. It is equipped with four full-duplex channels and can operate at frequencies between 1 MHz and 7.2 GHz. Each channel is capable of up to 400 MHz bandwidth. For communication with a host PC for data and control, 10/100/1000 Ethernet, QSFP-28, and USB-C are available. The X410 can be used for a variety of C/C++ and Python-based applications thanks to the USRP Hardware Driver (UHD), which is introduced in Section 3.3.1, in addition to having built-in libraries based on UHD for LabView and GNU Radio (*cf.* Section 3.3.4).

3.2.2 EVK02001 Antenna Array Transceiver

The EVK02001 is an RF front-end phased antenna array evaluation kit produced by SiVRS Semiconductors for low FR2 frequencies (24 - 29.5 GHz), which is popular in mm-wave research thanks to its reasonable cost compared to its competitors. It includes a transceiver



Figure 3.3: The USRP X410.



Figure 3.4: The EVK02001 with important components illustrated.

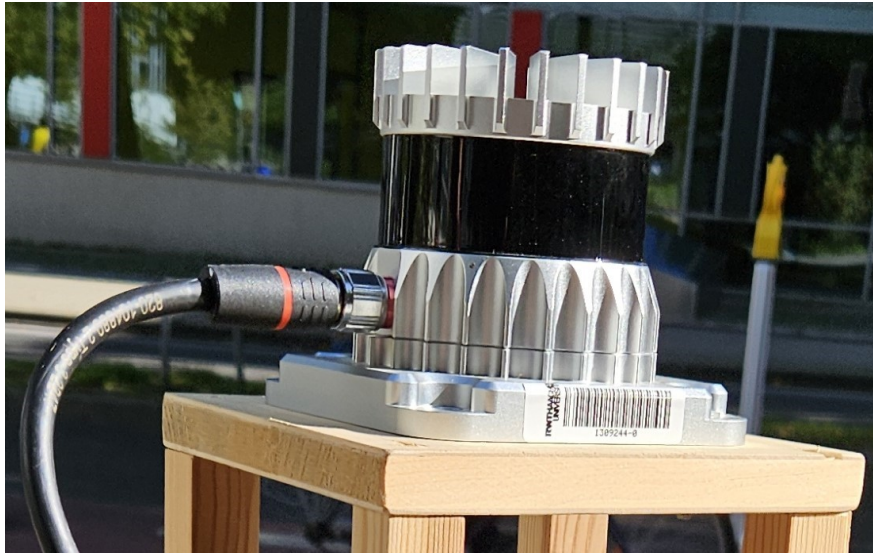


Figure 3.5: The OS-1 LiDAR with the 1000BASE-T connector.

IC, TRX BF/02, and a patch antenna RF module, BFM02003, and comes with a graphical user interface (GUI) and Python library for easy configuration [113]. It has 16 antenna elements (2x8) for TX and RX modes of operation each and provides 64 beambook entries for codebook-based beam switching [114]. The default beambook only includes 22 unique entries: 21 pencil beams (covering azimuth angles from -45° to 45° in 4.5° steps at 0° elevation) and an omnidirectional beam. The correspondence between beam IDs and azimuth beam pointing angles are provided in Appendix A.

The EVK motherboard has a MOLEX port, paired with switches, to provide direct access to the Serial Peripheral Interface (SPI) bus. Another port which provides external I2C/BF control also includes a general-purpose input/output (GPIO) pin to switch between TX and RX modes [115]. These MOLEX ports are indicated in Figure 3.4.

3.2.3 OS-1 LiDAR Sensor

The OS-1, seen in Figure 3.5, is a high-resolution LiDAR sensor by Ouster [116] that is used to make accurate 3D maps of the environment to identify potential blockages and reflection/multipath opportunities for propagation of mm-waves. It has a maximum range of 200 m, a vertical field of view (FoV) of $42.4^\circ \pm 1.0^\circ$, and a horizontal FoV of 360° . The LiDAR has a vertical resolution of up to 128 channels, a horizontal resolution of up to 2048 channels, and a rotation rate of 10 or 20 Hz. It provides cm-level range precision and accuracy and features a 1000BASE-T connector, which combines DC power and Gigabit Ethernet. Ouster provides a driver and software development kit (SDK) that allows the integration of the OS-1 with Robot Operating System 2 (ROS 2) [117].

3.2.4 ZED 2i Stereo Camera

The ZED 2i, seen in Figure 3.6, is a stereo camera by StereoLabs that is used to identify potential blockages and reflection/multipath opportunities for propagation of mm-waves, to serve as a ground truth for the LiDAR sensor, and to partner with the other sensors for

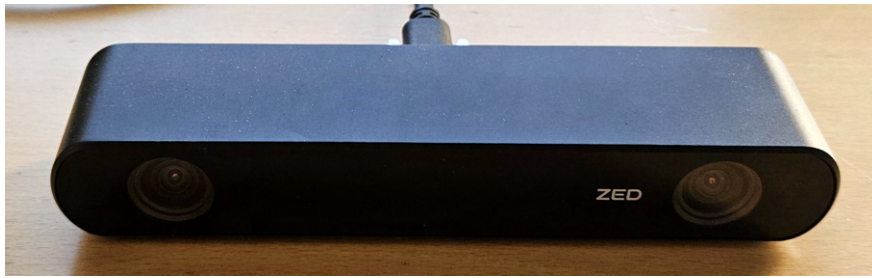


Figure 3.6: The ZED 2i camera.

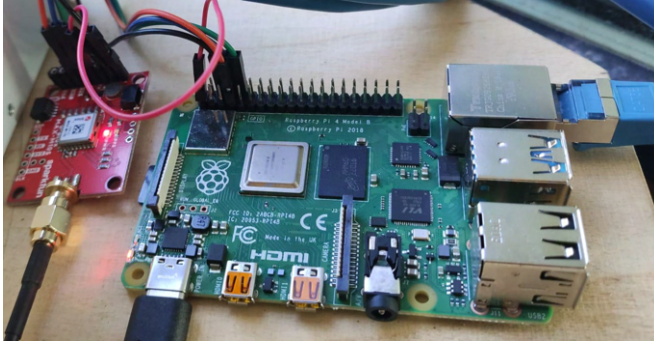
sensor fusion. The camera is capable of outputting stereo images up to 2K resolution at 15 frames per second (fps) or in 1080p at 30 fps. It has a depth range of 0.3 - 20 m, a maximum horizontal FoV of 110°, and a maximum vertical FoV of 70°. It is equipped with accelerometer, gyroscope, barometer, magnetometer, and temperature sensors. It utilizes a USB 3.0 Type-C cable for data and power, is compatible with plenty of operating systems, including Ubuntu, and can be integrated into plenty of development environments, including ROS 2 [118].

3.2.5 *Raspberry Pi 4 Model B, SparkFun GNSS Receiver Breakout - MAX-M10S and u-blox ANN-MB5 GNSS Antenna*

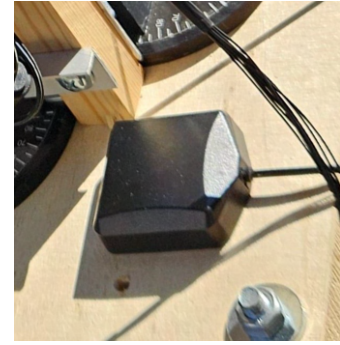
The Raspberry Pi 4 Model B, seen in Figure 3.7a, is a single-board computer that is often used for embedded computing applications and maker projects. It has a 40-pin GPIO header, a Gigabit Ethernet port, Wi-Fi and Bluetooth/BLE support, 2 USB 3.0 ports, 2 USB 2.0 ports, and 2 micro-HDMI ports, alongside other connectors for different peripherals [119]. The breakout board by SparkFun, also seen in Figure 3.7a, includes the u-blox MAX-M10S GNSS receiver, which can receive signals from all four GNSS constellations, has a pulse per second (PPS) pin, and supports Inter-Integrated Circuit (I2C) and universal asynchronous receiver-transmitter (UART) for serial communications [120]. The ANN-MB5 by u-blox, seen in Figure 3.7b, is a multi-band GNSS antenna that supports both the L1 and L5 frequency bands [121]. These components are combined to create a GNSS-based time server (*cf.* Section 3.5.3) and to capture GNSS location data during measurements. The use of the Raspberry Pi 4 is critical due to the additional accuracy it provides as a dedicated, single-purpose computer and its GPIO header, which allows us to eschew USB 3.0/Type-C connections, known to cause interference with GNSS signals [122].

3.2.6 *Host PCs*

A variety of host PCs are used for different tasks. The host PCs that run the Docker containers to manage the sensors require powerful graphics processing units (GPUs) to be able to run the ML-based object recognition models on the LiDAR point clouds and camera images in real time. For this purpose, a desktop PC with an NVIDIA RTX 4070 GPU and a laptop with an NVIDIA RTX A2000 GPU are used. Furthermore, the OAI RAN software requires powerful central processing units (CPUs) and specific performance optimizations to mitigate timing and stability. For this purpose, two desktop PCs with powerful CPUs and performance optimizations, one of which has been specifically designed to run the OAI



(a) The Raspberry Pi 4 (right) and GNSS receiver breakout board (left).



(b) The GNSS antenna.

Figure 3.7: Photographs of the components of the GNSS-based time server.

RAN for the gNB, are used. All host PCs run either Ubuntu 20.04 or 22.04 as the operating system.

3.2.7 Hunter 2.0 Robot

Hunter 2.0, seen in Figure 3.8, is an unmanned ground vehicle (UGV) by AgileX [123] that can support up to 150 kg of load. It is used to haul the receiver of the second testbed and for measurements where the receiver moves at typical walking speed. It comes with a remote control but can also be used for autonomous/remote driving applications thanks to its Robot Operating System (ROS) driver and Controller Area Network bus (CAN bus) interface [124].

3.3 Software Components

3.3.1 UHD

The USRP Hardware Driver (UHD) [125] is the free and open-source software driver for the USRP platform, developed by Ettus Research. It supports Linux distributions of Ubuntu and Fedora, alongside Mac OS X for Intel-based Macs and Windows 10. It can be used within C/C++ and Python-based applications standalone or integrated into frameworks such as GNU Radio, RFNoC, LabVIEW, MATLAB/Simulink, and OAI. UHD handles multiple operations pertaining to the USRP, such as timing I/Q samples and transporting them to the host PC, tuning the frequency and sample rate, and GPIO operations [126]. In the scope of this thesis, all applications are using UHD 4.6 built from source.

3.3.2 ROS 2

Robot Operating System 2 (ROS 2) is an SDK used to develop robotics applications [127]. It utilizes a publish/subscribe mechanism, where *nodes*¹ publish or subscribe to *topics* to communicate with each other [128]. ROS 2 and its predecessor, ROS, are used in many projects for robotics and automation applications, such as surgical robotics, aerospace research, social robotics, and autonomous driving [129, 130].

¹The unit of computation in ROS/ROS 2



Figure 3.8: The Hunter 2.0 UGV.

In both testbeds, we deploy Docker containers that run ROS 2 or communicate with ROS 2 nodes. These containers are used to: (1) run the camera and LiDAR drivers, capture and visualize the camera image and LiDAR point cloud streams; (2) form a planar relation between the images and point clouds; (3) perform object detection and tracking on the images and point clouds; (4) run an MQTT broker and publish beam management-related commands over MQTT; and (5) record the sensor streams and object detection data as ROS 2 *bags*. The object detection software for the camera is provided by StereoLabs as part of the ZED drivers for ROS/ROS 2 [131], whereas the object detection model and container image for the LiDAR are provided by the Institute for Automotive Engineering (ika), RWTH Aachen University. The applications, although sharing many tasks/containers, are tailored for each use case. Details are provided in Sections 3.4.3 and 3.5.4.

3.3.3 OpenAirInterface

The OpenAirInterface (OAI) 5G project, supported by the OpenAirInterface Software Alliance and its members, is a full-stack open-source implementation of the core network (CN) and radio access network (RAN) for 4G/LTE and 5G-NR for FR1 and FR2 that can run on SDRs such as the USRP X410 [9]. The CN supports primary network management actions such as connection, registration, and session management [132], while the RAN includes implementations of standalone (SA) and non-standalone (NSA) gNB and UE [133]. The OAI 5G project has received considerable interest in recent years as an open-source full-stack network software implementation (*cf.* Section 2.6).

In this thesis, we (1) integrate the low-cost EVK02001 antenna array into the OAI 5G RAN, which enables (2) the implementation of 5G-NR beam management via SSBs,

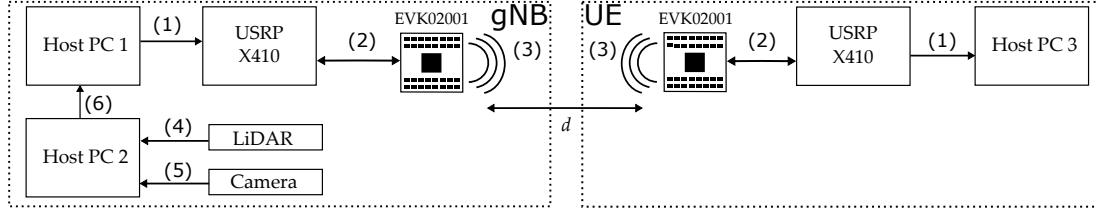


Figure 3.9: Block diagram for the OAI-based platform with connection types and signals: (1) samples and commands, (2) I/Q baseband signal, (3) RF signal ($f_c = 27$ GHz), (4) 2048x128 point cloud, (5) 1080p30 video stream, (6) MQTT connection

and (3) develop a configurable sensor management framework with multiple modalities to demonstrate sensor-aided beam management. All modifications on the RAN source code have been applied to the `develop` branch at tag 2024.w42 [134]. We intend to merge our modifications with the codebase in the future.

3.3.4 GNU Radio

GNU Radio is a free and open-source software development toolkit used to develop signal processing frameworks [135]. Its main processing units are *blocks*, which are brought together and connected to each other for the flow of control signals or data *streams* to make up *flowgraphs*. These blocks are grouped under *modules*. A flowgraph can either be repackaged as a block to be placed within another flowgraph or get converted into a Python or C++ executable². Users can add GUI widgets, which are based on Qt, to control parameters or visualize signals. GNU Radio has built-in support for UHD in the form of blocks that control USRPs, namely USRP Source for receiving signals and USRP Sink for transmitting signals. It also provides the functionality to develop custom modules, called out-of-tree (OoT) modules. In our applications, we use GNU Radio v3.10.6 compiled from source [136].

3.4 Implementation of Testbed 1: OAI-based 5G-Compliant Testbed with Environmental Awareness

This testbed is used to demonstrate the capabilities of sensor-aided beam management on a 5G-NR system. In order to develop a 5G-compliant mm-wave testbed with sensor-aided beam management, we implemented several features within the OAI 5G-NR RAN codebase. These implementation efforts and their novelty and contribution to 5G-and-Beyond mm-wave research are explained under three headings in the following subsections.

Figure 3.9 shows the block diagram for the end-to-end system. At the gNB, Host PC 1 is connected to the USRP X410 via 2x10 Gbps SFP+ cables, which carry I/Q samples and various commands, such as those for antenna control. Host PC 1 runs the OAI CN and the OAI RAN software for the gNB via the OAI dashboard. The EVK02001 is connected to the RF ports of the USRP X410 via two SubMiniature version A (SMA) cables and to the GPIO front panel of the USRP X410 via two MOLEX cables.³ One SMA cable carries I/Q samples to be transmitted from the USRP to the EVK02001; the other carries received

²Python is the default, which is what we use in our applications.

³The EVK02001 is also connected to Host PC 2 over USB for the initial configuration.

I/Q samples from the EVK02001 to the USRP. One MOLEX cable carries SPI signals in both directions to read from/write to internal registers of the EVK02001; the other carries GPIO pulses from the USRP to the EVK02001 to switch the EVK02001 between TX and RX operation modes. Host PC 2, which is equipped with an NVIDIA RTX 4070 GPU to run the object recognition models, is connected to the ZED 2i camera via USB 3.0 and to the OS-1 LiDAR via Gigabit Ethernet, which is then converted to 1000BASE-T before reaching the OS-1. The USB cable carries a stream of 1080p camera images at 30 fps and other data, whereas the Ethernet cable carries LiDAR point clouds of 2048x128 resolution at approximately 10 Hz, accompanied by metadata. Host PC 2 is also connected to Host PC 1 via Gigabit Ethernet for the MQTT connection. Host PC 2 captures sensor data, runs the object recognition models for both sensors to detect obstacles in real-time, and runs the Python node for communication with Host PC 1 via MQTT. We use two host PCs at the gNB, as the object recognition models are highly resource intensive and require running on a GPU to function in real-time. Moreover, the OAI RAN software is time-critical, and Host PC 1 is specifically optimized to run it. Therefore, we decided to separate the load between two host PCs to ensure correct operation and timing.

At the UE, Host PC 3 is connected to the USRP X410 via a 100 Gbps QSFP28 cable, which carries I/Q samples and various commands, such as those for antenna control. Host PC 3 runs the OAI RAN software for the UE. The EVK02001 is connected to the RF ports of the USRP X410 via two SMA cables and to the GPIO front panel of the USRP X410 via one MOLEX cable.⁴ One SMA cable carries I/Q samples to be transmitted from the USRP to the EVK02001; the other carries received I/Q samples from the EVK02001 to the USRP. The MOLEX cable carries GPIO pulses from the USRP to the EVK02001 to switch the EVK02001 between TX and RX operation modes.

3.4.1 SPI/GPIO Control for EVK02001

We implemented SPI/GPIO-based control signals to integrate the EVK02001 28 GHz antenna array with OAI in the form of a new library and additions to the existing source files, being the first group to do so. The library, named `lib_usrp_spi_sivers`, includes two main functions: (1) `usrp_spi_sivers_setup`, a function that is run at the beginning of execution to initialize the USRP X410 SDR and set the front panel GPIO pins in the correct mode of operation, and (2) `usrp_spi_sivers_select_beam_id_tx_rx`, a function that is called each time the beam ID is to be changed. The library is written to also support operation with the 60 GHz model, EVK06003, but functionality of OAI with EVK06003 in 60 GHz has not been verified.

The pins used for SPI and GPIO and their functionality are enlisted below. The pin names as given in the user manual for EVK02001 are provided in parentheses. The pin connections between the EVK02001 and the USRP X410 front-panel GPIO port are illustrated in Figure 3.10.

- **Clock (SPI_CLK):** Provides the oscillating square wave for timing/synchronization purposes.

⁴The EVK02001 is also connected to Host PC 3 over USB for the initial configuration.

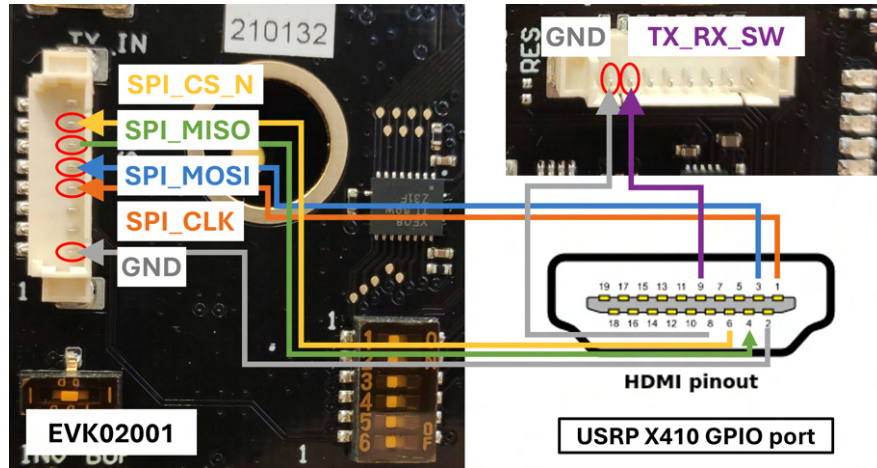


Figure 3.10: Pin connections between the EVK02001 and the USRP X410 for the OAI-based testbed.

- **Serial Data Out (SPI_MOSI)⁵:** The line on which data from the USRP X410 is carried to the EVK02001.
- **Serial Data In (SPI_MISO)⁶:** The line on which data from the EVK02001 is carried to the USRP X410.
- **Chip Select (SPI_CS_N):** The line that indicates if the USRP X410 is communicating with a specific EVK02001, which manifests itself as the USRP X410 pulling the line to low.
- **TX/RX Switch (TX_RX_SW_3V3_IN):** The line that triggers TX/RX switches at the EVK02001 based on the TX/RX state of the USRP X410.

The following are done within `usrp_spi_sivers_setup` according to [138]:

- The front panel and specific pin numbers to drive the aforementioned pins are defined.
- GPIO port voltage is set as 3.3 V per the EVK02001 User Manual [115].
- All pins except for TX/RX Switch are configured to be controlled by the SPI engine.
- All pins except for Serial Data In are configured as output pins.
- TX/RX Switch is set to be controlled by an Automatic Transmit/Receive (ATR) register for quick, standard-compliant TX/RX switches.

The values of ATR registers change according to the TX/RX status of the USRP X410. The four variants and their operation are as follows [139]:

⁵MOSI stands for Master Out Slave In. The Open Source Hardware Association issued a resolution to redefine SPI signal names, with the terms "master" and "slave" being replaced by "controller" and "peripheral" respectively [137].

⁶MISO stands for Master In Slave Out. See footnote 5.

- ATR_0X: The status of the pins when the radio is **idle**.
- ATR_RX: The status of the pins when the radio is **receiving** only.
- ATR_TX: The status of the pins when the radio is **transmitting** only.
- ATR_XX: The status of the pins when the radio is in **full-duplex** mode.

Each of these states has an associated register, which is pulled to logic high as the status becomes current. Although full-duplex operation is not possible for the EVK02001, we used the ATR_XX register to control the TX/RX Switch pin, since the radio is set to always be receiving in the current implementation of OAI for the USRP X410 [140]. EVK02001 is set to TX mode when the TX/RX switch pin is pulled to logic high and to RX mode when it is at ground level.

`usrp_spi_sivers_select_beam_id_tx_rx`, the function that is called every time a beam switch is to occur, calls the built-in UHD command `spi_ref->write_spi()`⁷ twice to write the new beam IDs into the EVK02001 registers `bf_tx_awv_ptr` and `bf_rx_awv_ptr`, i.e. changing both the TX and RX beam IDs.

3.4.2 Beam Management for 5G-NR

At the time of writing, OAI does not support beam management for 5G-NR FR2 networks, which is an important aspect of communication at mm-wave frequencies due to their physical characteristics (*cf.* Sections 2.2 and 2.4). Downlink-based beam management in 5G-NR is implemented by sending SSB control signals over various gNB antenna beams to identify viable gNB-UE beam combinations for communication. For 5G-NR, a maximum of 64 SSBs can be scheduled within a group of SSBs, called *Synchronization Signal Burst (SS Burst)*, which implies that at most 64 beams can be covered within an SS Burst. While SSBs and the framework to switch the beam based on the performance metrics for each beam after a sweep have been implemented in OAI, all current 5G-NR FR2 configurations only schedule a single SSB for IA over a predetermined beam and do not integrate beam switching capabilities of codebook-based phased antenna array transceivers. OAI provides configuration files for various 5G-NR bands and hardware configurations, in which the following variables concern SSBs:

- `ssb_PositionsInBurst_Bitmap`: Defines the SSB transmission pattern for up to 64 SSBs as a bitmap, where 0 and 1 indicate whether an SSB is disabled or enabled for transmission, respectively.
- `ssb_periodicityServingCell`: Defines the periodicity of the SS Burst.
- `set_analog_beamforming`: Enables analog beamforming using codebook-based antenna array transceivers.
- `beam_duration`: Defines the minimum duration of a beam in number of slots.

⁷Two other built-in UHD commands, `spi_ref->read_spi()` and `spi_ref->transact_spi()`, also perform a write operation, but incur an additional delay in the order of 1 ms since they are also reading back from the Serial Data In line, which is not desired.

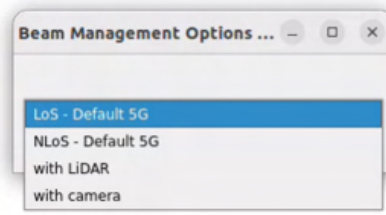


Figure 3.11: The dropdown menu with beam management options for OAI.

- `beam_weights`: Maps the SSBs to the beam IDs of the antenna array transceiver codebook.

We enable the transmission of multiple SSBs within an SS Burst and map the SSBs to the codebook-beams of the EVK02001 antenna array via a new configuration file for the 5G-NR band n257 at the gNB. The implementation and verification details thereof are out of the scope of this thesis.

3.4.3 Sensor Integration with OAI

To enable sensor-aided beam management for OAI, we implemented a flexible framework that can be extended for use with further sensor modalities. The current iteration of the framework utilizes two sensor modalities: (1) the LiDAR point cloud and (2) the camera image. Object recognition models are run in real time on the point cloud and image streams within ROS 2. Then, the list of detected objects are released on a ROS 2 topic for each sensor modality, namely the topic `/point_cloud_object_detection/object_list` for the objects detected on the LiDAR point cloud and the topic `/zed/zed_node/obj_det/objects` for the objects detected on the camera image. These lists contain the distance and angle of the object with respect to the point of origin on the virtual coordinate system.

A Python node within the same Docker container that runs an MQTT [141] server and PyQt [142] application listens to these two ROS 2 topics and retrieves distance and angle offset information of the detected objects. Then, it calculates whether these objects are actively obstructing, or about to obstruct, the LoS communication link with a simplistic formula that is optimized for the environment. If one of them is found to do so, the node sends a message over MQTT that dictates OAI to switch to the backup/NLoS communication link. If the node ceases to detect an object in the safe-zone, it sends a message over MQTT that dictates OAI to switch to the main/LoS communication link. An MQTT client implementation, namely `MQTTAsync` from the Paho MQTT project [143], is integrated into the OAI RAN to receive the messages from the Python node, upon which necessary action is taken, i.e. beam switch. The antenna array beams for the LoS and NLoS communication links are hardcoded on both the MQTT Python node and the OAI RAN software for the specific scenario. The algorithm is designed so that potential blockages are preemptively detected and the beam is changed before the obstacle blocks the LoS link, ensuring that the communication performance is not significantly affected.

The PyQt application enables the real-time selection of one of four beam management options via a dropdown menu, as seen in Figure 3.11: LoS - Default 5G, NLoS - Default 5G, with LiDAR, and with camera. The first two do not change the

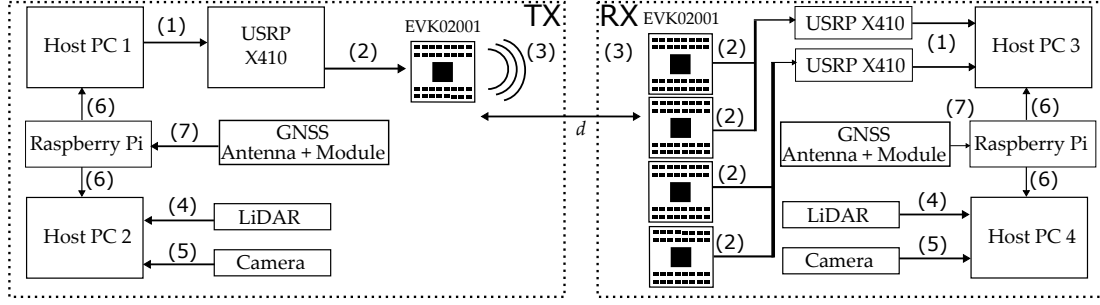


Figure 3.12: Block diagram for the fast-sweeping measurement platform with connection types and signals: (1) samples and commands, (2) I/Q baseband signal, (3) RF signal ($f_c = 27$ GHz), (4) 2048x128 point cloud, (5) 1080p30 video stream, (6) position information and time synchronization packets, (7) position information and PPS signal

beam based on sensor input and stay on the designated LoS and NLoS beams, whereas the other two perform beam management based on the aforementioned safe-zone-based scheme.

3.5 Implementation of Testbed 2: Fast-Sweeping Measurement Platform with Multiple Sensor Modalities

This testbed is used to capture RF and multi-modal sensor measurements to obtain a better understanding of the site-specific propagation characteristics of mm-waves. The data captured with this testbed is to be used to train machine learning/deep learning models for sensor-aided beam management and to develop ray tracing models.

Figure 3.12 shows the block diagram of the components that make up the transmitter (TX) and receiver (RX). At the TX, Host PC 1, running the GNU Radio flowgraph; Host PC 2, running the Docker container for sensors; a USRP X410; and a Raspberry Pi 4, running the GNSS-based time server, are all connected to each other over a Gigabit Ethernet switch. Packets related to time synchronization are transmitted and received between each host PC and the Raspberry Pi. Host PC 1 sends I/Q samples and various commands, such as those for antenna control, over Ethernet to the USRP. Host PC 2, equipped with an NVIDIA RTX 4070 GPU, is connected to the ZED 2i camera via USB 3.0 and to the OS-1 LiDAR via Gigabit Ethernet, which is then converted to 1000BASE-T before reaching the OS-1. The USB cable carries a stream of 1080p camera images at 30 fps and other data, whereas the Ethernet cable carries LiDAR point clouds of 2048x128 resolution at approximately 10 Hz, accompanied by metadata. The EVK02001 is connected to the RF port of the USRP X410 via one SMA cable and one MOLEX cable.⁸ The SMA cable carries I/Q samples to be transmitted from the USRP to the EVK02001, and the MOLEX cable carries SPI signals in both directions to read from/write to internal registers of the EVK02001. A high-speed 2 TB solid-state drive (SSD) is connected to Host PC 2 for the storage of the ROS 2 bags with the sensor data. The GNSS breakout board, to which the GNSS antenna is connected via the SMA port, is connected to the Raspberry Pi 4 via the 40-pin GPIO header. The breakout board sends the content of the received GNSS packets to the Raspberry Pi 4 via UART and the PPS signal over a GPIO pin.

⁸The EVK02001 is also connected to Host PC 1 over USB for the initial configuration.

At the RX, Host PC 3, running the GNU Radio flowgraphs; Host PC 4, running the Docker container for sensors; two USRP X410s; and a Raspberry Pi 4, running the GNSS-based time server and recording GNSS data, are all connected to each other over a Gigabit Ethernet switch. Packets related to time synchronization are transmitted and received between each host PC and the Raspberry Pi. Host PC 3 receives I/Q samples from the USRPs and sends various commands, such as those for antenna control, over Ethernet. Host PC 4, equipped with an NVIDIA RTX A2000 GPU, is connected to the ZED 2i camera via USB 3.0 and to the OS-1 LiDAR via Gigabit Ethernet, which is then converted to 1000BASE-T before reaching the OS-1. A high-speed 2 TB SSD is connected to Host PC 4 for the storage of the ROS 2 bags with the sensor data. Two EVK02001s are connected to each USRP X410 over one SMA cable and one MOLEX cable each.⁹ Channels 0 and 3 are grouped together on one USRP, while channels 1 and 2 are grouped together on the other. The SMA cables carry the received I/Q samples to the USRP, and the MOLEX cables carry SPI signals in both directions to read from/write to internal registers of each EVK02001. All components are mounted on the Hunter 2.0 robot, which is used to move the RX during some measurements, in addition to transporting the RX setup. All connections to both host PCs are made via USB Type-C to Gigabit Ethernet + USB-A connectors, as both are laptops that only have USB Type-C connectors on their motherboards.

We utilize two PCs on both the TX and RX, as both the GNU Radio flowgraphs and Docker containers are highly resource-intensive and time-critical programs. Preliminary tests with one host PC for each of TX and RX have revealed timing issues, especially with the received samples, which would result in errors during the matching of TX beam IDs and RSS values in post-processing (*cf.* Section 3.5.3). Therefore, the workload is split between two host PCs to ensure correct operation and timing.

3.5.1 Implementation of Fast Beam Sweeps

Analyzing the platform in [84] and its performance revealed that a full sweep¹⁰ took 34 seconds for a 90° sector, and a sweep of the entire azimuth plane took 160 seconds. This sweep duration would prevent us from capturing the effects of propagation events stemming from mobile agents, such as temporary blockages and reflections. Therefore, we set out to decrease the sweep duration of the platform. While the TX was observed to be able to operate faster with very few USRP late packet warnings, the RX showed vulnerabilities in the form of failing to decode received packets. This is attributed to the overhead associated with the packetized link with many resource-intensive operations, such as flow control, symbol/frame synchronization, payload modulation/demodulation, and encoding/decoding. As the platform with the packetized link would prevent us from speeding up the sweeps substantially, we developed a new platform that would be able to sweep the entire azimuth plane in **one second**, based on some components of the analyzed platform. The sweep duration of one second would allow us to capture dynamic propagation events stemming from mobile agents in the propagation environment and the mobility of the RX itself, something the analyzed platform would not have been able to achieve. Instead of using a packetized link to send the TX beam ID in a packet, our platform relies on precise time synchronization to match TX beam IDs with RSS and RX beam ID logs in post-processing. This required additional implementation effort to achieve a level of time

⁹All EVK02001s are also connected to Host PC 4 over USB for the initial configuration.

¹⁰A sweep that captures all beam pair links (BPLs) in a sector.

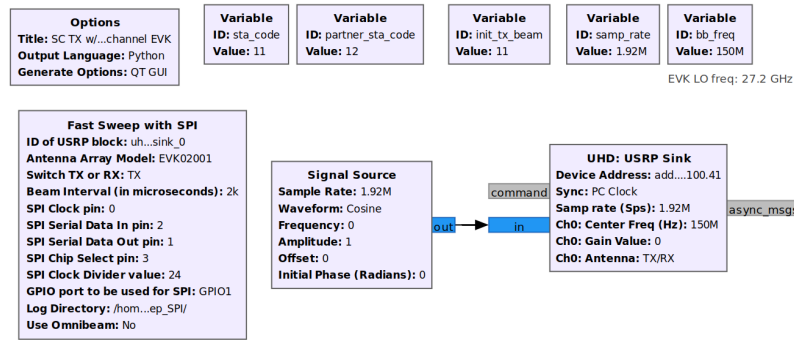


Figure 3.13: The screenshot of the GNU Radio flowgraph for the TX.

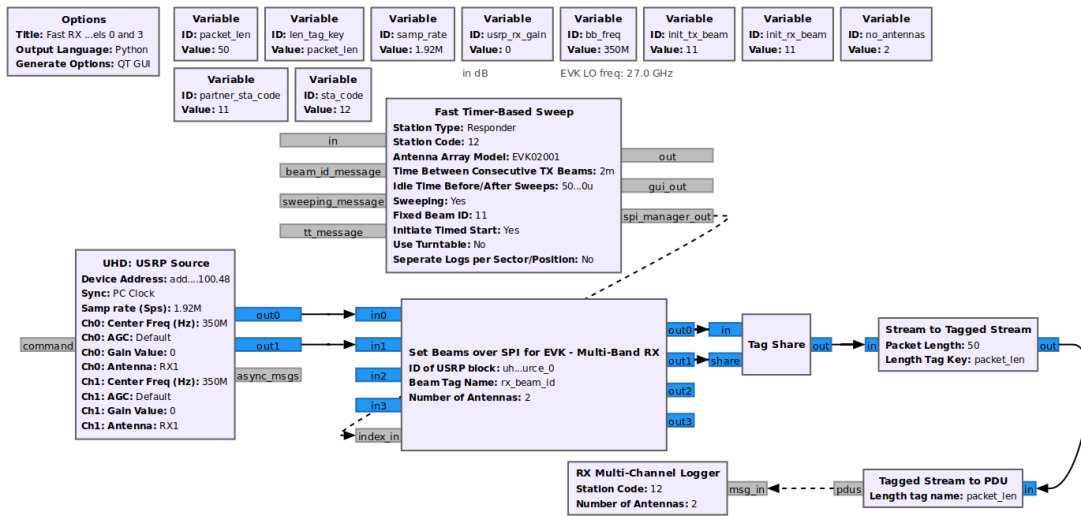


Figure 3.14: The screenshot of the GNU Radio flowgraph for the RX.

synchronization at the host PCs, which could not be achieved with the default Network Time Protocol (NTP) implementation in Ubuntu.

The GNU Radio flowgraph for the TX is depicted in Figure 3.13. The flowgraph for the TX consists of three blocks: a Signal Source block that generates a sinusoidal wave, a USRP Sink block that takes that sinusoidal wave and transmits it via the USRP X410 at the indicated baseband frequency, and an OoT Fast Sweep with SPI block that changes the TX beam at the EVK02001 over SPI at a regular interval and logs the timestamps of the beam switches in a comma-separated values (CSV) file.

The GNU Radio flowgraph for the RX is depicted in Figure 3.14. The flowgraph for the RX consists of six blocks: an OoT Fast Timer-Based Sweep block that changes the RX beam at a regular interval via timers, a USRP Source block that interfaces the signal received at the USRP X410 with GNU Radio, an OoT Set Beams over SPI for EVK - Multi-Band RX block that performs a variety of tasks, a Tag Share block that adds the tags from one stream to the other, a Stream to Tagged Stream block that converts a regular stream to a tagged stream, a Tagged Stream to PDU block that converts a tagged stream to a protocol data unit (PDU), and an OoT RX Multi-Channel Logger block that collects the timestamp,

RSS, RX channel and beam ID information from tags and logs them into a CSV file. The Set Beams over SPI for EVK - Multi-Band RX block (1) receives multiple data streams from the USRP Source block, (2) calculates the RSS from I/Q samples, (3) adds the timestamp, RSS value, RX beam ID, and antenna array ID (0 to 3) as tags to the data stream, and (4) changes the RX beam at the EVK02001 over SPI based on messages coming from the Fast Timer-Based Sweep block. These tasks are collected in a single block to ensure accurate labeling of RSS measurements and prevent delayed timestamping, which can occur between blocks due to delays in message passing. The calculated RSS was validated with a Rohde & Schwarz FSW spectrum analyzer. Having observed that the use of wideband orthogonal frequency-division multiplexing (OFDM) signals in GNU Radio leads to stability issues such as the TX throwing underflows, which indicates that the host PC cannot generate samples fast enough to be consumed by the USRP, and the RX throwing overflows, which indicates that the USRP drops samples as its buffers are full [144], a single-carrier (SC) signal is transmitted and received.

To achieve the target of one second per full sweep, we set the TX beam duration as 2 ms. Our tests have shown that the TX operation was stable for this beam duration, but decreasing the beam duration any further resulted in late packets at the USRP, which disrupt the transmission timing. For each RX beam, we sweep through the 21 pencil beams in the codebook of the EVK02001 antenna array. However, the measurements taken immediately after the RX beam switch are unreliable due to the RX antenna array requiring some time to stabilize and samples possibly getting dropped around beam switches. Therefore, we add a headroom of 3 ms, which corresponds to $1.5 * \text{TX beam duration}$, resulting in an RX beam duration of $21 * 2 + 3 = 45$ ms. The added headroom allows us to remeasure the RSS for the TX beam that coincided with the RX beam switch and account for minor timing issues at the TX. The RX sweeps through the 22 azimuth beams in the codebook of the EVK02001, i.e. the omnidirectional beam and 21 pencil beams, which results in a full-sweep duration of $22 * 0.045 = 0.99$ s for a 90° sector.

3.5.2 Multi-Antenna Support over SPI

In order to be able to perform a 360° azimuth sweep in one second, we deploy four EVK02001 antenna arrays on the RX, one for each 90° sector. This is in contrast to [84], where the azimuth sectors are covered by mechanically steering the antenna arrays with a turntable once the measurements in a sector are complete, which incurs a delay of 6 seconds between each sector. While the USRP X410 GPIO API User Manual states that the X4x0 models support up to four SPI peripherals [138], we have run into a variety of errors/bugs during our attempts to control four EVK02001s from the same USRP X410, such as the error that states that the board only supports up to two peripherals. Therefore, we have resorted to using two USRP X410s, each controlling two EVK02001s. Despite the availability of in-tree GNU Radio blocks to control USRPs, the SPI functionality within UHD is not available in GNU Radio by default. OoT blocks that make use of the SPI functionality built into UHD must include the standalone UHD library at compilation and enforce UHD version 4.2 or later, which is explained in Appendix B.

The port and pin settings for each SPI peripheral, i.e. EVK02001, are configured at the beginning of the execution of the flowgraph within the Set Beams over SPI for EVK - Multi-Band RX block. The physical connections between the SPI ports of the EVK02001s and the front-panel GPIO port of the USRP X410 are depicted in Figure 3.15

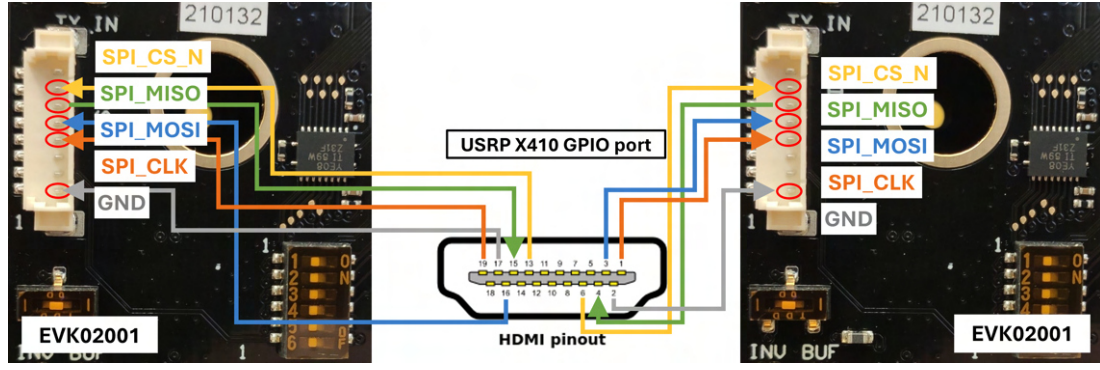


Figure 3.15: Pin connections between the EVK02001s and the USRP X410 for the RX of the measurement platform.

for each USRP on the RX¹¹. Each USRP receives over two channels, each connected to one EVK02001. The received I/Q samples, which are transported to the host PC over Gigabit Ethernet, are accessed from the USRP Source block in GNU Radio. Simultaneously, the Fast Timer-Based Sweep block triggers a beam switch every 45 ms, informing the Set Beams over SPI for EVK - Multi-Band RX block via message passing. Upon receiving the beam switch message, the Set Beams over SPI for EVK - Multi-Band RX block issues a command over SPI to each EVK02001, which changes the contents of the `bf_rx_awv_ptr` register of the EVK02001, changing the RX beam ID. Both USRPs are programmed to start receiving and sweeping at the same time by the GNU Radio flowgraphs. Therefore, all four EVK02001s simultaneously sweep their sector in one second, making the effective 360° azimuth sweep duration one second, an improvement of **two orders of magnitude**.

3.5.3 Time Synchronization Between TX and RX Host PCs

In this testbed, the RX does not have knowledge of the TX Beam ID during the measurement. Instead, the TX Beam ID switch times are logged at Host PC 1 and matched with the RX logs at Host PC 3, which include the RSS values and RX Beam IDs, in post-processing. To ensure accurate matching of TX and RX logs, we implement a time synchronization mechanism on both the TX and RX. As the TX beam changes every 2 ms, the host PCs should be synchronized within less than 1 ms of each other for accurate matching. The Network Time Protocol (NTP), the default time synchronization algorithm used in many operating systems, including Ubuntu¹², generally has a delay between 5 and 100 ms [146], which is one to three orders of magnitude larger than our requirement. Therefore, we decided to use the Precision Time Protocol (PTP), first released as IEEE Standard 1588-2002, which supports sub-μs accuracy within local area networks [147]. PTP utilizes a clock distribution architecture: a *timeTransmitter*¹³ acts as the source of time for all other clocks/devices, whereas a *timeReceiver*¹⁴ sets its clock in accordance with

¹¹A similar wiring is used at the TX, involving only the pins on the right-hand side of the diagram.

¹²The time synchronization daemon used by default in Debian and its downstream Ubuntu is `systemd-timesyncd` [145], which implements Simple Network Time Protocol (SNTP), a simpler version of NTP.

¹³Also known as a *master*. An amendment to IEEE 1588-2019 [148] defines alternatives to the master-slave terminology.

¹⁴Also known as a *slave*. See footnote 13.


```

Every 1,0s: cat /var/run/ptpd2.status      lnets-5531-4: Tue Nov  4 15:30:50 2025
Host info      : lnets-5531-4, PID 5392
Local time     : Tue Nov 04 15:30:50 CET 2025
Kernel time    : Tue Nov 04 14:30:50 GMT 2025
Interface      : eth0
Preset         : slaveonly
Transport      : ipv4, multicast
Delay mechanism : E2E
Sync mode      : TWO_STEP
PTP domain     : 42
Port state     : PTP_SLAVE
Local port ID  : c84bd6fffe03a33c(unknown)/1
Best master ID : dca632fffe7999d1(unknown)/1
Best master IP : 192.168.100.141
GM priority    : Priority1 128, Priority2 128, clockClass 13
Time properties : ARB timescale, tracbl: time N, freq N, src: INTERNAL_OSCILLATOR(0xa0)
UTC properties  : UTC valid: N, UTC offset: 0
Offset from Master : 0.000054011 s, mean -0.000007268 s, dev 0.000166154 s
Mean Path Delay  : 0.000336377 s, mean 0.000327935 s, dev 0.000002488 s
Clock status    : in control
Clock correction : 28.210 ppm, mean 27.704 ppm, dev 0.524 ppm
Message rates   : 1/s sync, 1/s delay, 1/2s announce
TimingService   : current PTP0, best PTP0, pref PTP0
TimingServices  : total 1, avail 1, oper 1, idle 0, in_ctrl 1
Performance    : Message RX 5/s, TX 1/s
Announce received : 322
Sync received    : 641
Follow-up received : 643
DelayReq sent    : 631
DelayResp received : 629
State transitions : 7
PTP Engine resets : 2

```

Figure 3.18: The output of the command `watch -n1 cat /var/run/ptpd2.status` on a host PC.

PC, displaying statistics regarding the operation of PTPd. The host PC, which is configured as the *timeReceiver* in PTPd, is indicated to be only microseconds behind the Raspberry Pi, which is configured as the *timeTransmitter*. When this system is deployed on all host PCs, all are synchronized within microseconds to the clock of a GNSS satellite¹⁵. Therefore, it can be concluded that the host PCs are synchronized within microseconds of each other, which satisfies our requirement of sub-ms synchronization.

In addition to the verification of time synchronization detailed in the previous paragraph, we empirically verify that our transmitter and receiver systems are time-synchronized. To verify accurate time synchronization between the transmitter and receiver, we conduct measurements in a controlled environment, our laboratory. Initially, we increase the TX beam duration, i.e. time between consecutive TX beam switches, to 100 ms to obtain a baseline pattern of the received RSS over a full TX sweep and fixed RX beam. Figure 3.19a shows the RSS over time at RX beam ID 11 for 22 TX beams, where the TX beam duration is 100 ms. TX beam ID 11 exhibits the highest RSS due to the perfect alignment between RX and TX beams via the LoS, whereas TX beam 4 exhibits the lowest RSS, followed by TX beam ID 0, the omnidirectional beam. With the TX beam ID only recorded at the TX itself and synchronized to the RSS samples in post-processing, Figure 3.19a displays accurate synchronization between the TX and RX, with the TX beam ID switches consistently matching changes in the RSS levels.

In a second measurement, we set the TX beam duration to our target of 2 ms and repeated the aforementioned process in the same environment. Figure 3.19b shows the RSS over time at RX beam ID 11 for 22 TX beams, where the TX beam duration is 2 ms. Once again, TX beam ID 11 exhibits the highest RSS, whereas TX beam 4 exhibits the lowest RSS, followed by TX beam ID 0. The RSS pattern is the same as that observed

¹⁵GNSSs maintain a *system time* based on an atomic clock to meet the requirements for very precise time synchronization. All satellites within a constellation are synchronized to the same *system time* [66].

in Figure 3.19a. Minor jitter that manifests itself as the change in RSS level before the TX beam ID changes can be spotted. This results in a brief period of few samples where the recorded TX beam ID does not match the actual TX beam ID. We account for this mismatch in post-processing by eliminating the samples affected by jitter. To account for such issues, we take between 10 and 20 samples for each TX/RX beam pair, in case some samples need to be discarded.

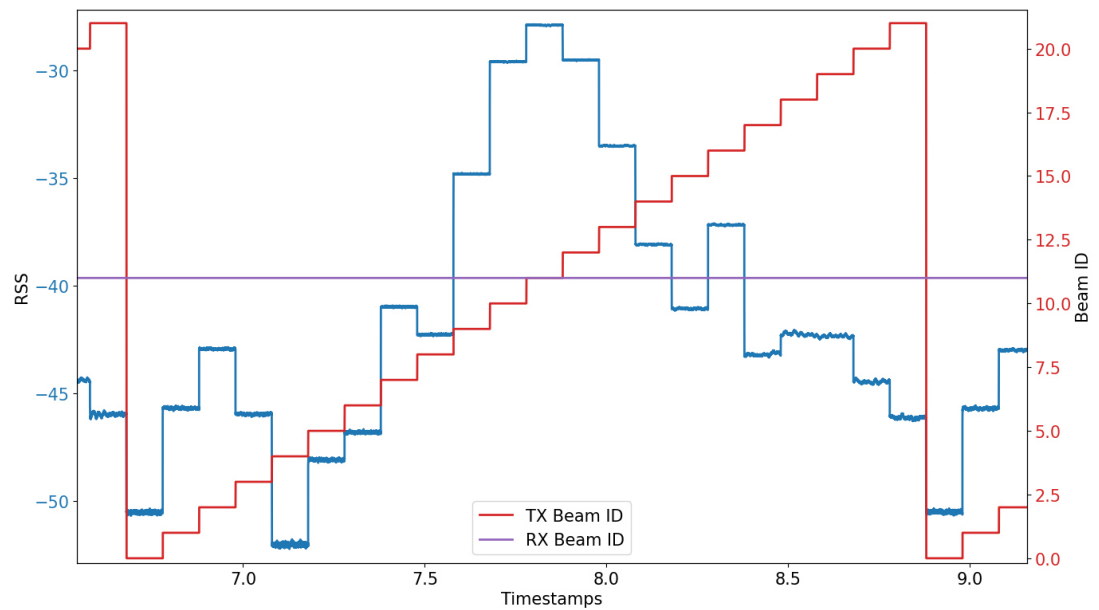
Comparing the measured RSS patterns after synchronization with the TX beam IDs between measurements, we confirm that the same RSS pattern with the same RSS level per TX beam is achieved across several TX beam sweeps, indicating time synchronization and measurement reliability.

3.5.4 Sensor Modalities

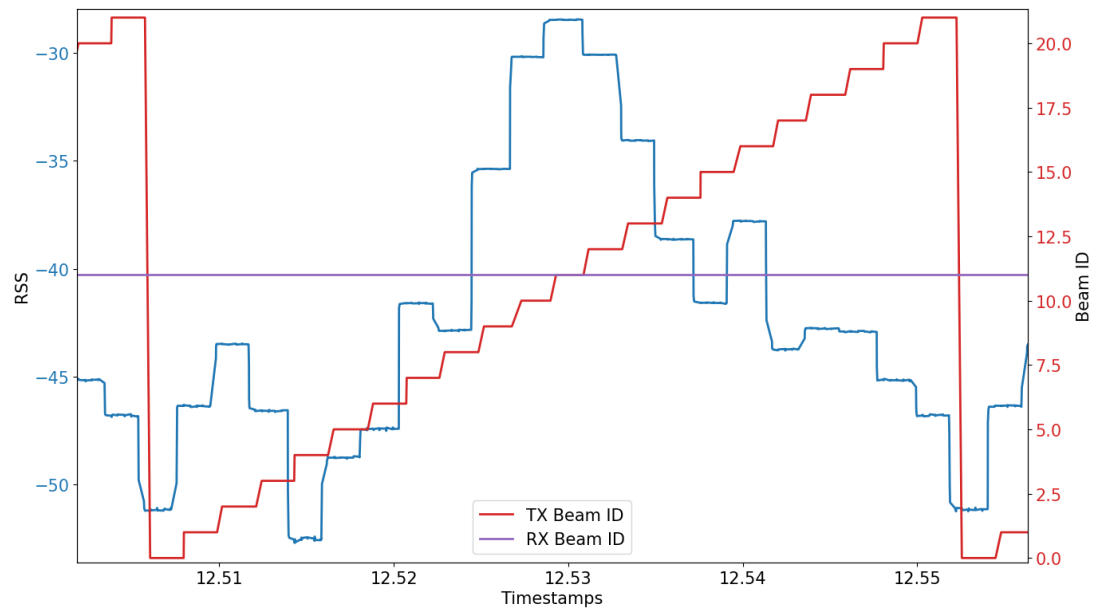
For the measurement testbed, we use a Docker setup similar to the one explained in Section 3.4.3, except for the MQTT functionality. Sensor data for each measurement are recorded into a high-speed SSD in the form of ROS 2 *bags*, structures to record, store, and playback data in ROS 2 [153]. The recorded ROS 2 topics and their content are as follows:

- `/drivers/ouster_lidar/metadata`: Information regarding the OS-1 LiDAR, including the configuration parameters. Only one message per ROS 2 bag.
- `/drivers/ouster_lidar/points`: The point cloud obtained by the LiDAR from the imaging of the environment.
- `/zed/zed_node/rgb/camera_info`: Camera configuration and calibration data.
- `/zed/zed_node/rgb/image_rect_color/compressed`: The compressed version of camera images. Requires decompression before playback.
- `/zed/zed_node/obj_det/objects`: The list of detected objects and their position.

In addition to camera and LiDAR, GNSS data is recorded on the Raspberry Pi 4 at the RX. The Python script for logging GNSS data uses the `gps3` library [154], which provides an interface to access the data available at `gpsd` [155], the daemon that manages GNSS modules connected to the Raspberry Pi. The data received from the GNSS module is accessed from the `gpsd` socket within `gps3`, and the time-position-velocity (TPV) reports, which contain information like time, latitude, longitude, depth, and speed, are logged as they arrive.



(a) Plot for TX beam duration of 100 ms.



(b) Plot for TX beam duration of 2 ms.

Figure 3.19: RSS in dBm, TX Beam ID and RX Beam ID vs. time in seconds for different TX beam durations.

4

Measurement Setup

4.1 Testbed 1: OAI-based 5G-Compliant Testbed with Environmental Awareness

To demonstrate the performance of sensor-aided beam management in a 5G-NR system, Testbed 1 was set up in the laboratory of the institute. The distance between the gNB and UE was 2.5 m. A reflective surface was placed 1 m away and parallel to the LoS link to facilitate a secondary, NLoS link. The measurement setup is visualized in Figure 4.1. The EVK02001 antenna arrays on both setups were placed at a height of 1 m. The antenna array register settings, as declared in Table 4.1, were optimized for the specific distance and multipath environment. The registers that are not referenced in Table 4.1 were left with their default values. Only a limited number of antenna elements, 4 at the gNB and 2 at the UE, as opposed to the total 16, could be used, as the signal was observed to become distorted as the number of antenna elements used increased, resulting in a failure during initial access. The locations of the antenna elements used are shown on Figure 4.2. We opted to use a pencil beam instead of the omnidirectional beam at the UE, as the omnidirectional beam proved to be too weak to associate with the gNB. We analyzed the empirical radiation patterns and chose to use beam ID 19 with respect to the location of the reflective surface that would facilitate the NLoS link. At the gNB, beam 11 was used for the LoS link, and beam 20 was used for the NLoS link. A safe-zone, as illustrated in Figure 4.1, was defined based on the dimensions of the setup. For the beam management options with LiDAR and with camera, the Python node with the MQTT server was configured to publish a message that triggered a switch from the LoS to NLoS link whenever a mobile blockage appeared in the safe-zone, and similarly, a message that triggered a switch from the NLoS to LoS link whenever the mobile blockage disappeared. The sensor data was

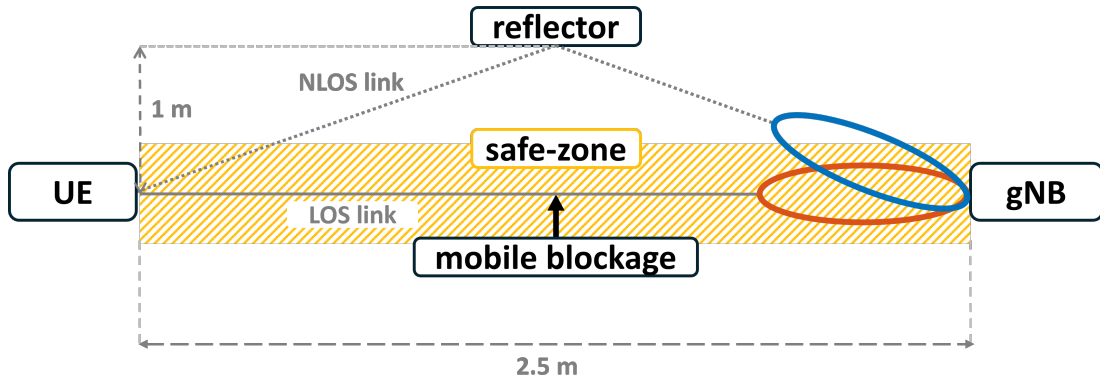


Figure 4.1: The diagram visualizing the measurement setup for Testbed 1. Important components are indicated on the figure.

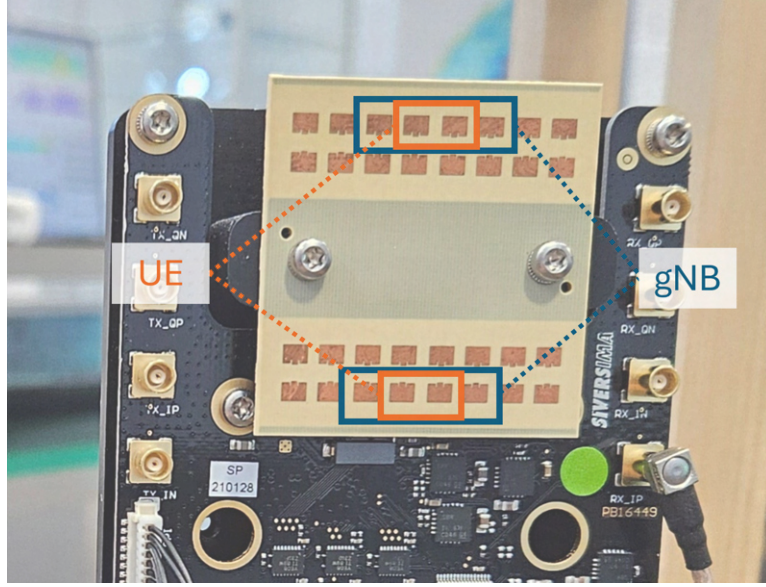


Figure 4.2: The antenna elements of the EVK02001 antenna array used for measurements in the gNB and UE of Testbed 1. The elements on the upper half are for TX, those on the lower half are for RX.

recorded for later analysis, and the performance metrics for the communication link were extracted from a JavaScript Object Notation (JSON) file automatically created at the gNB. The empirical radiation patterns for different combinations of antenna elements, which were measured in our laboratory, can be found in Appendix C.

Table 4.1: Antenna array settings used during the measurements for Testbed 1 for the gNB and UE.

Register Name	gNB	UE
trx_tx_on	0x1f05a0	0x1f0180
trx_rx_on	0x1f05a0	0x1f0180
tx_gain_ctrl_bfrf	0x44	0x44
rx_gain_ctrl_bfrf	0x44	0x44
rx_gain_ctrl_bb1	0x77	0x77

4.2 Testbed 2: Fast-Sweeping Measurement Platform with Multiple Sensor Modalities

The first measurement campaign, which served as a validation of the testbed's operation, was conducted in front of the institute building at Kackertstraße in Aachen-Laurensberg on 29th August 2025. The layout of the measurement environment and the locations can be seen in Figure 4.3. The TX was mounted at 3 m height on a platform above the entrance. The antenna array was tilted by an angle of $\theta_{TX} = -10^\circ$ in the elevation plane and steered towards the RX positions in the azimuth plane. The bounds of the resulting sector are

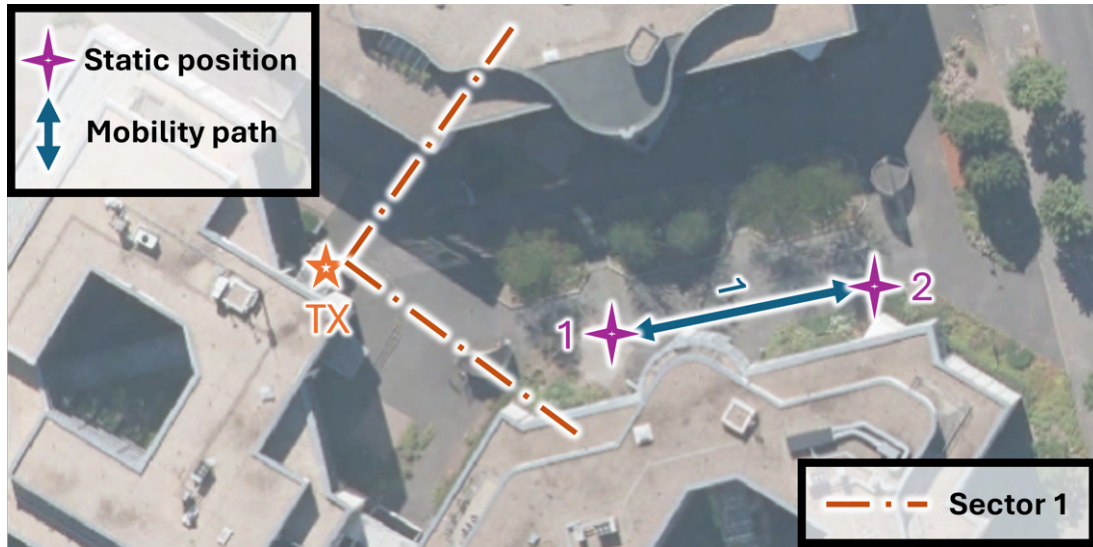
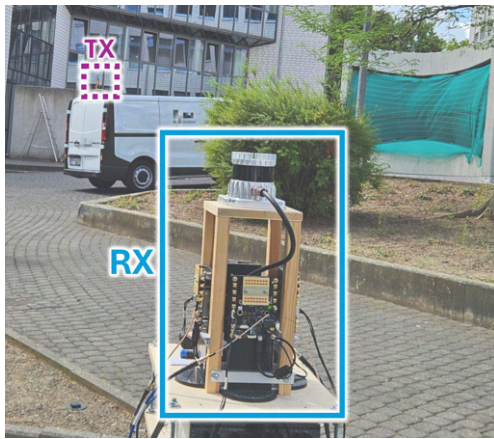


Figure 4.3: The location and sector of the TX, static RX positions and mobility path for the measurements with Testbed 2 in front of the institute, indicated on the satellite image.



(a) Photo taken from the RX.



(b) Photo taken from the TX.

Figure 4.4: Photographs from the measurements at the institute for POS1. The RX and TX are indicated on each photo with solid and dotted frames respectively.

outlined in Figure 4.3. The RX was placed at two static positions to collect measurements, indicated on Figure 4.3, with regard to pedestrian activity and multipath environment. A third measurement was taken for a mobility scenario where the robot, on top of which the RX is mounted, was moving at typical walking speed along the walkpath indicated on Figure 4.3. Sensor data was collected alongside RSS measurements over the entire azimuth plane to explain the site-specific propagation behavior of mm-waves. Figure 4.4a shows a photograph taken from the RX at POS1, and Figure 4.4b shows a photograph taken from the TX for the same RX position.

The preliminary findings from the first measurement campaign were analyzed to verify the testbed functionality, upon which a second measurement campaign was conducted in the vicinity of the SuperC administrative building and main library of RWTH Aachen

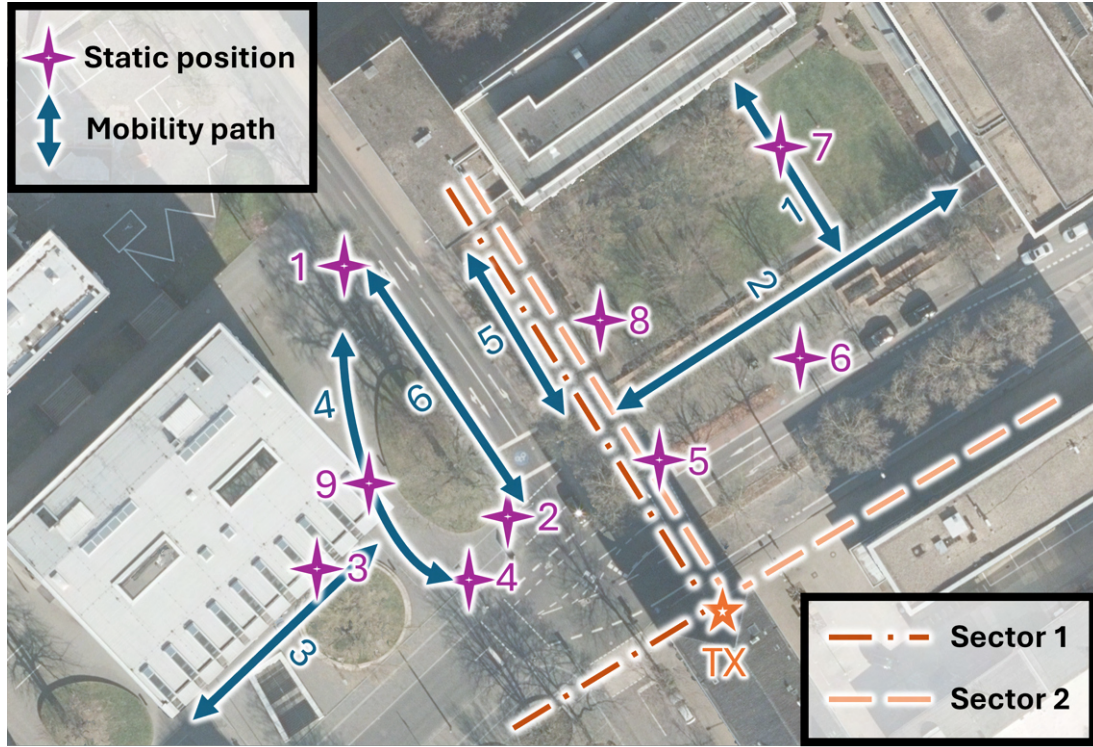


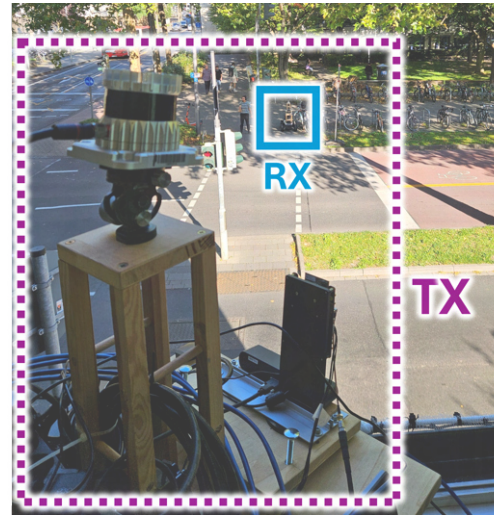
Figure 4.5: The location and sectors of the TX, static RX positions and mobility paths for the measurements with Testbed 2 in front of SuperC and the library, indicated on the satellite image.

University in Aachen city center between 15th September and 16th October 2025. The purpose of this measurement campaign was to capture RF measurements with directional TX and RX alongside multi-modal sensor data in a highly urbanized environment to build a dataset, which can subsequently be used to accurately assess the multipath events stemming from the characteristics of the propagation environment and dynamic propagation events, such as blockages, and to develop machine learning/deep learning models for novel beam management applications. The RX was placed at **nine positions** for static measurements with regard to the characteristics of the static propagation environment, such as glass facades acting as reflectors, and prospects of dynamic propagation events stemming from pedestrian, cyclist, and vehicle activity. Furthermore, the RX was moved back and forth at typical walking speed on **six walkpaths** to achieve an understanding of how link opportunities develop throughout pedestrian movement. Measurements at each position and walkpath took approximately three hours. The static positions and walkpaths are indicated on Figure 4.5. For all measurements, the TX was placed on a windowsill on the first floor of the Backsteingebäude across from the main library of RWTH Aachen University, tilted by an angle of $\theta_{TX} = -10^\circ$ in the elevation plane and angled towards either SuperC or the library depending on the location of the RX, as shown with the sector bounds in Figure 4.5. Figure 4.6 shows two photos taken from RX and TX respectively, during the measurement at POS5 at the library. Similarly, Figure 4.7 shows two photos taken from RX and TX respectively, during the measurement at POS1 at SuperC. The different directions in which the TX is tilted in the azimuth domain with regard to the RX

4.2. Testbed 2: Fast-Sweeping Measurement Platform with Multiple Sensor Modalities42

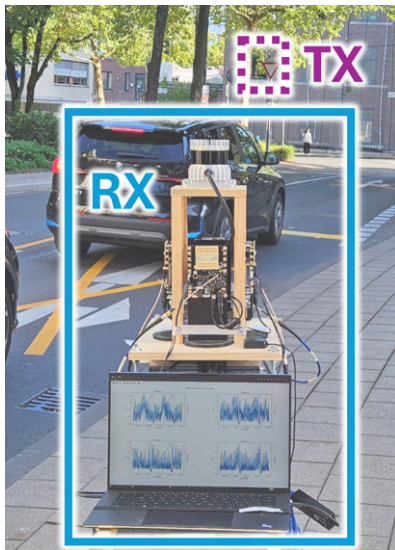


(a) Photo taken from the RX.

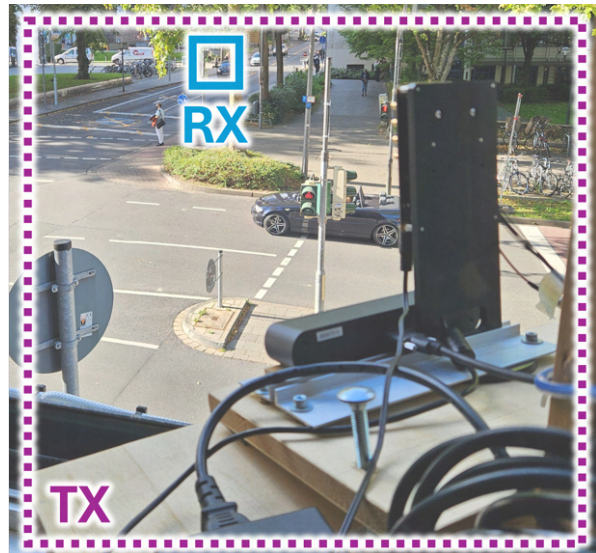


(b) Photo taken from the TX.

Figure 4.6: Photographs from the measurements at the library for POS5. The RX and TX are indicated on each photo with solid and dotted frames respectively.



(a) Photo taken from the RX.



(b) Photo taken from the TX.

Figure 4.7: Photographs from the measurements at SuperC for POS1. The RX and TX are indicated on each photo with solid and dotted frames respectively.

position can be spotted in Figures 4.6b and 4.7b. We aim to release the resulting dataset to the public in the future.

5

Measurement Results and Analysis

In this chapter, we present and analyze the results that have been obtained from our measurements, the details of which have been explained in Chapter 4. The capabilities of sensor-aided beam management within the OAI-based testbed are demonstrated in Section 5.1. The outdoor measurement campaigns conducted with the fast-sweeping measurement platform are evaluated for static RX in Section 5.2.

5.1 Demonstration of Sensor-Aided Beam Management in OAI

The implementation in OAI provides four operation modes for beam management, namely LoS - Default 5G, NLoS - Default 5G, with LiDAR, and with camera. Figure 5.1 shows the RSRP measured at the UE over time for the four aforementioned beam management operation modes. A quick glance reveals a disruption in the link quality for the LoS - Default 5G and with LiDAR options, whereas the link remains relatively stable for the NLoS - Default 5G and with camera options.

Three snapshots of the LoS link taken by the camera mounted at the gNB are provided in Figure 5.2 to assist with the analysis. Figure 5.2a shows the environment for $t \in [0, 15) \cup$

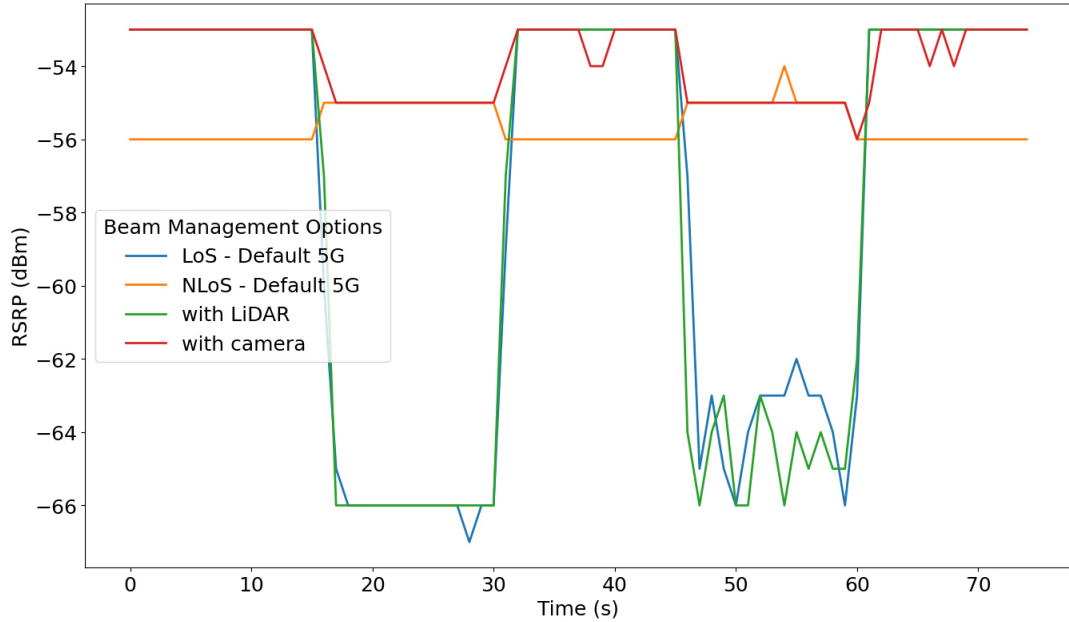


Figure 5.1: RSRP in dBm vs time in seconds for the four beam management options in the OAI-based testbed.

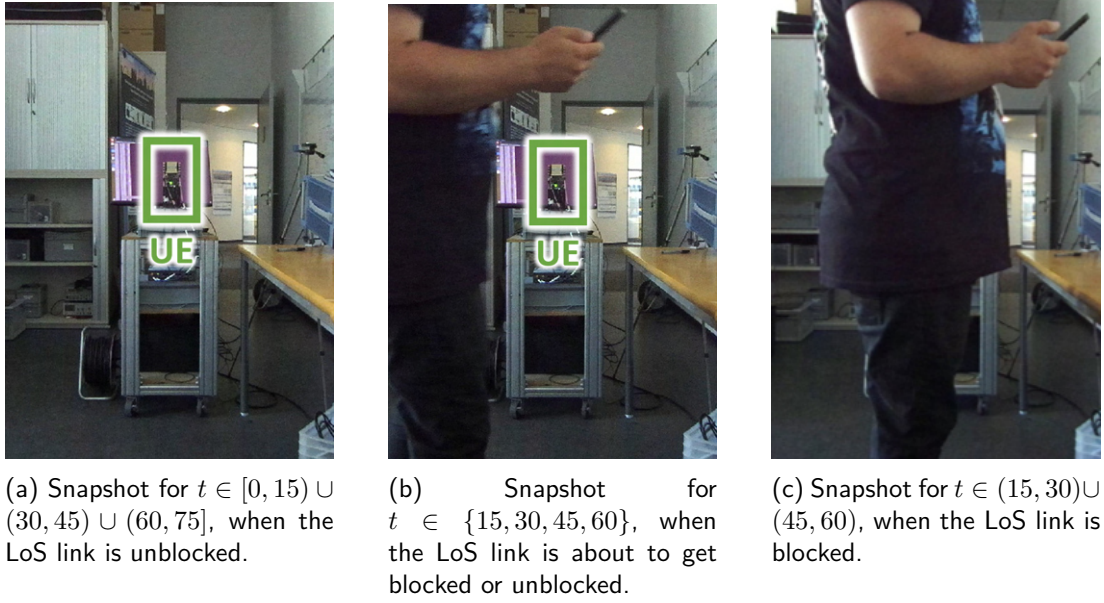


Figure 5.2: Camera snapshots that exemplify the behavior at specific time intervals and instances, taken at the gNB during measurements for the OAI-based testbed. The UE is indicated when visible.

$(30, 45) \cup (60, 75]$, when the LoS link is unblocked; Figure 5.2b shows the environment for $t \in \{15, 30, 45, 60\}$, when the pedestrian is walking into or out of the LoS link; and Figure 5.2c shows the environment for $t \in (15, 30) \cup (45, 60)$, when the pedestrian is blocking the LoS link. For the LoS - Default 5G option, where the gNB always remains on beam 11, a significant drop from -53 dBm to -66 dBm is observed between $t \in (15, 30)$, and an average RSRP of -64 dBm is observed between $t \in (45, 60)$. This occurs because of the pedestrian blocking the LoS link, as seen in Figure 5.2c. The system takes no action to preserve link quality, which results in a perceivable degradation of the quality of communication. For the NLoS - Default 5G, where the gNB always remains on beam ID 20, a slight increase from -56 dBm to -55 dBm is observed for $t \in (15, 30) \cup (45, 60)$. The pedestrian acts as a reflector for the mm-waves instead of a source of blockage, which results in slightly more reflections reaching the UE and increasing the RSRP. For the with LiDAR option, where the beam is supposed to be switched when a blockage around the LoS link is detected on the LiDAR point cloud, a significant drop from -53 dBm to -66 dBm is observed between $t \in (15, 30)$, and an average RSRP of -64 dBm is observed between $t \in (45, 60)$. This behavior matches the one for the LoS - Default 5G option, which indicates that the LiDAR failed to detect the pedestrian blocking the LoS; therefore, the beam switch did not occur. Such behavior has been observed in multiple indoor settings, which indicates that the object recognition model fails to identify pedestrians in the point cloud in indoor scenarios. The reason is likely that the object recognition model was trained for scenarios where the LiDAR sensor was mounted on a car in an outdoor setting/vehicle traffic. In contrast, for the with camera option, where the beam is supposed to be switched when a blockage around the LoS link is detected on the camera image, only a slight decrease from -53 dBm to -55 dBm is observed for the same interval. The RSRP for the with camera option is identical to that in the LoS - Default 5G option for $t \in [0, 15) \cup (30, 45) \cup (60, 75]$ and

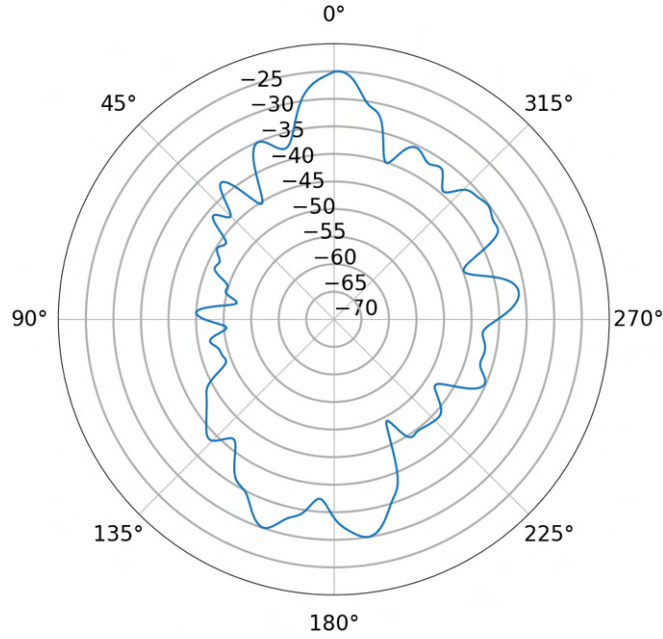


Figure 5.3: Maximum RSS over all TX beams in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for $t = t_0$ at POS1 at the institute.

to that in the NLoS – Default 5G for $t \in (15, 30) \cup (45, 60)$. This indicates that when the LoS is not blocked, OAI uses beam 11, the beam over which the LoS link is established, and when the LoS is blocked, the object recognition model deployed on the camera images detects the pedestrian and triggers a beam switch to beam 20, the beam over which the NLoS link is established, before the RSRP drops significantly. This behavior demonstrates the proactivity of our system to ensure link quality in dynamic propagation environments.

5.2 Sensor-Aided Propagation Analysis for Static Positions

In this section, we analyze the spatial characteristics of the mm-wave channel and corresponding link opportunities at static RX positions. As a rule of thumb, $\phi_{RX} = 0^\circ$ in polar plots is the RX direction which points towards the transmitter, i.e. the LoS direction. The correspondence between RX direction ϕ_{RX} , channel ID and RX beam ID is provided in Appendix D.

We start our analysis with POS1 from the measurement campaign in front of the institute, which provides a simple propagation environment. Figure 5.3 shows the RSS over the entire azimuth plane $\phi_{RX} \in [0^\circ, 360^\circ)$ for one point in time as a polar plot. The RSS for each individual RX beam orientation is the maximum received RSS for that RX beam across all TX beams. The highest RSS was measured at $\phi_{RX} = 0^\circ$, the LoS, as -25 dBm. A high RSS value of -30 dBm was measured at $\phi_{RX} = 160^\circ$ and $\phi_{RX} = 190^\circ$, and another high RSS value of approximately -35 dBm was measured at $\phi_{RX} = 280^\circ$ and $\phi_{RX} = 310^\circ$. These angles provide alternative link opportunities via NLoS propagation paths. RSS values as low as -50 dBm were measured for the area between $\phi_{RX} \in [50^\circ, 115^\circ]$ and also for the area between $\phi_{RX} \in [200^\circ, 270^\circ]$. In order to understand the reasons behind these high and low RSS measurements, the satellite image in Figure 5.4 is examined. The high

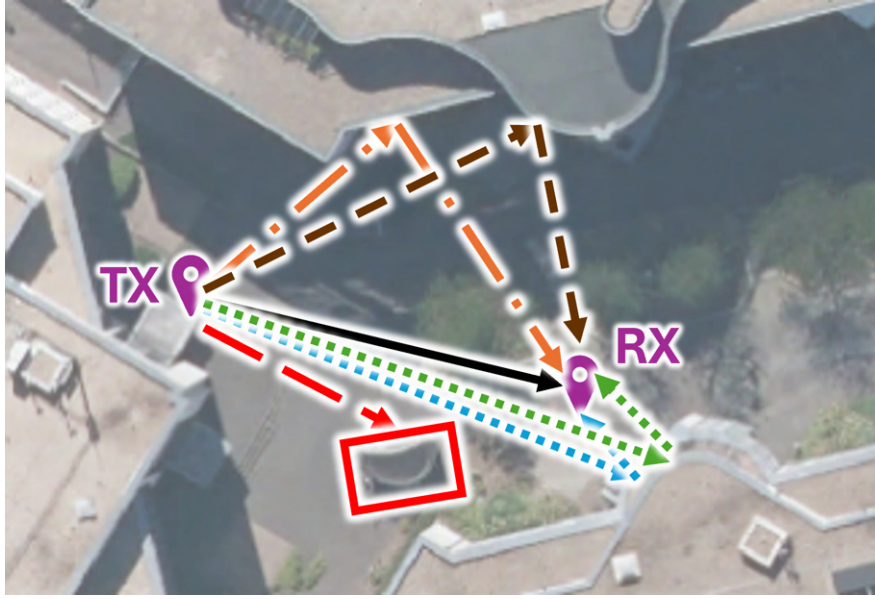


Figure 5.4: The locations of RX and TX, and the propagation events for POS1 indicated on the satellite image of the institute.

RSS measured at $\phi_{RX} = 160^\circ$ and $\phi_{RX} = 190^\circ$ appears to be the result of reflections coming from the glass facade of the building behind the RX, illustrated in blue and green, respectively, whereas the high RSS measured at $\phi_{RX} = 280^\circ$ and $\phi_{RX} = 310^\circ$ appears to be the result of reflections coming from the glass facade of the building across the road from the RX, illustrated in brown and orange, respectively. The low-RSS area between $\phi_{RX} \in [50^\circ, 115^\circ]$ is the result of the concrete structure blocking mm-waves that would have gotten reflected from the glass facade otherwise, illustrated in red, whereas the low-RSS area between $\phi_{RX} \in [200^\circ, 270^\circ]$ is attributed to the lack of reflective surfaces in that area.

We extend our analysis to a more complex environment with more dynamic propagation events such as blockages, which are found at POS7 in front of the library near SuperC. Analyzing the spatial characteristics of the mm-wave channel based on a single time instance, i.e. a full sweep over one second, incorporates propagation effects that are specific to the mobile environment at that time instance, such as blockage of dominant propagation paths or mobile obstacles acting as reflectors that can enable new propagation paths. Figure 5.5 shows the measured RSS maximized over all TX beams over the entire azimuth plane for multiple consecutive beam sweeps over a duration of 300 seconds. A large-scale view of Figure 5.5 shows that the highest RSS was measured at the LoS with -23 dBm, followed by peaks of -34 dBm and -38 dBm at $\phi_{RX} = 40^\circ$ and $\phi_{RX} = 100^\circ$, respectively. A small-scale analysis reveals that propagation behavior was quite similar over time at LoS, $\phi_{RX} = 40^\circ$, and $\phi_{RX} = 100^\circ$. However, there are a few time instances where the RSSs at LoS and $\phi_{RX} = 40^\circ$ were reduced to as low as -39 dBm and -44 dBm, respectively, due to temporary blockage events. The RSS was consistently low for the area between $\phi_{RX} \in [260^\circ, 330^\circ]$ due to lack of reflections. However, the RSS in that area increased up to -27 dBm at $\phi_{RX} = 260^\circ$ at a few points in time, due to temporary

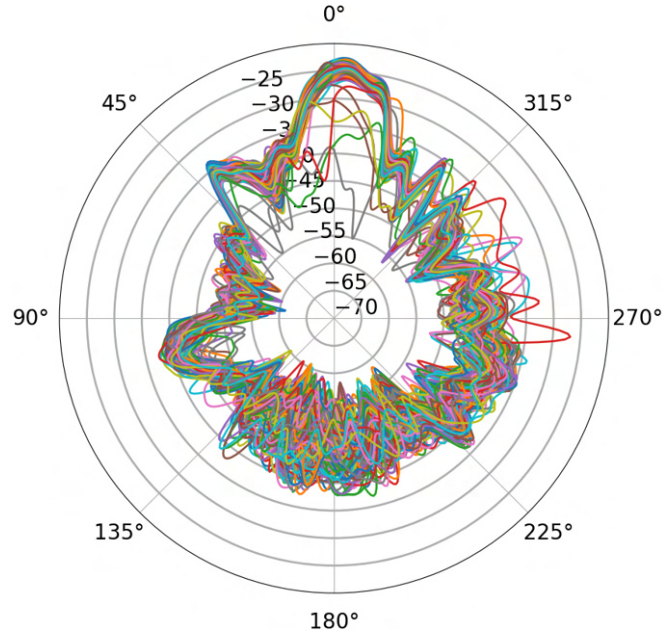


Figure 5.5: Maximum RSS over all TX beams in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for POS7 at the library over 300 seconds.

reflection paths. In contrast, the area between $\phi_{RX} \in [135^\circ, 200^\circ]$ was highly inconsistent, with measurements ranging from -37 to -61 dBm over 300 seconds, possibly due to a highly dynamic propagation environment, such as one with pedestrian activity.

Even though we are able to infer some propagation characteristics from the polar plot in Figure 5.5, it is highly impractical to create such plots for a long measurement duration—in this case, three hours—as it would be even less legible than this plot. Therefore, we introduce the time-averaged polar plot in Figure 5.6, which displays the maximum RSS over all TX beams averaged over the entire duration of the measurement, which is three hours, over the entire azimuth plane. The highest average RSS can be found at the LoS as -25 dBm. Other high RSS averages include -35 dBm and -40 dBm at $\phi_{RX} = 40^\circ$ and $\phi_{RX} = 100^\circ$, respectively. This pattern has already been characterized during the analysis of Figure 5.5. Differently from Figure 5.5, the analysis of Figure 5.6 reveals that the average RSS was not higher than -50 dBm for the area between $\phi_{RX} \in [135^\circ, 225^\circ]$, an area that could not be characterized during the analysis of Figure 5.5, as it exhibited different propagation behavior at different points in time. The time-averaged polar plot smooths out the peaks and dips in RSS caused by temporary propagation events and can therefore be said to represent the propagation characteristics of the "empty"¹ environment.

While the polar plot in Figure 5.6 provides a simple understanding of the propagation characteristics of the "empty" environment, it lacks the angle of departure (AoD) information that is crucial for inferring exact propagation paths. In contrast, Figure 5.7 shows the RSS over the entire azimuth plane averaged over three hours and across several TX beams

¹As in the absence of any sources of temporary reflections and blockages.

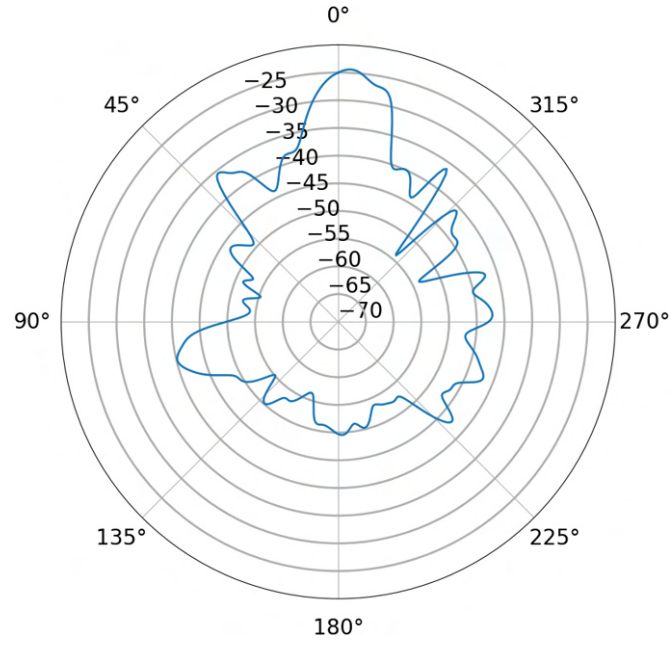


Figure 5.6: Maximum RSS over all TX beams in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for POS7 at the library, averaged over three hours.

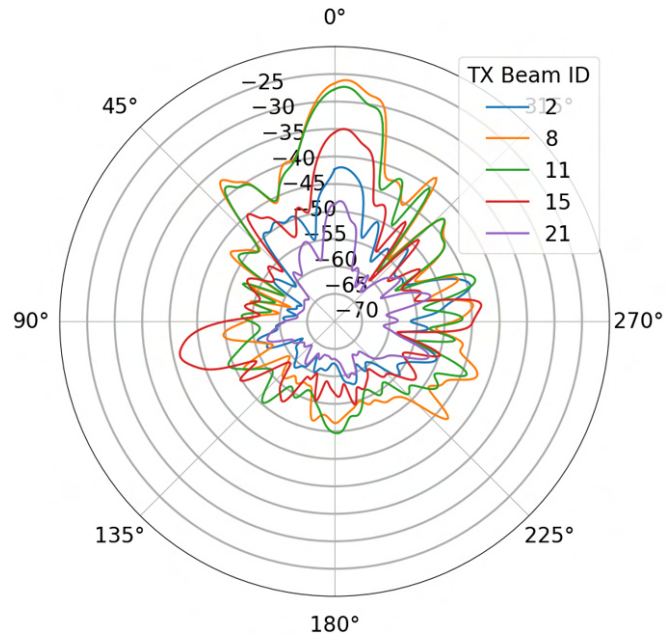


Figure 5.7: RSS in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for POS7 at the library averaged over three hours, across several TX beams.

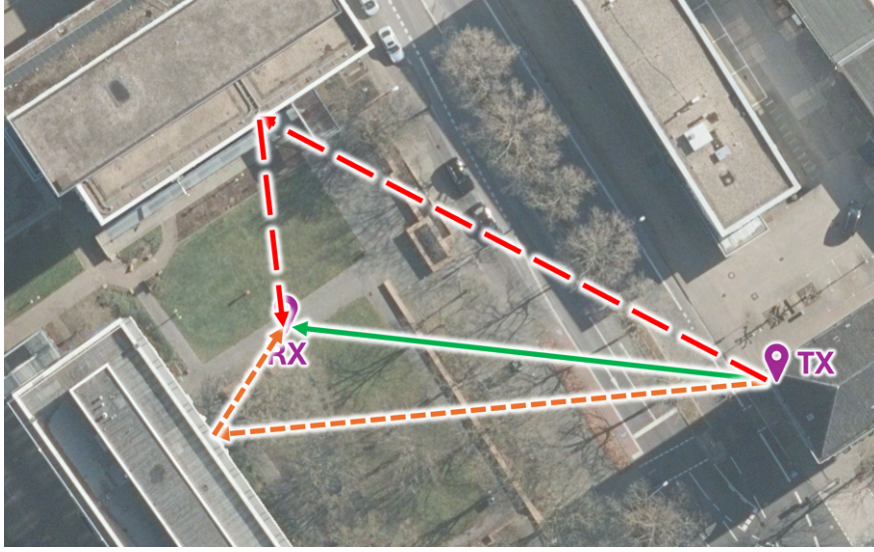


Figure 5.8: Satellite image of the environment for POS7 at the library, with important components and propagation paths illustrated.

as a polar plot. The highest RSS was measured² at the LoS for all³ TX beams, with the highest across all TX beams measured over TX beam 8 as -27 dBm. The highest RSS after the LoS was measured at $\phi_{RX} = 40^\circ$ for TX beams 8, 11, and 15, with the highest among them measured over TX beam 8 as -37 dBm. Another high-RSS area can be found at $\phi_{RX} = 100^\circ$ for TX beam 15, measured as -41 dBm. Yet another high-RSS area can be found at $\phi_{RX} = 230^\circ$ for TX beam 8, measured as -43 dBm. A significant degradation in RSS is observed for scenarios with TX misalignment, with the RSS dropping from -27 dBm over TX beams 8 and 11 to -35 dBm over TX beam 15. In order to understand how the propagation environment affects the examined propagation behavior, we analyze Figure 5.8, which displays the locations of the RX and TX alongside major propagation paths over the satellite image of the measurement site. The reflection at $\phi_{RX} = 100^\circ$, illustrated in red, is the result of reflections coming from the building at the upper left-hand corner in the image. Similarly, the reflection at $\phi_{RX} = 230^\circ$, illustrated in orange, is the result of reflections coming from the building at the lower left-hand corner in the image. No large source of reflections at $\phi_{RX} = 40^\circ$ can be spotted on the image, indicating that the reflections might have occurred due to a smaller object. Another possibility is that the high RSS measurement at $\phi_{RX} = 40^\circ$ might have occurred due to the energy collected by sidelobes. The measurement shown at $\phi_{RX} = 40^\circ$ was made over a beam with a strong sidelobe that points to the LoS, which resulted in the accumulation of energy collected over that sidelobe during the measurement. This, possibly combined with minor reflections at that angle, created results that indicate a viable propagation path at $\phi_{RX} = 40^\circ$, even though there is none.

²Despite being an average of multiple measurements rather than a single measurement, they will be referred to as measurements for the remainder of this chapter, for the sake of simplicity. Since they represent the characteristics of the "empty" environment, they can be assumed to be equivalent to a single measurement from the "empty" environment for all practical purposes.

³As in all TX beams displayed on the plot. This usage applies for the remainder of this chapter.

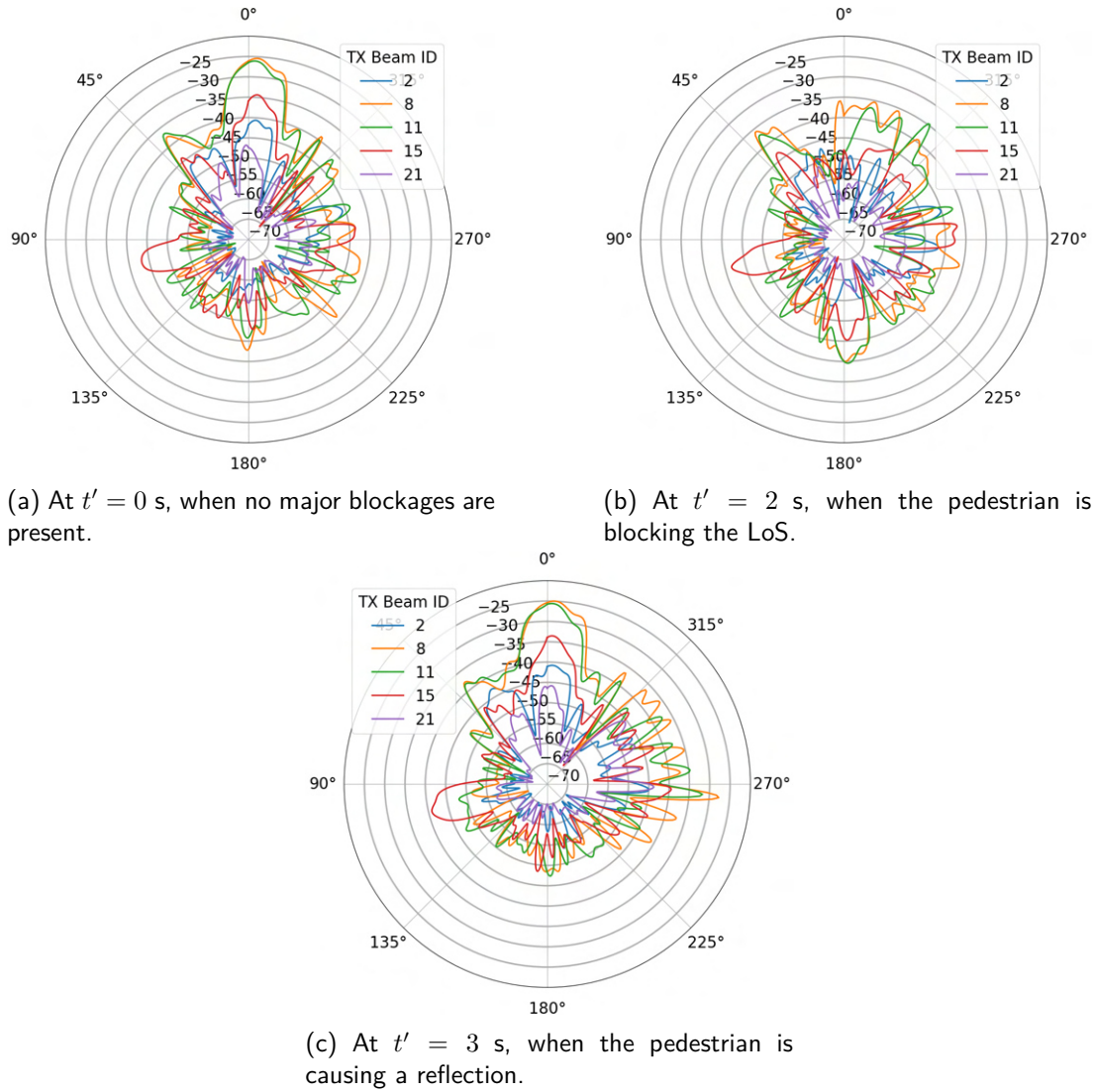
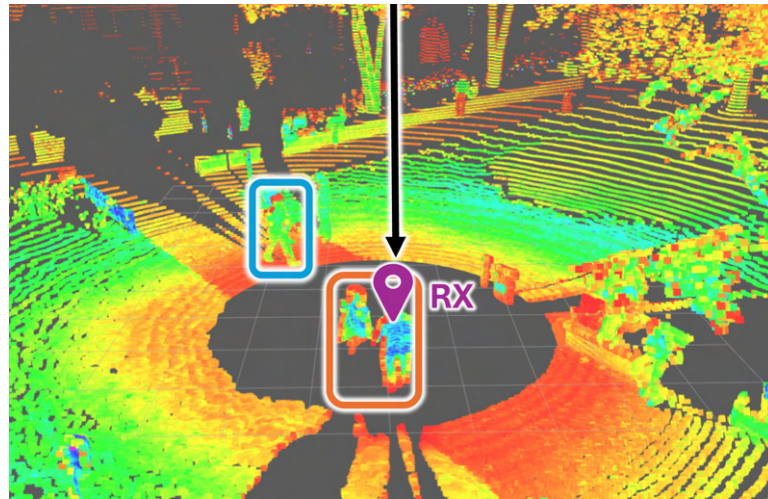
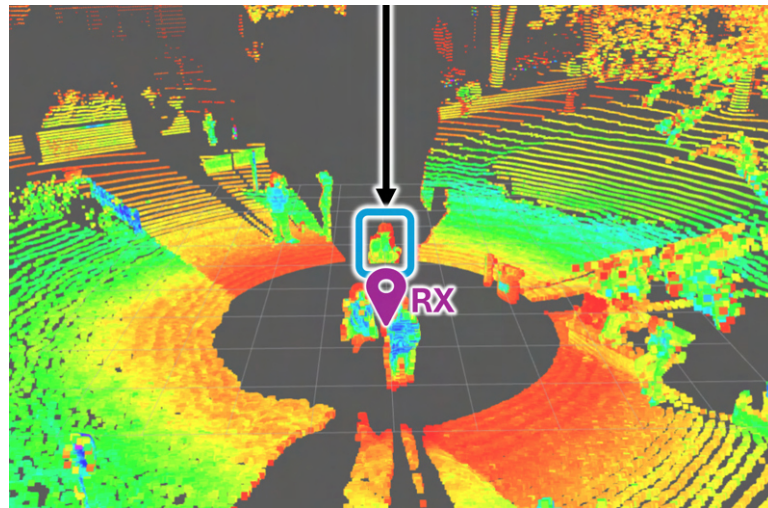


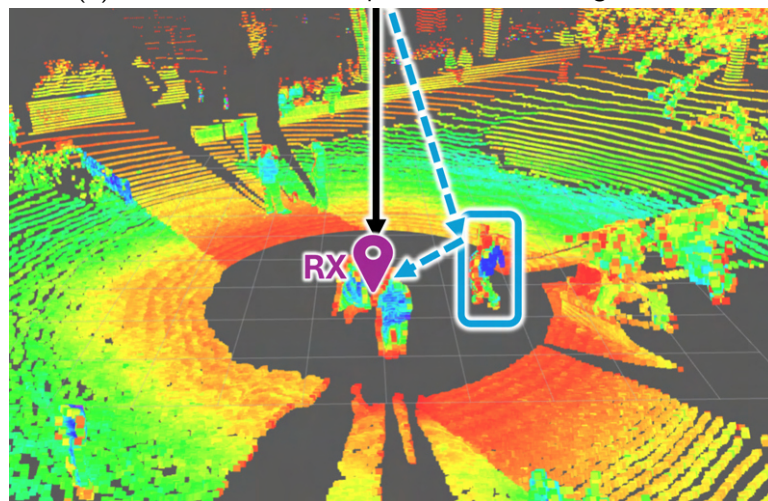
Figure 5.9: RSS in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ across several TX beams for POS7 at the library, at different points in time.



(a) At $t' = 0$ s, when no major blockages are present.



(b) At $t' = 2$ s, when the pedestrian is blocking the LoS.



(c) At $t' = 3$ s, when the pedestrian is causing a reflection.

Figure 5.10: LiDAR point clouds for the measurements in Figure 5.9, with important components indicated. The transmitter is left out of frame.

While the time-averaged polar plots facilitate a good understanding of the "empty" propagation environment, they conceal information regarding dynamic blockage events due to mobile obstacles in the environment, such as the points in time singled out during the analysis of Figure 5.5. This reveals the necessity for analyzing singular points in time to understand how the propagation environment dynamically changes in mere seconds. Figure 5.9 shows the measured RSS over the entire azimuth plane and across several TX beams at three points in time as polar plots. These points in time are among the ones singled out for dynamic propagation events during the analysis of Figure 5.5. Dynamic propagation events at this position are primarily caused by pedestrian activity. Figure 5.9a shows the polar plot for $t' = 0$ s, where there are few deviations from the propagation behavior indicated by Figure 5.6. The highest RSS was measured at the LoS for all TX beams, with the highest across all TX beams measured over TX beam 8 as -28 dBm. The highest RSS after the LoS was measured at $\phi_{RX} = 40^\circ$ for TX beams 8, 11, and 15, with the highest among them measured over TX beam 11 as -38 dBm. Another high-RSS area can be found at $\phi_{RX} = 100^\circ$ for TX beam 15, measured as -43 dBm. Different from the propagation behavior indicated in Figure 5.6 is a higher RSS measurement at $\phi_{RX} = 180^\circ$, where the highest across all TX beams was measured over TX beam 8 as -43 dBm. Figure 5.9b, which shows the polar plot for $t' = 2$ s, tells a different story. The area around the LoS seems to be blocked, with RSS dropping below -35 dBm over TX beams 8 and 11. In contrast, the RSS at $\phi_{RX} = 180^\circ$ appears to have slightly increased to -40 dBm over TX beams 8 and 11. Figure 5.9c, which shows the polar plot for $t' = 3$ s, indicates that the LoS is now unblocked, and new reflections have emerged in the area between $\phi_{RX} \in [260^\circ, 315^\circ]$. The highest RSS within that area was measured at $\phi_{RX} = 260^\circ$ over TX beam 8 as -28 dBm, an increase of 15 dB from $t' = 2$ s. Furthermore, the reflection at $\phi_{RX} = 180^\circ$ for the earlier time instances is not observed at $t' = 3$ s, with the measured RSS decreasing to around -50 dBm. In order to assess the cause of these temporary propagation events, we use sensor input recorded at the same time with the RF measurements at the RX. While using the camera images may be more practical for propagation events that strictly concern the area around the LoS, we use the LiDAR point clouds here, as we also investigate the source of the reflections around $\phi_{RX} \in [245^\circ, 315^\circ]$ at $t' = 3$ s. Figure 5.10 shows the LiDAR point clouds captured at these points in time. Figure 5.10a, the point cloud captured at $t' = 0$ s, shows that while the LoS, illustrated with a black arrow, is not blocked, a pedestrian is approaching the RX, marked at the upper left-hand side of the RX. Furthermore, the cause of the increase in RSS at $\phi_{RX} = 180^\circ$ is revealed to be two pedestrians standing behind the RX, who act as a reflector to the mm-waves transmitted over TX beams 8 and 11. Figure 5.10b, the point cloud captured at $t' = 2$ s, shows that the pedestrian has walked into the LoS and caused a blockage, which is reflected on the measured RSS. Figure 5.10c, the point cloud captured at $t' = 3$ s, shows that the pedestrian has walked out of the LoS and next to the RX, causing the reflections in the area between $\phi_{RX} \in [245^\circ, 315^\circ]$. However, a single pedestrian should not be able to single-handedly cause a reflection over 70° . This peculiarity in the polar plot is attributed to the duration of our measurement, which is one second for each 90° sector. As the direction of the RX sweep is clockwise, the RX seems to have swept in the same direction as the movement of the pedestrian, measuring at each beam when the pedestrian was acting as a reflector to that beam pointing angle.

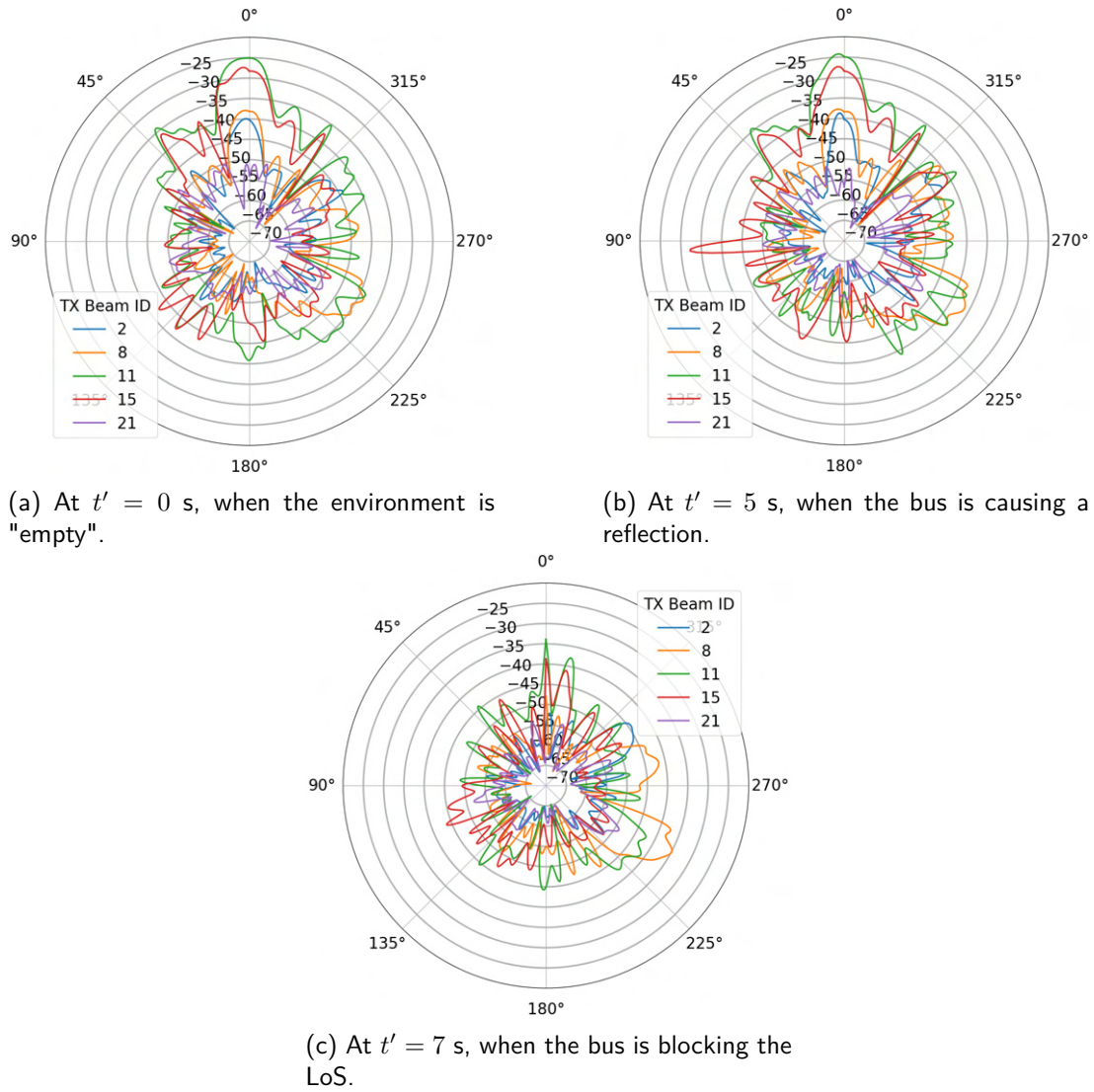


Figure 5.11: RSS in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ]$ for multiple TX beams for POS2 at SuperC, at different points in time.

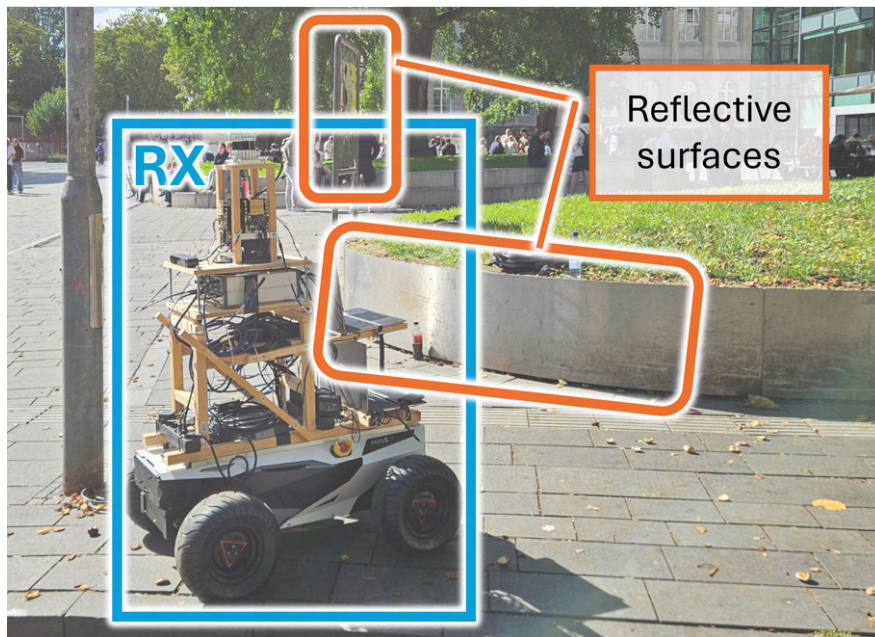
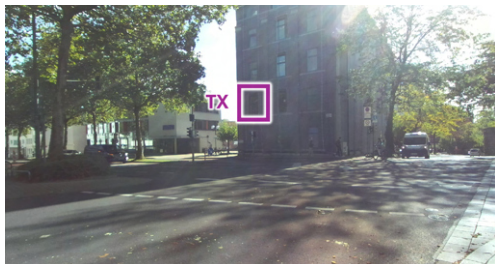


Figure 5.12: Photograph of the propagation environment taken at the RX for POS2 at SuperC.



(a) At $t' = 0$ s, when the environment is "empty".



(b) At $t' = 5$ s, when the bus is causing a reflection.



(c) At $t' = 7$ s, when the bus is blocking the LoS.

Figure 5.13: Camera snapshots from the RX at POS2 at SuperC for the measurements in Figure 5.11. The transmitter is indicated on the images when visible.

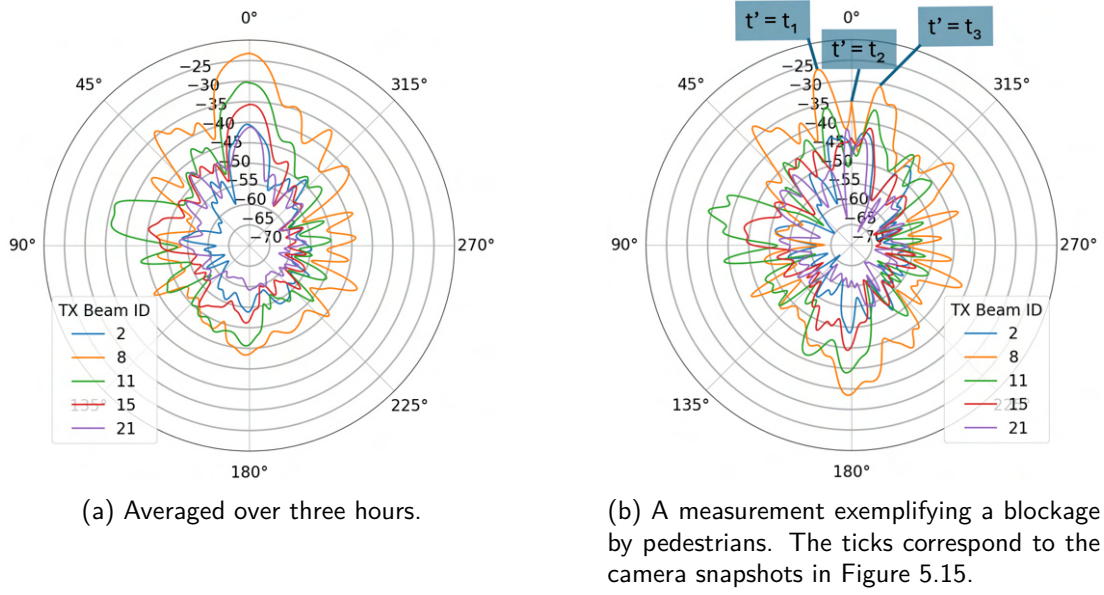


Figure 5.14: RSS in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ across several TX beams for POS4 at SuperC, for different timescales.

POS2 at SuperC serves to elaborate on the impact of street traffic with pedestrians, cyclists, and motor vehicles. Figure 5.11 shows the RSS over the entire azimuth plane and across several TX beams at three points in time as polar plots. A strong LoS with an RSS of -26 dBm over TX beam 11 can be spotted in Figure 5.11a, taken at $t' = 0$ s, and Figure 5.11b, taken at $t' = 5$ s, in contrast to the blocked LoS with an RSS of -35 dBm over TX beam 11 in Figure 5.11c, taken at $t' = 7$ s. The same behavior applies to $\phi_{RX} = 40^\circ$, with the RSS measured over TX beam 11 decreasing from -34 dBm at $t' = 0$ s and $t' = 5$ s to -44 dBm at $t' = 7$ s. In contrast, the reflection at $\phi_{RX} = 230^\circ$ got stronger, with the RSS having increased from -39 dBm at $t' = 0$ s and $t' = 5$ s over TX beams 8 and 11 to -35 dBm at $t' = 7$ s over TX beam 8. The reflections at and around $\phi_{RX} = 230^\circ$ can be attributed to the metal information board and metal ground plates, indicated on the photograph in Figure 5.12. In order to assess the sources of dynamic propagation events, such as the blockage at LoS at $t' = 7$ s, we analyze the camera snapshots from the same points in time, as seen in Figure 5.13. Figure 5.13a shows that the LoS is unblocked at $t' = 0$ s, whereas Figure 5.13b shows that a bus is driving next to the RX at $t' = 5$ s, which causes a reflection, as indicated by the RSS measurement of -32 dBm at $\phi_{RX} = 95^\circ$ over TX beam 15 in Figure 5.11b, a 17 dB increase from $t' = 0$ s. Figure 5.13c shows that the LoS is completely blocked by the bus at $t' = 7$ s, hence the 9 dB decrease in RSS.

Figure 5.14 shows two polar plots for POS4 at SuperC. Figure 5.14a shows the RSS values averaged over three hours (the entire duration of the measurement) across several TX beams. The highest RSS is measured at the LoS across all TX beams, with the highest across all TX beams measured over TX beam 8 as -24 dBm. High RSS values of -35 dBm were also measured at $\phi_{RX} = 40^\circ$ and $\phi_{RX} = 330^\circ$ over TX beam 8. Another high-RSS area can be found at $\phi_{RX} = 75^\circ$, with the RSS measured as -36 dBm over TX

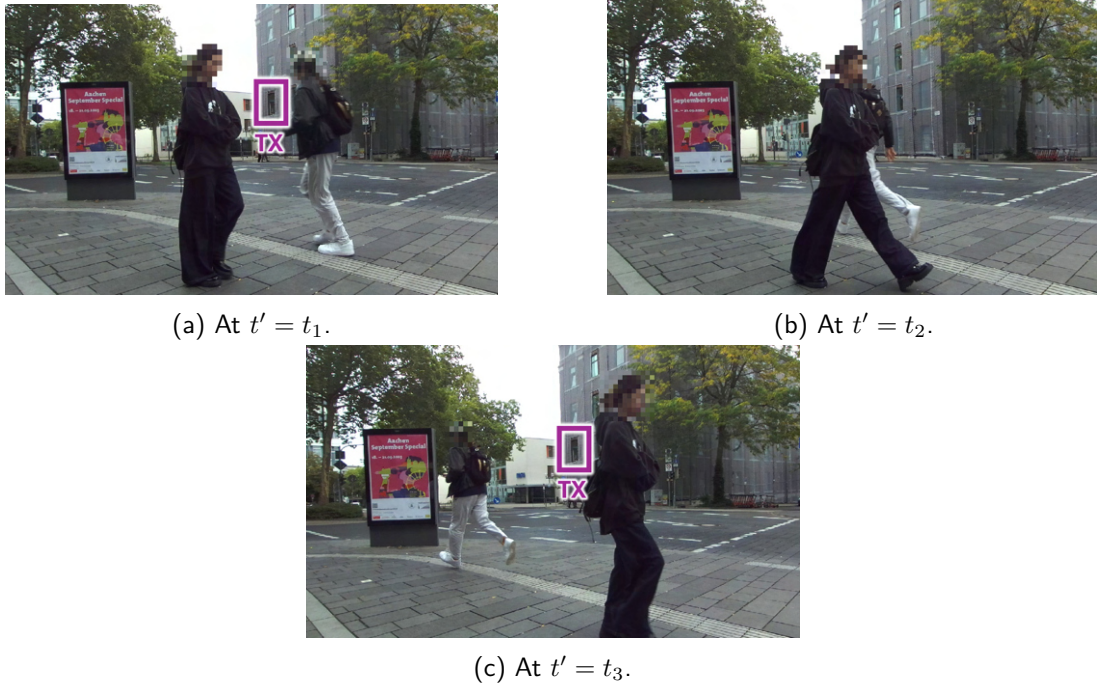


Figure 5.15: Camera snapshots from the RX at POS4 at SuperC, from different points in time corresponding to the measurement for the polar plot in Figure 5.14b. The TX is indicated when visible.

beam 11. Figure 5.14b, taken from a time instance when the LoS was blocked, exhibits additional reflections around $\phi_{RX} = 180^\circ$, with an RSS measurement of -34 dBm over TX beam 8, 10 dB higher compared to Figure 5.14a. Despite the RSS measured over TX beam 8 at $\phi_{RX} = 0^\circ$ dropping by more than 10 dB to -35 dBm, the RSS measurements at the neighboring angles of $\phi_{RX} = 10^\circ$ and $\phi_{RX} = 350^\circ$ do not exhibit such a drastic degradation. In order to verify the source of the blockage at LoS and understand the behavior at $\phi_{RX} = 10^\circ$ and $\phi_{RX} = 350^\circ$, we analyze three camera snapshots from the RX around moment of the blockage in Figure 5.15. All three snapshots verify the presence of pedestrians moving in and out of the LoS, causing the blockage. The fluctuating level of RSS around $\phi_{RX} = 0^\circ$ is attributed to the RX sweep duration, which is one second for a 90° sector. As the RX sweeps clockwise, there is a 90 ms difference between the measurements taken at $\phi_{RX} = 10^\circ$ and $\phi_{RX} = 0^\circ$, which also applies for the measurements taken at $\phi_{RX} = 0^\circ$ and $\phi_{RX} = 350^\circ$. These time instances are labeled as $t' = t_1$, $t' = t_2$, and $t' = t_3$ for $\phi_{RX} = 10^\circ$, $\phi_{RX} = 0^\circ$, and $\phi_{RX} = 350^\circ$, respectively, as seen in Figure 5.14b. Figure 5.15a shows that the pedestrians walking towards each other have not blocked the LoS at $t' = t_1$ yet, which explains the RSS measurement of -27 dBm at $\phi_{RX} = 10^\circ$. Figure 5.15b shows that the pedestrians have aligned to block the LoS at $t' = t_2$, which explains the 8 dB decrease in RSS at $\phi_{RX} = 0^\circ$, measured as -35 dBm. Figure 5.15c shows that the pedestrians have walked in opposite directions and freed up the area around the LoS, which explains the 4 dB increase in RSS at $\phi_{RX} = 350^\circ$, measured as -31 dBm.

Although camera images provide good insights into dynamic propagation events occurring around the LoS, they fall short of accounting for propagation characteristics of the areas far from the LoS due to the narrower FoV of cameras compared to the 360° FoV

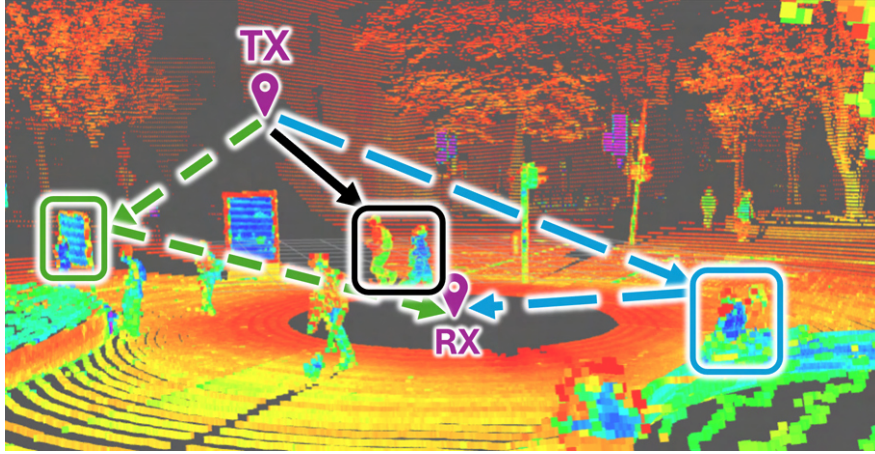


Figure 5.16: LiDAR point cloud recorded at the RX at the moment of the blockage (*cf.* Figure 5.14b) for POS4 at SuperC, with important components and propagation paths illustrated.

of LiDAR sensors. For instance, the camera images in Figure 5.15 do not facilitate the explanation of the reflection at $\phi_{RX} = 75^\circ$ in Figure 5.14a or the high-RSS area around $\phi_{RX} = 180^\circ$ in Figure 5.14b, which is absent in Figure 5.14a, as these angles are not within the FoV of the camera. Therefore, we depend on the LiDAR point clouds for such scenarios. Figure 5.16 shows the LiDAR point cloud from the RX recorded at the moment of the blockage. The point cloud reveals the cause of the temporary reflection around $\phi_{RX} = 180^\circ$ as two people sitting behind the receiver, illustrated in blue on the right-hand side of the point cloud. The reflection at $\phi_{RX} = 75^\circ$ can be attributed to the metal board on the left-hand side of the point cloud, illustrated in green.

Conclusion and Future Work

In this thesis, two mm-wave testbeds were developed towards the design and evaluation of novel sensor- and ML-aided beam management schemes. The first testbed enables the design and real-time evaluation of beam management approaches that incorporate information from sensors in real-world scenarios and full-stack end-to-end mm-wave networks. The popular 28 GHz phased antenna array EVK02001 from Sivers Semiconductors was integrated into the OAI RAN codebase to provide a low-cost alternative to existing solutions. The integration of the EVK02001 enabled the transmission of SSBs over multiple beams, a feature not yet fully implemented in OAI up to this point. Two sensors, a LiDAR and a camera, were interfaced with OAI over MQTT to facilitate the demonstration of sensor-aided beam management techniques. The different beam management options for OAI were demonstrated at the Berlin 6G Conference 2025 and with measurements at the institute. The second testbed is a measurement platform designed to rapidly gather multi-modal sensor and mm-wave RF data for the training of novel ML-based sensor-aided beam management algorithms. The testbed is capable of obtaining directional RSS measurements over the entire azimuth plane within one second. This enables the creation of datasets not only at static positions but also during mobility. Highly accurate, μs -level time synchronization between the TX and RX was achieved via the implementation of a GNSS-based time server. Two outdoor measurement campaigns in the medium-sized German city of Aachen were conducted to verify accurate functionality of the testbed and create datasets with RF measurements and multi-modal sensor data. These datasets are envisioned to be used to train machine learning/deep learning models for sensor-aided beam management.

The measurements made with the first testbed were analyzed to assess the performance of four different beam management configurations in the full-stack 5G network. The link quality suffered significantly not only for the option where the gNB was configured to remain on the LoS link but also for the option where the gNB was configured to switch beams based on the detection of obstacles around the LoS link on the LiDAR point cloud. The former was expected, but the latter implied that the object recognition model deployed on the LiDAR point cloud failed to detect pedestrians, which was attributed to the object recognition model having been trained for outdoor vehicular scenarios. In contrast, the link quality was stable for the option where the gNB was configured to remain on the NLoS link and for the option where the gNB was configured to switch beams based on the detection of obstacles around the LoS link on the camera image. The latter option performed the beam switch preemptively, i.e. before the pedestrian actually blocked the LoS, which resulted in a seamless beam switch with no perceivable effects to the link quality. The measurements made with the second testbed were used to analyze the spatial and temporal characteristics of the mm-wave channel and assess link opportunities at static RX positions.

The findings from the measurements confirmed the reliance of communication at mm-wave frequencies on LoS or strong NLoS propagation paths. The mm-wave channel was shown to be highly site-specific, with minor location shifts significantly changing propagation paths and associated link opportunities. Obstacles as small as pedestrians were found to have significant effects on the link quality, such as causing a degradation of 15 dB. Mobile obstacles were also shown to act as temporary reflectors depending on their position.

To conclude, the utilization of sensors for beam management and the assessment of the site-specific propagation characteristics are shown to be highly beneficial and promising. The creation of a large number of open and comparable multi-modal sensor and mm-wave RF datasets for the training of machine learning beam management approaches remains an ongoing process. The development of machine learning/deep learning algorithms using the datasets is a key area for future work. While the effects of the full sweep duration of one second for the second testbed have been outlined in Section 5.2, our evaluation of the testbed revealed little room for improvement on this front, since the TX beam duration is limited by the occurrence of USRP late packets, which stem from the performance limitations of GNU Radio. The OAI-based testbed can be envisioned to become the successor of the measurement platform, providing full-stack and 3GPP-compliant timing datasets. However, this necessitates major modifications to the OAI source code and requires vast improvements to the stability of the OAI RAN, especially in the presence of mobility, blockages, and other dynamic propagation events.

A

Beam ID to Azimuth Angle for EVK02001

Table A.1: The correspondence between beam IDs and azimuth angles for the EVK02001 RF front-end.

Beam ID	Azimuth Angle
0	0° (omni-beam)
1	-45°
2	-40.5°
3	-36°
4	-31.5°
5	-27°
6	-22.5°
7	-18°
8	-13.5°
9	-9°
10	-4.5°
11	0°
12	4.5°
13	9°
14	13.5°
15	18°
16	22.5°
17	27°
18	31.5°
19	36°
20	40.5°
21	45°

B

Including the Standalone UHD Library and Enforcing the Correct UHD Version for a GNU Radio Out-of-Tree Module

For the development of a GNU Radio OoT module that needs to access the SPI-related functions in UHD, the standalone UHD library must be used, since the built-in UHD blocks in GNU Radio do not provide that functionality. This can be achieved with the following additions to `/gr-modulename/lib/CMakeLists.txt`:

1. Add the following lines before the line starting with `add_library` (should be somewhere around line 25):

```
find_package(UHD "4.2.0" REQUIRED)
include_directories(
    ${UHD_INCLUDE_DIRS}
)
```

This is so that CMake finds the UHD package with the required version, which is 4.2 or later for the SPI-related functions.

2. Add `${UHD_LIBRARIES}` to the line with `target_link_libraries` (the one below the aforementioned line starting with `add_library`). For an OoT module called `SPIControl`, this would look like the following:

```
target_link_libraries(gnuradio-SPIControl
    gnuradio::gnuradio-runtime ${UHD_LIBRARIES})
```

This is so that CMake links the UHD libraries during compilation.

If the OoT module compiles successfully but throws a Python error at runtime that looks something like the two below:

```
_ZTIN3uhd15assertion_errorE
_ZN3uhd12spi_config_tC1ENS0_6edge_tE
```

this might be the reason. If CMake is not explicitly instructed to link UHD 4.x libraries, it somehow defaults to UHD 3.x libraries.

A more human-readable version of the error can be obtained via the `c++filt` tool, e.g. by typing `c++filt _ZTIN3uhd15assertion_errorE` into the Ubuntu terminal.

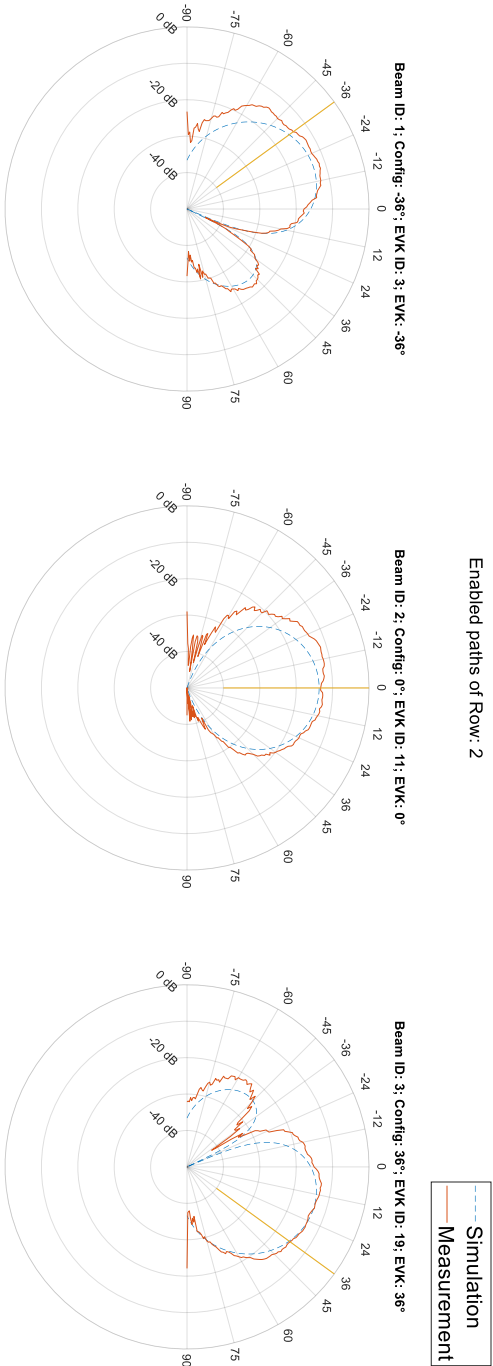
C

Radiation Patterns for EVK02001 Antenna Array

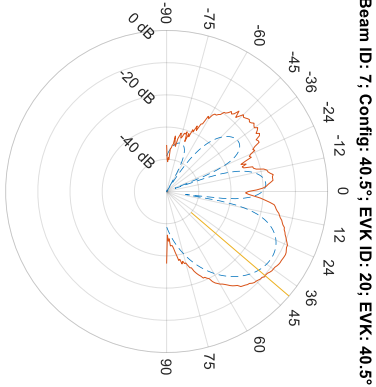
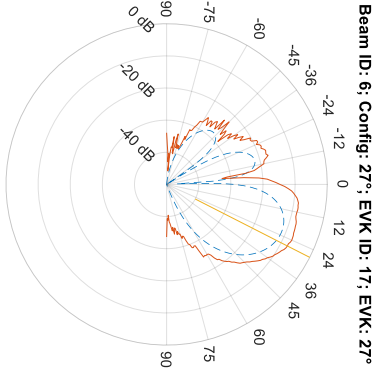
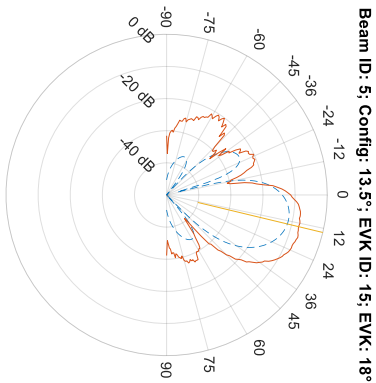
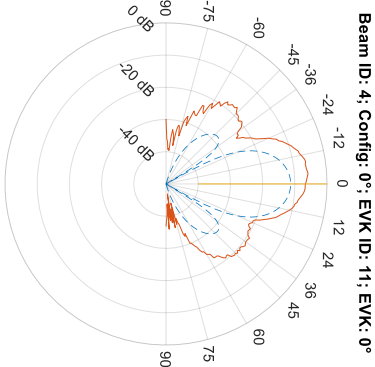
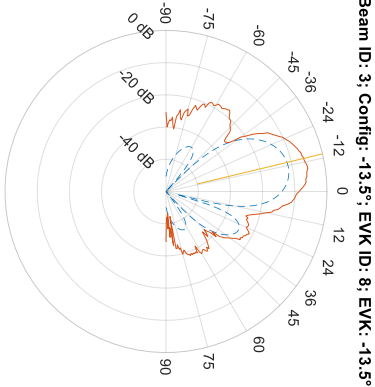
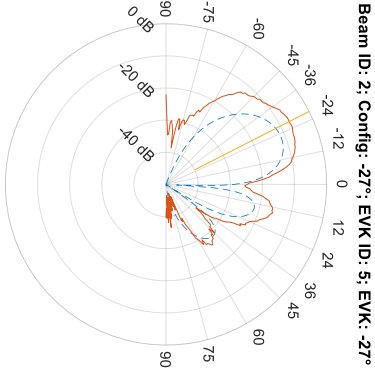
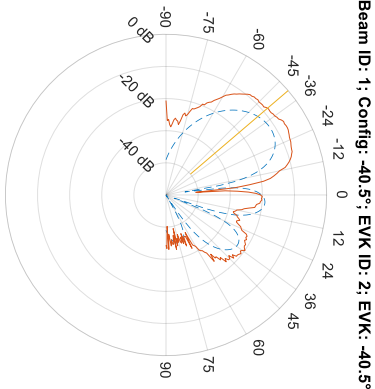
The following pages include the radiation patterns measured at our institute as well as simulated radiation patterns for the EVK02001 antenna array transceiver by Sivers Semiconductors. The patterns are shown for configurations where 2, 4, and 6 antenna elements within a row are enabled. The values of the EVK02001 registers `trx_tx_on`/`trx_rx_on` that correspond to each configuration, alongside with the beam pointing angles and TX/RX beam IDs of the unique beam patterns are also provided.

Beam ID	Beam Ang	EVK ID	Actual Ang
2*1: 0xf0180 2*2: 0xf03c0			
1	-36	3	-36
2	0	11	0
3	36	19	36
4*1: 0xf05a0 4*2: 0xf0ff0			
1	-40,5	2	-40,5
2	-27	5	-27
3	-13,5	8	-13,5
4	0	11	0
5	13,5	15	18
6	27	17	27
7	40,5	20	40,5
6*1: 0xf15a8 6*2: 0xf3ffc			
1	-45,0	1	-45,0
2	-36,0	3	-36,0
3	-27,0	5	-27,0
4	-18,0	7	-18,0
5	-9,0	9	-9,0
6	0,0	11	0,0
7	9,0	14	13,5
8	18,0	15	18,0
9	27,0	17	27,0
10	36,0	19	36,0
11	45,0	21	45,0

Enabled paths of Row: 2

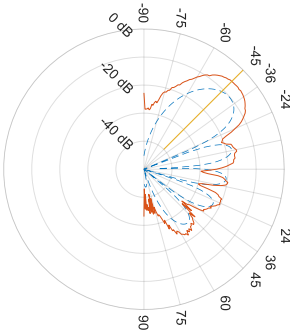


Enabled paths of Row: 4

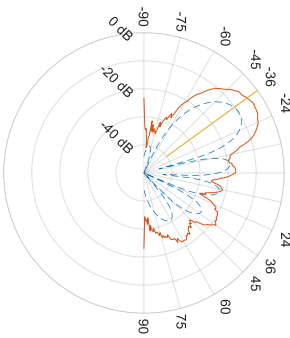


Enabled paths of Row: 6

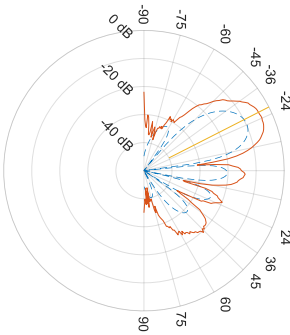
Beam ID: 1; Config: -45°; EVK ID: 1; EVK: -45°



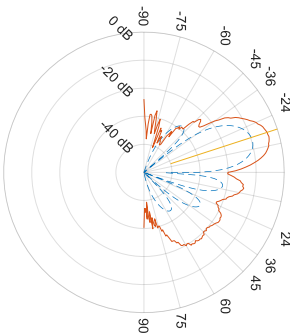
Beam ID: 2; Config: -36°; EVK ID: 3; EVK: -36°



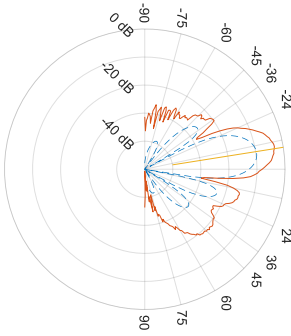
Beam ID: 3; Config: -27°; EVK ID: 5; EVK: -27°



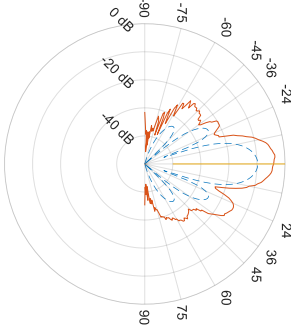
Beam ID: 4; Config: -18°; EVK ID: 7; EVK: -18°



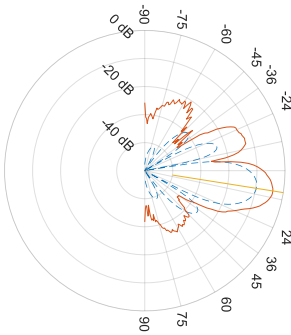
Beam ID: 5; Config: -9°; EVK ID: 9; EVK: -9°



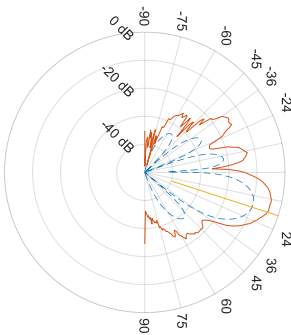
Beam ID: 6; Config: 0°; EVK ID: 11; EVK: 0°



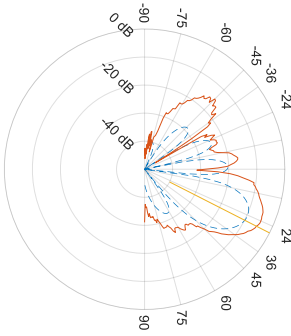
Beam ID: 7; Config: 9°; EVK ID: 14; EVK: 13.5°



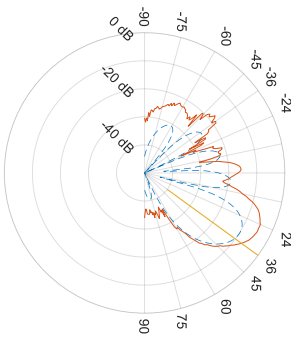
Beam ID: 8; Config: 18°; EVK ID: 15; EVK: 18°



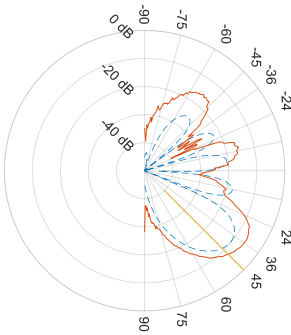
Beam ID: 9; Config: 27°; EVK ID: 17; EVK: 27°



Beam ID: 10; Config: 36°; EVK ID: 19; EVK: 36°



Beam ID: 11; Config: 45°; EVK ID: 21; EVK: 45°



D

Correspondence Between RX Channel ID, RX Beam ID and RX Direction

Table D.1: (RX Channel ID, RX Beam ID) to RX Direction (°).

Beginning of Table		
RX Channel ID	RX Beam ID	RX Direction (°)
0	1	45
0	2	40.5
0	3	36
0	4	31.5
0	5	27
0	6	22.5
0	7	18
0	8	13.5
0	9	9
0	10	4.5
0	11	0
0	12	355.5
0	13	351
0	14	346.5
0	15	342
0	16	337.5
0	17	333
0	18	328.5
0	19	324
0	20	319.5
0	21	315
1	1	315
1	2	310.5
1	3	306
1	4	301.5
1	5	297
1	6	292.5
1	7	288
1	8	283.5
1	9	279
1	10	274.5

Continuation of Table D.1.		
RX Channel ID	RX Beam ID	RX Direction (°)
1	11	270
1	12	265.5
1	13	261
1	14	256.5
1	15	252
1	16	247.5
1	17	243
1	18	238.5
1	19	234
1	20	229.5
1	21	225
2	1	225
2	2	220.5
2	3	216
2	4	211.5
2	5	207
2	6	202.5
2	7	198
2	8	193.5
2	9	189
2	10	184.5
2	11	180
2	12	175.5
2	13	171
2	14	166.5
2	15	162
2	16	157.5
2	17	153
2	18	148.5
2	19	144
2	20	139.5
2	21	135
3	1	135
3	2	130.5
3	3	126
3	4	121.5
3	5	117
3	6	112.5
3	7	108
3	8	103.5
3	9	99
3	10	94.5
3	11	90

Continuation of Table D.1.		
RX Channel ID	RX Beam ID	RX Direction (°)
3	12	85.5
3	13	81
3	14	76.5
3	15	72
3	16	67.5
3	17	63
3	18	58.5
3	19	54
3	20	49.5
3	21	45
End of Table		

E

Abbreviations

3GPP 3rd Generation Partnership Project

5G fifth generation

6G sixth generation

5G-NR 5G New Radio

AoA angle of arrival

AoD angle of departure

ADC analog-to-digital converter

API application programming interface

ATR Automatic Transmit/Receive

BF beamforming

BPL beam pair link

BS base station

CAN bus Controller Area Network bus

CI context information

CN core network

COTS commercial off-the-shelf

CPU central processing unit

CSV comma-separated values

DAC digital-to-analog converter

DL deep learning

DoA direction of arrival

eMBB enhanced mobile broadband

eNB Evolved NodeB

FoV field of view

FPGA field-programmable gate array

fps frames per second

FR1 Frequency Range 1

FR2 Frequency Range 2

FR3 Frequency Range 3

FSPL free-space path loss

FWA fixed wireless access

gNB Next Generation NodeB

GNSS global navigation satellite system

GPIO general-purpose input/output

GPS Global Positioning System

GPU graphics processing unit

GUI graphical user interface

I2C Inter-Integrated Circuit

IA initial access

IEEE Institute of Electrical and Electronics Engineers

IoT Internet of Things

JSON JavaScript Object Notation

LiDAR light detection and ranging

LoS line-of-sight

LTE long-term evolution

MIMO multiple-input multiple-output

mIoT massive Internet of Things

ML machine learning

mm-wave millimeter-wave

mMTC massive machine type communications

MOB mobility path

NSA non-standalone

NLoS non-line-of-sight

NTP Network Time Protocol

OAI OpenAirInterface

OFDM orthogonal frequency-division multiplexing

OoT out-of-tree

PDU protocol data unit

POS static position

PPS pulse per second

PTP Precision Time Protocol

RAN radio access network

RAT radio access technology

REM radio environment map

RF radio frequency

RFNoC RF Network-on-Chip

RFSoc RF System-on-Chip

ROS Robot Operating System

ROS 2 Robot Operating System 2

RSRP reference signal received power

RSS received signal strength

RX receiver

SA standalone

SC single-carrier

SDK software development kit

SDR software-defined radio

SINR signal-to-interference-plus-noise ratio

SMA SubMiniature version A

SNR signal-to-noise ratio

SNTP Simple Network Time Protocol

SPI Serial Peripheral Interface

SSB Synchronization Signal Block

SS Burst Synchronization Signal Burst

SSD solid-state drive

TPV time-position-velocity

TX transmitter

UART universal asynchronous receiver-transmitter

UE user equipment

UGV unmanned ground vehicle

UHD USRP Hardware Driver

URLLC ultra-reliable and low-latency communications

USRP Universal Software Radio Peripheral

V2I vehicle-to-infrastructure

V2X vehicle-to-everything

V2V vehicle-to-vehicle

List of Tables

2.1	Reflection losses in dB for various materials at 9.6, 28.8, and 57.6 GHz [36].	6
2.2	Reflection coefficients for incident angles of 10° and 45°, and penetration losses at indicated thicknesses for different building materials at 28 GHz [38].	7
2.3	A selection of mm-wave experimental platforms and datasets.	15
4.1	Antenna array settings used during the measurements for Testbed 1 for the gNB and UE.	39
A.1	The correspondence between beam IDs and azimuth angles for the EVK02001 RF front-end.	60
D.1	(RX Channel ID, RX Beam ID) to RX Direction (°).	66

List of Figures

2.1	Specific attenuation curves of O_2 , H_2O and rain at sea level, drawn with [32,33].	6
3.1	The testbed for (1) being demonstrated at the Berlin 6G Conference 2025, with the gNB and UE indicated.	17
3.2	The receiver (RX) and transmitter (TX) from the testbed for (2), deployed in an outdoor measurement campaign.	18
3.3	The USRP X410.	19
3.4	The EVK02001 with important components illustrated.	19
3.5	The OS-1 LiDAR with the 1000BASE-T connector.	20
3.6	The ZED 2i camera.	21
3.7	Photographs of the components of the GNSS-based time server.	22
3.8	The Hunter 2.0 UGV.	23
3.9	Block diagram for the OAI-based platform with connection types and signals: (1) samples and commands, (2) I/Q baseband signal, (3) RF signal ($f_c = 27$ GHz), (4) 2048x128 point cloud, (5) 1080p30 video stream, (6) MQTT connection	24
3.10	Pin connections between the EVK02001 and the USRP X410 for the OAI-based testbed.	26
3.11	The dropdown menu with beam management options for OAI.	28
3.12	Block diagram for the fast-sweeping measurement platform with connection types and signals: (1) samples and commands, (2) I/Q baseband signal, (3) RF signal ($f_c = 27$ GHz), (4) 2048x128 point cloud, (5) 1080p30 video stream, (6) position information and time synchronization packets, (7) position information and PPS signal	29
3.13	The screenshot of the GNU Radio flowgraph for the TX.	31
3.14	The screenshot of the GNU Radio flowgraph for the RX.	31
3.15	Pin connections between the EVK02001s and the USRP X410 for the RX of the measurement platform.	33
3.16	The output of the command <code>watch chronyc sources -v</code> on the Raspberry Pi.	34
3.17	The output of the command <code>watch chronyc tracking -c</code> on the Raspberry Pi.	34
3.18	The output of the command <code>watch -n1 cat /var/run/ptpd2.status</code> on a host PC.	35
3.19	RSS in dBm, TX Beam ID and RX Beam ID vs. time in seconds for different TX beam durations.	37
4.1	The diagram visualizing the measurement setup for Testbed 1. Important components are indicated on the figure.	38
4.2	The antenna elements of the EVK02001 antenna array used for measurements in the gNB and UE of Testbed 1. The elements on the upper half are for TX, those on the lower half are for RX.	39

4.3	The location and sector of the TX, static RX positions and mobility path for the measurements with Testbed 2 in front of the institute, indicated on the satellite image.	40
4.4	Photographs from the measurements at the institute for POS1. The RX and TX are indicated on each photo with solid and dotted frames respectively. . . .	40
4.5	The location and sectors of the TX, static RX positions and mobility paths for the measurements with Testbed 2 in front of SuperC and the library, indicated on the satellite image.	41
4.6	Photographs from the measurements at the library for POS5. The RX and TX are indicated on each photo with solid and dotted frames respectively.	42
4.7	Photographs from the measurements at SuperC for POS1. The RX and TX are indicated on each photo with solid and dotted frames respectively.	42
5.1	RSRP in dBm vs time in seconds for the four beam management options in the OAI-based testbed.	43
5.2	Camera snapshots that exemplify the behavior at specific time intervals and instances, taken at the gNB during measurements for the OAI-based testbed. The UE is indicated when visible.	44
5.3	Maximum RSS over all TX beams in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for $t = t_0$ at POS1 at the institute.	45
5.4	The locations of RX and TX, and the propagation events for POS1 indicated on the satellite image of the institute.	46
5.5	Maximum RSS over all TX beams in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for POS7 at the library over 300 seconds.	47
5.6	Maximum RSS over all TX beams in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for POS7 at the library, averaged over three hours.	48
5.7	RSS in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for POS7 at the library averaged over three hours, across several TX beams.	48
5.8	Satellite image of the environment for POS7 at the library, with important components and propagation paths illustrated.	49
5.9	RSS in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ across several TX beams for POS7 at the library, at different points in time.	50
5.10	LiDAR point clouds for the measurements in Figure 5.9, with important components indicated. The transmitter is left out of frame.	51
5.11	RSS in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ for multiple TX beams for POS2 at SuperC, at different points in time.	53
5.12	Photograph of the propagation environment taken at the RX for POS2 at SuperC.	54
5.13	Camera snapshots from the RX at POS2 at SuperC for the measurements in Figure 5.11. The transmitter is indicated on the images when visible.	54
5.14	RSS in dBm vs. $\phi_{RX} \in [0^\circ, 360^\circ)$ across several TX beams for POS4 at SuperC, for different timescales.	55
5.15	Camera snapshots from the RX at POS4 at SuperC, from different points in time corresponding to the measurement for the polar plot in Figure 5.14b. The TX is indicated when visible.	56
5.16	LiDAR point cloud recorded at the RX at the moment of the blockage (cf. Figure 5.14b) for POS4 at SuperC, with important components and propagation paths illustrated.	57

Bibliography

- [1] M. Shafi, A. F. Molisch, P. J. Smith, T. Haustein, P. Zhu, P. De Silva, F. Tufvesson, A. Benjebbour, and G. Wunder, "5G: A Tutorial Overview of Standards, Trials, Challenges, Deployment, and Practice," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 6, pp. 1201–1221, Jun. 2017.
- [2] P. Jonsson, P. Cerwall, A. Lundvall, D. von Koch, and D. Steven, "Ericsson Mobility Report June 2025," Ericsson, Tech. Rep., Jun. 2025, accessed 08.11.2025. [Online]. Available: <https://www.ericsson.com/49e9b6/assets/local/reports-papers/mobility-report/documents/2025/ericsson-mobility-report-june-2025.pdf>
- [3] 3GPP, "Release 15 Description; Summary of Rel-15 Work Items (Release 15)," 3rd Generation Partnership Project (3GPP), Technical Report (TR) 21.915, Sep. 2019, version 15.0.0. [Online]. Available: <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3389>
- [4] A. N. Uwaechia and N. M. Mahyuddin, "A Comprehensive Survey on Millimeter Wave Communications for Fifth-Generation Wireless Networks: Feasibility and Challenges," *IEEE Access*, vol. 8, pp. 62 367–62 414, 2020.
- [5] Q. Xue, C. Ji, S. Ma, J. Guo, Y. Xu, Q. Chen, and W. Zhang, "A Survey of Beam Management for mmWave and THz Communications Towards 6G," *IEEE Communications Surveys & Tutorials*, vol. 26, no. 3, pp. 1520–1559, 2024.
- [6] D. Roy, B. Salehi, S. Banou, S. Mohanti, G. Reus-Muns, M. Belgiovine, P. Ganesh, C. Dick, and K. Chowdhury, "Going beyond RF: A survey on how AI-enabled multimodal beamforming will shape the NextG standard," *Computer Networks*, vol. 228, p. 109729, Jun. 2023.
- [7] J. Gu, B. Salehi, D. Roy, and K. R. Chowdhury, "Multimodality in mmWave MIMO Beam Selection Using Deep Learning: Datasets and Challenges," *IEEE Communications Magazine*, vol. 60, no. 11, pp. 36–41, Nov. 2022.
- [8] A. M. Nor, S. Halunga, and O. Fratu, "Survey on positioning information assisted mmWave beamforming training," *Ad Hoc Networks*, vol. 135, p. 102947, Oct. 2022.
- [9] OpenAirInterface Software Alliance, "OpenAirInterface - 5G software alliance for democratising wireless innovation," accessed 12.10.2025. [Online]. Available: <https://openairinterface.org/>
- [10] 3GPP, "Service requirements for the 5G system; Stage 1 (Release 20)," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 22.261, Sep. 2025, version 20.4.0. [Online]. Available: <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3107>

- [11] Qualcomm, "Spectrum for 4G and 5G: Global Update on 5G Spectrum," Tech. Rep., Nov. 2019, accessed 19.10.2025. [Online]. Available: <https://www.qualcomm.com/content/dam/qcomm-martech/dm-assets/documents/spectrum-for-4g-and-5g.pdf>
- [12] 3GPP, "NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (Release 19)," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.101-1, Jun. 2025, version 19.2.0. [Online]. Available: <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3283>
- [13] Z. Pi and F. Khan, "An introduction to millimeter-wave mobile broadband systems," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 101–107, Jun. 2011.
- [14] 3GPP, "NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone (Release 19)," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 38.101-2, Jun. 2025, version 19.1.0. [Online]. Available: <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3284>
- [15] D. Shakya, M. Ying, T. S. Rappaport, H. Poddar, P. Ma, Y. Wang, and I. Al-Wazani, "Comprehensive FR1(C) and FR3 Lower and Upper Mid-Band Propagation and Material Penetration Loss Measurements and Channel Models in Indoor Environment for 5G and 6G," *IEEE Open Journal of the Communications Society*, vol. 5, pp. 5192–5218, 2024.
- [16] P. Tang, J. Zhang, H. Xu, H. Miao, and X. Liu, "Preliminary perspectives on 3GPP standardization of the propagation channel model for FR3 bands for NR," *Science China Information Sciences*, vol. 68, no. 3, Feb. 2025.
- [17] G. A. Baduge, M. Vaezi, J. K. Dassanayake, M. Z. Hameed, E. Ollila, and S. A. Vorobyov, "Frequency Range 3 for ISAC in 6G: Potentials and Challenges," 2025.
- [18] Rohde & Schwarz, "Rohde & Schwarz enables Qualcomm to pioneer new frequency ranges for future 5G-Advanced and 6G networks," Feb. 2024, Rohde & Schwarz Blog, accessed 28.09.2025. [Online]. Available: https://www.rohde-schwarz.com/uk/about/news-press/all-news/rohde-schwarz-enables-qualcomm-to-pioneer-new-frequency-ranges-for-future-5g-advanced-and-6g-networks-press-release-detailpage_229356-1466880.html
- [19] G. Xu, Y. Nam, S. Lee, A. Tehrani, D. Y. Lee, A. Prasad, C. Tarver, and M. Tonnemacher, "Upper Mid-Band Spectrum for 6G: Opportunities and Key Enablers," Aug. 2024, Samsung Research Blog, accessed 28.09.2025. [Online]. Available: <https://research.samsung.com/blog/Upper-Mid-Band-Spectrum-for-6G-Opportunities-and-Key-Enablers>
- [20] Segan, Sascha, "Here's the Real Truth About Verizon's 5G Network," PCMag, Apr. 2019, accessed 11.11.2025. [Online]. Available: <https://www.pcmag.com/news/heres-the-real-truth-about-verizons-5g-network>

- [21] Wi-Fi Alliance®, “Wi-Fi CERTIFIED WiGig™ brings multi-gigabit performance to Wi-Fi devices,” Oct. 2016, press release, accessed 07.10.2025. [Online]. Available: <https://www.wi-fi.org/news-events/newsroom/wi-fi-certified-wigig-brings-multi-gigabit-performance-to-wi-fi-devices>
- [22] *IEEE Standard for Information technology–Telecommunications and information exchange between systems–Local and metropolitan area networks–Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 3: Enhancements for Very High Throughput in the 60 GHz Band*, Std. 802.11ad-2012, 2012.
- [23] *IEEE Standard for Information Technology–Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks–Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Enhanced Throughput for Operation in License-exempt Bands above 45 GHz*, Std. 802.11ay-2021, 2021.
- [24] Z. Pi, J. Choi, and R. Heath, “Millimeter-wave gigabit broadband evolution toward 5G: fixed access and backhaul,” *IEEE Communications Magazine*, vol. 54, no. 4, pp. 138–144, Apr. 2016.
- [25] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, “Millimeter Wave Beamforming for Wireless Backhaul and Access in Small Cell Networks,” *IEEE Transactions on Communications*, vol. 61, no. 10, pp. 4391–4403, Oct. 2013.
- [26] J. Choi, V. Va, N. Gonzalez-Prelcic, R. Daniels, C. R. Bhat, and R. W. Heath, “Millimeter-Wave Vehicular Communication to Support Massive Automotive Sensing,” *IEEE Communications Magazine*, vol. 54, no. 12, pp. 160–167, Dec. 2016.
- [27] C. R. Storck and F. Duarte-Figueiredo, “A Survey of 5G Technology Evolution, Standards, and Infrastructure Associated With Vehicle-to-Everything Communications by Internet of Vehicles,” *IEEE Access*, vol. 8, pp. 117 593–117 614, 2020.
- [28] M. Xiao, S. Mumtaz, Y. Huang, L. Dai, Y. Li, M. Matthaiou, G. K. Karagiannidis, E. Bjornson, K. Yang, C.-L. I, and A. Ghosh, “Millimeter Wave Communications for Future Mobile Networks,” *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 9, pp. 1909–1935, Sep. 2017.
- [29] W. L. Stutzman and G. A. Thiele, *Antenna Theory and Design*, 3rd ed. Hoboken, NJ: Wiley, 2013.
- [30] H. Friis, “A Note on a Simple Transmission Formula,” *Proceedings of the IRE*, vol. 34, no. 5, pp. 254–256, May 1946.
- [31] T. S. Rappaport, *Wireless communications*, 2nd ed., ser. Prentice Hall communications engineering and emerging technologies series. Upper Saddle River, NJ: Prentice Hall, 2009.

- [32] MathWorks, "gaspl - RF signal attenuation due to atmosphere gaseous absorption," accessed 11.11.2025. [Online]. Available: <https://www.mathworks.com/help/phased/ref/gaspl.html>
- [33] —, "rainpl - RF signal attenuation due to rainfall using ITU model," accessed 11.11.2025. [Online]. Available: <https://www.mathworks.com/help/phased/ref/rainpl.html>
- [34] I. A. Hemadeh, K. Satyanarayana, M. El-Hajjar, and L. Hanzo, "Millimeter-Wave Communications: Physical Channel Models, Design Considerations, Antenna Constructions, and Link-Budget," *IEEE Communications Surveys & Tutorials*, vol. 20, no. 2, pp. 870–913, 2018.
- [35] Y. Bandy, G. Mohammad Rather, and G. R. Begh, "Effect of atmospheric absorption on millimetre wave frequencies for 5G cellular networks," *IET Communications*, vol. 13, no. 3, pp. 265–270, Feb. 2019.
- [36] E. Violette, R. Espeland, R. DeBolt, and F. Schwering, "Millimeter-wave propagation at street level in an urban environment," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 26, no. 3, pp. 368–380, May 1988.
- [37] K. Sato, T. Manabe, T. Ihara, H. Saito, S. Ito, T. Tanaka, K. Sugai, N. Ohmi, Y. Murakami, M. Shibayama, Y. Konishi, and T. Kimura, "Measurements of reflection and transmission characteristics of interior structures of office building in the 60-GHz band," *IEEE Transactions on Antennas and Propagation*, vol. 45, no. 12, pp. 1783–1792, 1997.
- [38] H. Zhao, R. Mayzus, S. Sun, M. Samimi, J. K. Schulz, Y. Azar, K. Wang, G. N. Wong, F. Gutierrez, and T. S. Rappaport, "28 GHz millimeter wave cellular communication measurements for reflection and penetration loss in and around buildings in New York city," in *2013 IEEE International Conference on Communications (ICC)*. IEEE, Jun. 2013, pp. 5163–5167.
- [39] M. K. Samimi and T. S. Rappaport, "Characterization of the 28 GHz Millimeter-Wave Dense Urban Channel for Future 5G Mobile Cellular," NYU Wireless, Technical Report TR 2014-001, Jun. 2014, accessed 24.10.2025. [Online]. Available: <https://wireless.engineering.nyu.edu/static-homepage/tech-reports/Characterization-of-the-28-GHz-Millimeter-Wave.pdf>
- [40] P. Tenerelli and C. Bostian, "Measurements of 28 GHz diffraction loss by building corners," in *Ninth IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (Cat. No.98TH8361)*, vol. 3. IEEE, 1998, pp. 1166–1169.
- [41] I. Rodriguez, H. C. Nguyen, T. B. Sorensen, J. Elling, J. A. Holm, P. Mogensen, and B. Vejlgaard, "Analysis of 38 GHz mmWave Propagation Characteristics of Urban Scenarios," in *Proceedings of European Wireless 2015; 21th European Wireless Conference*, 2015, pp. 1–8.
- [42] Aalto University, AT&T, BUPT, CMCC, Ericsson, Huawei, Intel, KT Corporation, Nokia, NTT DOCOMO, New York University, Qualcomm, Samsung, University of

- Bristol, University of Southern California, "5G Channel Model for bands up to 100 GHz," White Paper, Oct. 2016, v2.3, accessed 24.10.2025. [Online]. Available: <http://www.5gworkshops.com/5GCM.html>
- [43] C. Dillard, T. Gallagher, C. Bostian, and D. Sweeney, "Rough Surface Scattering From Exterior Walls at 28 GHz," *IEEE Transactions on Antennas and Propagation*, vol. 52, no. 12, pp. 3173–3179, Dec. 2004.
 - [44] A. F. Molisch, Ed., *Wireless communications*, 2nd ed. Chichester, West Sussex, U.K: Wiley, 2011.
 - [45] M. Shafi, J. Zhang, H. Tataria, A. F. Molisch, S. Sun, T. S. Rappaport, F. Tufvesson, S. Wu, and K. Kitao, "Microwave vs. Millimeter-Wave Propagation Channels: Key Differences and Impact on 5G Cellular Systems," *IEEE Communications Magazine*, vol. 56, no. 12, pp. 14–20, Dec. 2018.
 - [46] V. Raghavan, V. Podshivalov, J. Hulten, M. A. Tassoudji, A. Sampath, O. H. Koymen, and J. Li, "Spatio-Temporal Impact of Hand and Body Blockage for Millimeter-Wave User Equipment Design at 28 GHz," *IEEE Communications Magazine*, vol. 56, no. 12, pp. 46–52, Dec. 2018.
 - [47] V. Raghavan, S. Noimanivone, S. K. Rho, B. Farin, P. Connor, R. A. Motos, Y.-C. Ou, K. Ravid, M. A. Tassoudji, O. H. Koymen, and J. Li, "Hand and Body Blockage Measurements With Form-Factor User Equipment at 28 GHz," *IEEE Transactions on Antennas and Propagation*, vol. 70, no. 1, pp. 607–620, Jan. 2022.
 - [48] U. T. Virk and K. Haneda, "Modeling Human Blockage at 5G Millimeter-Wave Frequencies," *IEEE Transactions on Antennas and Propagation*, vol. 68, no. 3, pp. 2256–2266, Mar. 2020.
 - [49] Y. Xing and T. S. Rappaport, "Propagation Measurement System and Approach at 140 GHz-Moving to 6G and Above 100 GHz," in *2018 IEEE Global Communications Conference (GLOBECOM)*. IEEE, Dec. 2018.
 - [50] C. A. Balanis, *Antenna Theory*, 4th ed., ser. New York Academy of Sciences Series. Newark: John Wiley & Sons, Incorporated, 2016.
 - [51] S. Kutty and D. Sen, "Beamforming for Millimeter Wave Communications: An Inclusive Survey," *IEEE Communications Surveys & Tutorials*, vol. 18, no. 2, pp. 949–973, 2016.
 - [52] M. Giordani, M. Polese, A. Roy, D. Castor, and M. Zorzi, "A Tutorial on Beam Management for 3GPP NR at mmWave Frequencies," *IEEE Communications Surveys & Tutorials*, vol. 21, no. 1, pp. 173–196, 2019.
 - [53] Y.-N. R. Li, B. Gao, X. Zhang, and K. Huang, "Beam Management in Millimeter-Wave Communications for 5G and Beyond," *IEEE Access*, vol. 8, pp. 13 282–13 293, 2020.

- [54] 3GPP, "Study on New Radio Access Technology Physical Layer Aspects (Release 14)," 3rd Generation Partnership Project, Technical Report (TR) 38.802, Sep. 2017, version 14.2.0. [Online]. Available: <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3066>
- [55] W. Yi, W. Zhiqing, and F. Zhiyong, "Beam training and tracking in mmWave communication: A survey," *China Communications*, vol. 21, no. 6, pp. 1–22, Jun. 2024.
- [56] M. Giordani, M. Mezzavilla, C. N. Barati, S. Rangan, and M. Zorzi, "Comparative analysis of initial access techniques in 5G mmWave cellular networks," in *2016 Annual Conference on Information Science and Systems (CISS)*. Institute of Electrical and Electronics Engineers (IEEE), Mar. 2016.
- [57] S. Noh, M. D. Zoltowski, and D. J. Love, "Multi-Resolution Codebook Based Beamforming Sequence Design in Millimeter-Wave Systems," in *2015 IEEE Global Communications Conference (GLOBECOM)*. IEEE, Dec. 2015, pp. 1–6.
- [58] R. Zhang, H. Zhang, W. Xu, and X. You, "Subarray-Based Simultaneous Beam Training for Multiuser mmWave Massive MIMO Systems," *IEEE Wireless Communications Letters*, vol. 8, no. 4, pp. 976–979, Aug. 2019.
- [59] K. Chen and C. Qi, "Beam Training Based on Dynamic Hierarchical Codebook for Millimeter Wave Massive MIMO," *IEEE Communications Letters*, vol. 23, no. 1, pp. 132–135, Jan. 2019.
- [60] H. Yu, P. Guan, W. Qu, and Y. Zhao, "An Improved Beam Training Scheme Under Hierarchical Codebook," *IEEE Access*, vol. 8, pp. 53 627–53 635, 2020.
- [61] C. Qi, K. Chen, O. A. Dobre, and G. Y. Li, "Hierarchical Codebook-Based Multiuser Beam Training for Millimeter Wave Massive MIMO," *IEEE Transactions on Wireless Communications*, vol. 19, no. 12, pp. 8142–8152, Dec. 2020.
- [62] A. S. Mubarak, H. Esmail, M. Salah, O. A. Omer, and U. S. Mohamed, "Geometry-assisted initial access and link maintenance in mmwave 5g communication networks," *Wireless Personal Communications*, vol. 137, no. 2, pp. 769–793, Jul. 2024.
- [63] M. Giordani, M. Mezzavilla, and M. Zorzi, "Initial Access in 5G mmWave Cellular Networks," *IEEE Communications Magazine*, vol. 54, no. 11, pp. 40–47, Nov. 2016.
- [64] A. Ali, N. González-Prelcic, and R. W. Heath, "Millimeter Wave Beam-Selection Using Out-of-Band Spatial Information," *IEEE Transactions on Wireless Communications*, vol. 17, no. 2, pp. 1038–1052, Feb. 2018.
- [65] N. González-Prelcic, R. Méndez-Rial, and R. W. Heath, "Radar aided beam alignment in MmWave V2I communications supporting antenna diversity," in *2016 Information Theory and Applications Workshop (ITA)*. IEEE, Jan. 2016, pp. 1–7.
- [66] O. Montenbruck and P. J. G. Teunissen, Eds., *Springer Handbook of Global Navigation Satellite Systems*, 1st ed., ser. Springer eBook Collection. Cham: Springer, 2017.

- [67] F. Devoti, I. Filippini, and A. Capone, "MM-wave Initial Access: A Context Information Overview," in *2018 IEEE 19th International Symposium on "A World of Wireless, Mobile and Multimedia Networks" (WoWMoM)*. IEEE, Jun. 2018, pp. 1–9.
- [68] C. Baquero Barneto, E. Rastorgueva-Foi, M. F. Keskin, T. Riihonen, M. Turunen, J. Talvitie, H. Wymeersch, and M. Valkama, "Millimeter-Wave Mobile Sensing and Environment Mapping: Models, Algorithms and Validation," *IEEE Transactions on Vehicular Technology*, vol. 71, no. 4, pp. 3900–3916, Apr. 2022.
- [69] T. Bushi, T. Nakahira, S. Shinohara, Y. Asai, K. Ohira, and H. Shimonishi, "Real Time Reconstruction of Radio Environment Maps in Indoor Millimeter-Wave Beamforming with Beam Changes," in *2024 20th International Conference on Network and Service Management (CNSM)*. IEEE, Oct. 2024, pp. 1–7.
- [70] M. Alrabeiah, A. Hredzak, Z. Liu, and A. Alkhateeb, "ViWi: A Deep Learning Dataset Framework for Vision-Aided Wireless Communications," in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. IEEE, May 2020.
- [71] W. Xu, F. Gao, S. Jin, and A. Alkhateeb, "3D Scene-Based Beam Selection for mmWave Communications," *IEEE Wireless Communications Letters*, vol. 9, no. 11, pp. 1850–1854, Nov. 2020.
- [72] Y. Tian, G. Pan, and M.-S. Alouini, "Applying Deep-Learning-Based Computer Vision to Wireless Communications: Methodologies, Opportunities, and Challenges," *IEEE Open Journal of the Communications Society*, vol. 2, pp. 132–143, 2021.
- [73] B. Salehi, M. Belgiovine, S. G. Sanchez, J. Dy, S. Ioannidis, and K. Chowdhury, "Machine Learning on Camera Images for Fast mmWave Beamforming," in *2020 IEEE 17th International Conference on Mobile Ad Hoc and Sensor Systems (MASS)*. IEEE, Dec. 2020, pp. 338–346.
- [74] W. Zhong, L. Zhang, H. Jin, X. Liu, Q. Zhu, Y. He, F. Ali, Z. Lin, K. Mao, and T. S. Durrani, "Image-Based Beam Tracking With Deep Learning for mmWave V2I Communication Systems," *IEEE Transactions on Intelligent Transportation Systems*, vol. 25, no. 11, pp. 19 110–19 116, Nov. 2024.
- [75] M. Alrabeiah, A. Hredzak, and A. Alkhateeb, "Millimeter Wave Base Stations with Cameras: Vision-Aided Beam and Blockage Prediction," in *2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring)*. IEEE, May 2020, pp. 1–5.
- [76] A. Alkhateeb, G. Charan, T. Osman, A. Hredzak, J. Morais, U. Demirhan, and N. Srinivas, "DeepSense 6G: A Large-Scale Real-World Multi-Modal Sensing and Communication Dataset," *IEEE Communications Magazine*, vol. 61, no. 9, pp. 122–128, Sep. 2023.
- [77] S. Jiang, G. Charan, and A. Alkhateeb, "LiDAR Aided Future Beam Prediction in Real-World Millimeter Wave V2I Communications," *IEEE Wireless Communications Letters*, vol. 12, no. 2, pp. 212–216, Feb. 2023.

- [78] T. Woodford, X. Zhang, E. Chai, K. Sundaresan, and A. Khojastepour, "SpaceBeam: LiDAR-driven one-shot mmWave beam management," in *Proceedings of the 19th Annual International Conference on Mobile Systems, Applications, and Services*. ACM, Jun. 2021, pp. 389–401.
- [79] M. Dias, A. Klautau, N. González-Prelcic, and R. W. Heath, "Position and LIDAR-Aided mmWave Beam Selection using Deep Learning," in *2019 IEEE 20th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*. IEEE, Jul. 2019, pp. 1–5.
- [80] A. Klautau, N. Gonzalez-Prelcic, and R. W. Heath, "LiDAR Data for Deep Learning-Based mmWave Beam-Selection," *IEEE Wireless Communications Letters*, vol. 8, no. 3, pp. 909–912, Jun. 2019.
- [81] D. Marasinghe, N. Rajatheva, and M. Latva-aho, "LiDAR Aided Human Blockage Prediction for 6G," in *2021 IEEE Globecom Workshops (GC Wkshps)*. IEEE, Dec. 2021, pp. 1–6.
- [82] S. Wu, C. Chakrabarti, and A. Alkhateeb, "LiDAR-Aided Mobile Blockage Prediction in Real-World Millimeter Wave Systems," in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, Apr. 2022, pp. 2631–2636.
- [83] J. Hackett and M. Shah, "Multi-sensor fusion: a perspective," in *Proceedings., IEEE International Conference on Robotics and Automation*. IEEE Comput. Soc. Press, May 1990, pp. 1324–1330.
- [84] A. Schott, A. Ichkov, B. Açıkgöz, N. Beckmann, L. Reiher, and L. Simić, "A Multi-Band mm-Wave Experimental Platform Towards Environment-Aware Beam Management in the Beyond-5G Era," in *Proceedings of the 30th Annual International Conference on Mobile Computing and Networking*. ACM, Dec. 2024, pp. 1882–1889.
- [85] G. Charan, T. Osman, A. Hredzak, N. Thawdar, and A. Alkhateeb, "Vision-Position Multi-Modal Beam Prediction Using Real Millimeter Wave Datasets," in *2022 IEEE Wireless Communications and Networking Conference (WCNC)*. IEEE, Apr. 2022, pp. 2727–2731.
- [86] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.
- [87] J. Zhang, X. Zhang, P. Kulkarni, and P. Ramanathan, "OpenMili: a 60 GHz software radio platform with a reconfigurable phased-array antenna," in *Proceedings of the 22nd Annual International Conference on Mobile Computing and Networking*. ACM, Oct. 2016, pp. 162–175.
- [88] L. Grannemann, A. Ichkov, P. Mähönen, and L. Simić, "Urban Outdoor Measurement Study of Phased Antenna Array Impact on Millimeter-Wave Link Opportunities and Beam Misalignment," *IEEE Transactions on Wireless Communications*, vol. 20, no. 3, pp. 1727–1741, Mar. 2021.

- [89] A. Moreno, J. O. Lacruz, and J. Widmer, "Open Source RFNoC-Based Testbed for Millimeter-Wave Experimentation using USRP Software Defined Radios," in *2020 IEEE International Symposium on Circuits and Systems (ISCAS)*. IEEE, Oct. 2020, pp. 1–5.
- [90] D. Raychaudhuri, I. Seskar, G. Zussman, T. Korakis, D. Kilper, T. Chen, J. Kolodziejski, M. Sherman, Z. Kostic, X. Gu, H. Krishnaswamy, S. Maheshwari, P. Skrimponis, and C. Gutterman, "Challenge: Cosmos: A city-scale programmable testbed for experimentation with advanced wireless," in *Proceedings of the 26th Annual International Conference on Mobile Computing and Networking*. ACM, Apr. 2020, pp. 1–13.
- [91] T. Chen, P. Maddala, P. Skrimponis, J. Kolodziejski, X. Gu, A. Paidimarri, S. Rangan, G. Zussman, and I. Seskar, "Programmable and Open-Access Millimeter-Wave Radios in the PAWR COSMOS Testbed," in *Proceedings of the 15th ACM Workshop on Wireless Network Testbeds, Experimental evaluation & CHaracterization*. ACM, Oct. 2021, pp. 1–8.
- [92] I. K. Jain, R. Subbaraman, T. H. Sadarahalli, X. Shao, H.-W. Lin, and D. Bharadia, "mMobile: Building a mmWave Testbed to Evaluate and Address Mobility Effects," in *Proceedings of the 4th ACM Workshop on Millimeter-Wave Networks and Sensing Systems*. ACM, Sep. 2020, pp. 1–6.
- [93] J. O. Lacruz, D. Garcia, P. J. Mateo, J. Palacios, and J. Widmer, "mm-FLEX: an open platform for millimeter-wave mobile full-bandwidth experimentation," in *Proceedings of the 18th International Conference on Mobile Systems, Applications, and Services*. ACM, Jun. 2020, pp. 1–13.
- [94] J. O. Lacruz, R. R. Ortiz, and J. Widmer, "A real-time experimentation platform for sub-6 GHz and millimeter-wave MIMO systems," in *Proceedings of the 19th Annual International Conference on Mobile Systems, Applications, and Services*. ACM, Jun. 2021, pp. 427–439.
- [95] S. Mm, I. K. Jain, L. Wilson, S. S. R. Jonnavithula, and D. Bharadia, "mm-O-RAN: Building a Millimeter-wave O-RAN Testbed," in *Proceedings of the 30th Annual International Conference on Mobile Computing and Networking*. ACM, Dec. 2024, pp. 1820–1822.
- [96] A. Klautau, P. Batista, N. González-Prelcic, Y. Wang, and R. W. Heath, "5G MIMO Data for Machine Learning: Application to Beam-Selection Using Deep Learning," in *2018 Information Theory and Applications Workshop (ITA)*. IEEE, Feb. 2018, pp. 1–9.
- [97] B. Salehi, J. Gu, D. Roy, and K. Chowdhury, "FLASH: Federated Learning for Automated Selection of High-band mmWave Sectors," in *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*. IEEE, May 2022, pp. 1719–1728.
- [98] M. Mehlhose, P. Marques, L. Pereira, N. Pandeya, T. Alves, and A. Haj-Omar, "Integrated Communication and Sensing mmWave 5G-NR Research Platform utilizing the Open-Source OAI Stack with Camera-Assisted Beam Management," in *2025 IEEE*

- 5th International Symposium on Joint Communications & Sensing (JC&S)*. IEEE, Jan. 2025, pp. 1–2.
- [99] I. K. Jain, R. Subbaraman, and D. Bharadia, “Demo and dataset for mmWave multi-beam tracking using mMobile 28 GHz testbed,” in *Proceedings of the 12th ACM Wireless of the Students, by the Students, and for the Students (S3) Workshop*. ACM, Oct. 2021, pp. 8–8.
- [100] Y. Y. Chun, M. H. Mokhtar, A. A. A. Rahman, and A. K. Samingan, “Performance study of LTE experimental testbed using OpenAirInterface,” in *2016 18th International Conference on Advanced Communication Technology (ICACT)*. IEEE, Jan. 2016, pp. 617–622.
- [101] M. Einhaus, M. B. Charaf, I. Kim, and P. Arnold, “Bandwidth Part Adaptation and Processing Time Evaluation with OpenAirInterface,” in *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*. IEEE, Aug. 2018, pp. 1–5.
- [102] S. Kumar, A. K. Meshram, A. Astro, J. Querol, T. Schlichter, G. Casati, T. Heyn, F. Völk, R. T. Schwarz, A. Knopp, P. Marques, L. Pereira, R. Magueta, A. Kapovits, and F. Kaltenberger, “OpenAirInterface as a platform for 5G-NTN Research and Experimentation,” in *2022 IEEE Future Networks World Forum (FNWF)*. IEEE, Oct. 2022, pp. 500–506.
- [103] F. Völk, T. Schlichter, F. Kaltenberger, T. Heyn, G. Casati, R. T. Schwarz, and A. Knopp, “Field Trial of a 5G Non-Terrestrial Network Using OpenAirInterface,” *IEEE Open Journal of Vehicular Technology*, vol. 3, pp. 243–250, 2022.
- [104] F. Völk, T. Schlichter, S. Kumar, R. T. Schwarz, A. Knopp, M. Hammouda, T. Heyn, J. Querol, S. Chatzinotas, and A. Kapovits, “5G Non-Terrestrial Networks With OpenAirInterface: An Experimental Study Over GEO Satellites,” *IEEE Access*, vol. 12, pp. 155 098–155 109, 2024.
- [105] R. Mundlamuri, R. Gangula, F. Kaltenberger, and R. Knopp, “5G NR Positioning with OpenAirInterface: Tools and Methodologies,” in *2025 20th Wireless On-Demand Network Systems and Services Conference (WONS)*, 2025, pp. 1–7.
- [106] F. Kaltenberger, A. P. Silva, A. Gosain, L. Wang, and T.-T. Nguyen, “OpenAirInterface: Democratizing innovation in the 5G Era,” *Computer Networks*, vol. 176, p. 107284, Jul. 2020.
- [107] Y. Ye, C. Pan, C. Zhang, and J. Wang, “Performance Evaluation for 5G NR Communication System based on OpenAirInterface,” in *2024 International Conference on Electrical Engineering and Photonics (EEExPolytech)*. IEEE, Oct. 2024, pp. 19–22.
- [108] H. Cheng, P. Johari, M. A. Arfaoui, F. Periard, P. Pietraski, G. Zhang, and T. Melo-dia, “Real-Time AI-Enabled CSI Feedback Experimentation with Open RAN,” in *2024 19th Wireless On-Demand Network Systems and Services Conference (WONS)*. IEEE, Jan. 2024, pp. 121–124.

- [109] TMYTEK, “mmW-OAI | 5G NR FR2 Standalone (SA) ready. Open Source Full Stack Control.” accessed 12.10.2025. [Online]. Available: <https://tmytek.com/solutions/mmW-OAI>
- [110] Z. U. Khan, T. O’Farrell, and K. L. Ford, “Direct IF Sampling Receivers for 5G Millimeter-Wave Communications Systems,” in *2023 IEEE 34th Annual International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC)*. IEEE, Sep. 2023, pp. 1–5.
- [111] R. Mundlamuri, S. Badran, R. Gangula, F. Kaltenberger, J. M. Jornet, and T. Melodia, “5G Over Terahertz Using OpenAirInterface,” in *2024 19th Wireless On-Demand Network Systems and Services Conference (WONS)*. IEEE, Jan. 2024, pp. 29–32.
- [112] National Instruments, “Ettus USRP X410 Specifications,” accessed 19.10.2025. [Online]. Available: <https://www.ni.com/docs/de-DE/bundle/ettus-usrp-x410-specs/page/specs.html>
- [113] Sivers Semiconductors, “Evaluation Kit EVK02001,” accessed 09.10.2025. [Online]. Available: <https://www.sivers-semiconductors.com/5g-millimeter-wave-mmwave-and-satcom/wireless-products/evaluation-kits/evaluation-kit-evk02001/>
- [114] Sivers IMA, *TRX BF/02 Product Data Sheet*, Apr. 2020, [Revision 2.0. Confidential under NDA.].
- [115] Sivers Semiconductors, *EVK02001/00 User Manual*, May 2021, [Revision 1.6. Confidential under NDA.].
- [116] Ouster, “OS1: High-Res Mid-Range Lidar Sensor for Automation & Security,” accessed 09.10.2025. [Online]. Available: <https://ouster.com/products/hardware/os1-lidar-sensor>
- [117] —, *Ouster OS1 Datasheet*, accessed 09.10.2025. [Online]. Available: <https://data.ouster.io/downloads/datasheets/datasheet-rev7-v3p1-os1.pdf>
- [118] StereoLabs, “ZED 2i Stereo Camera,” accessed 09.10.2025. [Online]. Available: <https://www.stereolabs.com/en-de/store/products/zed-2i>
- [119] Raspberry Pi, “Raspberry Pi 4 Model B specifications,” accessed 09.10.2025. [Online]. Available: <https://www.raspberrypi.com/products/raspberry-pi-4-model-b/specifications/>
- [120] SparkFun Electronics, “SparkFun GNSS Receiver Breakout - MAX-M10S (Qwiic),” accessed 09.10.2025. [Online]. Available: <https://www.sparkfun.com/sparkfun-gnss-receiver-breakout-max-m10s-qwiic.html>
- [121] u-blox, *ANN-MB5 Datasheet*, accessed 09.10.2025. [Online]. Available: https://content.u-blox.com/sites/default/files/documents/ANN-MB5_Datasheet_UBX-22038811.pdf
- [122] Intel, “USB 3.0* Radio Frequency Interference Impact on 2.4 GHz Wireless Devices,” White Paper 327216-001, Apr. 2012, accessed 06.10.2025. [Online]. Available: <https://www.usb.org/sites/default/files/327216.pdf>

- [123] AgileX, “Hunter 2.0,” accessed 10.10.2025. [Online]. Available: <https://global.agilex.ai/products/hunter-2-0>
- [124] AgileX Robotics Team, *HUNTER2.0 USER MANUAL*, Aug. 2023, v2.0.4., accessed 10.10.2025. [Online]. Available: https://cdn.shopify.com/s/files/1/0551/0630/6141/files/HUNTER2.0_USER_MANUAL2023.12_50805.pdf?v=1711434366
- [125] Ettus Research, “The USRP™ Hardware Driver Repository,” official GitHub repository, accessed 12.10.2025. [Online]. Available: <https://github.com/EttusResearch/uhd>
- [126] —, “UHD - Ettus Knowledge Base,” accessed 12.10.2025. [Online]. Available: <https://kb.ettus.com/UHD>
- [127] S. Macenski, T. Foote, B. Gerkey, C. Lalancette, and W. Woodall, “Robot Operating System 2: Design, architecture, and uses in the wild,” *Science Robotics*, vol. 7, no. 66, p. eabm6074, 2022. [Online]. Available: <https://www.science.org/doi/abs/10.1126/scirobotics.abm6074>
- [128] “Basic Concepts - ROS 2 Documentation: Kilted documentation,” 2025, accessed 22.10.2025. [Online]. Available: <https://docs.ros.org/en/kilted/Concepts/Basic.html>
- [129] A. Koubaa, *Robot Operating System (ROS)*, ser. Studies in Computational Intelligence Series. Cham: Springer International Publishing AG, 2016.
- [130] L. Reiher, B. Lampe, T. Woopen, R. Van Kempen, T. Beemelmans, and L. Eckstein, “Enabling Connectivity for Automated Mobility: A Novel MQTT-based Interface Evaluated in a 5G Case Study on Edge-Cloud Lidar Object Detection,” in *2022 International Conference on Electrical, Computer, Communications and Mechatronics Engineering (ICECCME)*. IEEE, Nov. 2022, pp. 1–9.
- [131] StereoLabs, “Adding Object Detection in ROS,” accessed 16.10.2025. [Online]. Available: <https://www.stereolabs.com/docs/ros/object-detection>
- [132] OpenAirInterface Software Alliance, “5G CORE NETWORK,” accessed 02.11.2025. [Online]. Available: <https://openairinterface.org/oai-5g-core-network-project/>
- [133] —, “5G RAN,” accessed on 02.11.2025. [Online]. Available: <https://openairinterface.org/oai-5g-ran-project/>
- [134] —, “oai / openairinterface5G,” Oct. 2024, gitLab repository, branch develop, tag 2024.w42, accessed 10.11.2025. [Online]. Available: https://gitlab.eurecom.fr/oai/openairinterface5g/-/tree/2024.w42?ref_type=tags
- [135] GNU Radio, “What Is GNU Radio,” accessed 13.10.2025. [Online]. Available: https://wiki.gnuradio.org/index.php?title=What_Is_GNU_Radio
- [136] —, “GNU Radio - the Free and Open Software Radio Ecosystem,” official GitHub repository, accessed 13.10.2025. [Online]. Available: <https://github.com/gnuradio/gnuradio>

- [137] The Open Source Hardware Association (OSHW), "A Resolution to Redefine SPI Signal Names," accessed 02.11.2025. [Online]. Available: <https://oshwa.org/resources/a-resolution-to-redefine-spi-signal-names/>
- [138] Ettus Research, *USRP Hardware Driver and USRP Manual: X4x0 GPIO API*, accessed 13.10.2025. [Online]. Available: https://files.ettus.com/manual/page_x400_gpio_api.html
- [139] —, *USRP Hardware Driver and USRP Manual: GPIO API*, accessed 12.10.2025. [Online]. Available: https://files.ettus.com/manual/page_gpio_api.html#xgpio_fpanel_atr
- [140] OpenAirInterface Software Alliance, "radio/USRP/usrp_lib.cpp - 2024.w42 - oai / openairinterface5G," Jun. 2024, source file in GitLab repository, branch develop, tag 2024.w42, accessed 10.11.2025. [Online]. Available: https://gitlab.eurecom.fr/oai/openairinterface5g/-/blob/2024.w42/radio/USRP/usrp_lib.cpp?ref_type=tags
- [141] MQTT.org, "MQTT - The Standard for IoT Messaging," accessed 16.10.2025. [Online]. Available: <https://mqtt.org/>
- [142] Qt Group, "Qt for Python," accessed 16.10.2025. [Online]. Available: <https://doc.qt.io/qtforpython-6/>
- [143] Eclipse Paho, "Paho Asynchronous MQTT C Client Library: Asynchronous MQTT client library for C (MQTTAsync)," accessed 10.11.2025. [Online]. Available: <https://eclipse-paho.github.io/paho.mqtt.c/MQTTAsync/html/>
- [144] Ettus Research, "USRP Hardware Driver and USRP Manual: General Application Notes - Overflow/Underflow Notes," accessed 10.11.2025. [Online]. Available: https://files.ettus.com/manual/page_general.html#general_ounotes
- [145] Debian Manpages, *systemd-timesyncd(8)*, accessed 16.10.2025. [Online]. Available: <https://manpages.debian.org/trixie/systemd-timesyncd/systemd-timesyncd.8.en.html>
- [146] NTP.org, "The NTP FAQ and HOWTO - 5. How does it work?" Jun. 2022, accessed 16.10.2025. [Online]. Available: <https://www.ntp.org/ntpfaq/NTP-s-algo/>
- [147] *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems*, IEEE Instrumentation and Measurement Society Std., Nov. 2002, [IEEE 1588-2002].
- [148] *IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems Amendment 2: Master-Slave Optional Alternative Terminology*, IEEE Instrumentation and Measurement Society Std., Mar. 2023, [IEEE 1588g-2022].
- [149] PTPd, "PTPd official source - master branch a.k.a. trunk," official GitHub repository, accessed 16.10.2025. [Online]. Available: <https://github.com/ptpd/ptpd>

- [150] J. Henderson, "Clock Synchronisation over Wi-Fi Networks," accessed 16.10.2025. [Online]. Available: <https://web.archive.org/web/20250312072603/https://jackhenderson.com.au/projects/time-synchronisation>
- [151] J. Paul, "DIY Stratum 1 NTP Server: Secure Time Sync with Raspberry Pi Under \$200," Aug. 2024, accessed 16.10.2025. [Online]. Available: <https://www.jpaul.me/2024/08/diy-stratum-1-ntp-server-secure-time-sync-with-raspberry-pi-under-200/>
- [152] chrony Project, *chronyc(1) Manual Page*, accessed 16.10.2025. [Online]. Available: <https://chrony-project.org/doc/3.5/chronyc.html>
- [153] ROS 2, "rosvbag2," Nov. 2025, GitHub repository, accessed 10.11.2025. [Online]. Available: <https://github.com/ros2/rosvbag2>
- [154] wadda, "gps3: Python 2.7 - 3.5 interface to gpssd," Nov. 2017, GitHub repository, accessed 10.11.2025. [Online]. Available: <https://github.com/wadda/gps3>
- [155] "GPSd - Put your GPS on the net," project page, accessed 10.11.2025. [Online]. Available: <https://gpsd.io/index.html>

Eidesstattliche Versicherung

Statutory Declaration in Lieu of an Oath

Name, Vorname/Last Name, First Name

Matrikelnummer (freiwillige Angabe)

Matriculation No. (optional)

Ich versichere hiermit an Eides Statt, dass ich die vorliegende Arbeit/Bachelorarbeit/
Masterarbeit* mit dem Titel

I hereby declare in lieu of an oath that I have completed the present paper/Bachelor thesis/Master thesis* entitled

selbstständig und ohne unzulässige fremde Hilfe (insbes. akademisches Ghostwriting)
erbracht habe. Ich habe keine anderen als die angegebenen Quellen und Hilfsmittel benutzt.
Für den Fall, dass die Arbeit zusätzlich auf einem Datenträger eingereicht wird, erkläre ich,
dass die schriftliche und die elektronische Form vollständig übereinstimmen. Die Arbeit hat in
gleicher oder ähnlicher Form noch keiner Prüfungsbehörde vorgelegen.

independently and without illegitimate assistance from third parties (such as academic ghostwriters). I have used no other than
the specified sources and aids. In case that the thesis is additionally submitted in an electronic format, I declare that the written
and electronic versions are fully identical. The thesis has not been submitted to any examination body in this, or similar, form.

Ort, Datum/City, Date

Unterschrift/Signature

*Nichtzutreffendes bitte streichen

*Please delete as appropriate

Belehrung:

Official Notification:

§ 156 StGB: Falsche Versicherung an Eides Statt

Wer vor einer zur Abnahme einer Versicherung an Eides Statt zuständigen Behörde eine solche Versicherung
falsch abgibt oder unter Berufung auf eine solche Versicherung falsch aussagt, wird mit Freiheitsstrafe bis zu drei
Jahren oder mit Geldstrafe bestraft.

Para. 156 StGB (German Criminal Code): False Statutory Declarations

Whoever before a public authority competent to administer statutory declarations falsely makes such a declaration or falsely
testifies while referring to such a declaration shall be liable to imprisonment not exceeding three years or a fine.

§ 161 StGB: Fahrlässiger Falscheid; fahrlässige falsche Versicherung an Eides Statt

(1) Wenn eine der in den §§ 154 bis 156 bezeichneten Handlungen aus Fahrlässigkeit begangen worden ist, so
tritt Freiheitsstrafe bis zu einem Jahr oder Geldstrafe ein.

(2) Strafflosigkeit tritt ein, wenn der Täter die falsche Angabe rechtzeitig berichtigt. Die Vorschriften des § 158
Abs. 2 und 3 gelten entsprechend.

Para. 161 StGB (German Criminal Code): False Statutory Declarations Due to Negligence

(1) If a person commits one of the offences listed in sections 154 through 156 negligently the penalty shall be imprisonment not
exceeding one year or a fine.

(2) The offender shall be exempt from liability if he or she corrects their false testimony in time. The provisions of section 158 (2)
and (3) shall apply accordingly.

Die vorstehende Belehrung habe ich zur Kenntnis genommen:

I have read and understood the above official notification:

Ort, Datum/City, Date

Unterschrift/Signature