mMobile: Building a mmWave Testbed to Evaluate and Address Mobility Effects

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ABSTRACT

Beamforming methods need to be critically evaluated and improved to achieve the promised performance of millimeter-wave (mmWave) 5G NR in high mobility applications like Vehicle-to-Everything (V2X) communication. Conventional beam management methods developed for higher frequency applications do not directly carry over to the 28 GHz mmWave regime, where propagation and reflection characteristics are vastly different. Further, real system deployments and tests are required to verify these methods in a practical setting. In this work, we develop mMobile, a custom 5G NR compliant mmWave testbed to evaluate beam management algorithms. We describe the architecture and challenges in building such a testbed. We then create a novel, low-complexity beam tracking algorithm by exploiting the 5G NR waveform structure and evaluate its performance on the testbed. The algorithm can sustain almost twice the average throughput compared to the baseline. We also release our outdoor mobility dataset that can be used to improve mobility management further.

CCS CONCEPTS

• **Hardware** → **Beamforming**; Wireless devices; • **Networks** → Network mobility; • **General and reference** → *Measurement*.

KEYWORDS

mmWave, 5G NR, beam-management, testbed, dataset, mobility

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1 INTRODUCTION

The 5G New Radio (NR) standard promises high data rates and new applications through the use of mmWave systems. Some of these include highly dynamic and mobile environments like those in an intersection or vehicle-to-everything (V2X) communication. However, mmWave signals attenuate relatively quicker over the air and objects, requiring directional beamforming to allow practical implementation. This requirement gives rise to a host of new challenges that the community has addressed over the past decade. Recent deployments of mmWave 5G base stations across the world have been impeded by mobility based connection losses, which points to the fact that beamforming management (beam-management) in the mobile outdoor environments is the linchpin of such networks.

There are two distinct parts in beam-management: initial beam acquisition (when the nodes power-up, or have lost the mmWave link) and beam tracking (when the link is active but has to be maintained as user moves). While there is a lot of prior work on the beam-acquisition [9, 26], the same is not valid for the latter. Added to this, a large proportion of these solutions are designed for 60 GHz IEEE 802.11 ad systems, which are different from 28 GHz 5G NR in propagation characteristics [15, 19, 20], protocol design and intended use cases [1]. To fundamentally study the underlying channel behavior in mobile mmWave systems, and effectively address beam-management from the perspective of a versatile system like 5G NR, we identify and present two critical challenges that the community has to overcome.

The first is the lack of flexible and accessible mmWave testbeds at 28 GHz, with support for full RF bandwidth, processing, and cutting edge phased array performance that 5G NR demands. To this end, we share our experiences and architectural choices in building such a testbed. It supports base station class baseband processing with custom phased arrays and allows integration with SDRs for mobile experimentation. We demonstrate an OFDM link on the testbed, with subcarrier spacing and channel bandwidth compatible with a 5G NR base station (gNB). Our testbed supports up to 256-QAM modulation at reasonable SNR, and our phased arrays [12] can sustain outdoor line-of-sight link up to 300m.

The second challenge is the design and system-level evaluation of beam tracking algorithms. As a demonstration, we design and evaluate a simple beam tracking algorithm based on channel power correlation with expected beam patterns. We verify that even such a simple algorithm can improve throughput over 1.3× in an indoor setting and 1.6× outdoors when compared to a baseline that depends solely on frequent beam-acquisition [9, 26]. As the availability of such fine-grained channel measurement data increases, more complex algorithms leveraging the accurate beamforming capabilities and the controllable nature of the 5G NR protocol can be evaluated.

Finally, the access to such a testbed is generally out-of-reach to a large research community. Cosmos project [21] is under development to allow remote access, but the mobility experiments

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would be limited to the streets of New York City. To enable the research community to test and verify novel algorithms for 5G NR mobility management, we release a one-of-its-kind mobility dataset. We build the dataset of channel measurements with two important goals. First, it should allow the testing of algorithms based on 5G NR specific features such as the SSB and CSI-RS. Second, it should easily allow other testbeds to collect and publish similar measurements. We envision this dataset will be useful for testing any new algorithm for mmWave user tracking and mobility management. The dataset is catered to meet these requirements. We release the dataset [3] and plan to add more experiments in future[1].

2 RELATED WORK

Hardware testbed: To evaluate the performance of cutting-edge applications and verify novel protocols, we need a wireless testbed with flexible configurability. Most testbeds [13, 16, 23, 29, 30] are designed for 60 GHz research based on IEEE 802.11ad which is not suitable for our design at 28 GHz for 5G New Radio. Moreover, OpenMilli [29] uses mechanically steerable horn antenna not suitable for mobile networks. X60 [23] uses expensive hardware equipment from National Instruments (over $200,000) and not affordable for most research groups. M-cube [30] uses cheap commercial phased arrays and is designated for Massive MIMO research. A similar 60 GHz testbed [10, 27] is used to demonstrate the high overhead of beam management in V2X scenarios. However, 60 GHz testbeds are not suitable for 28 GHz research because of vast differences in the phased array and circuits design. The phased arrays at 60 GHz suffers from higher feed loss and often produce irregular patterns [7]. Also, 60 GHz propagation suffers from higher path loss and atmospheric oxygen absorption at that frequency. In contrast, our testbed at 28 GHz provides a realistic channel measurements for evaluating outdoor mobility for V2X scenarios.

There are few testbeds at 24 and 28 GHz as well. MIRA [4, 9, 11] testbed uses 24 GHz phased array but is limited to only 8 antennas. IBM phased array [22] uses 64 dual-polarized antennas for beamforming, but the baseband bandwidth is limited to that provided by commercial SDRs. In contrast, our mMobile testbed consists of state-of-the-art phased arrays [12] with 64 antennas that work very well over 4GHz bandwidth (27-31 GHz). mMobile's baseband processing is done on an FPGA platform that supports up to 1 GHz of baseband bandwidth.

While commercial 5G deployment is on its early stage, many organizations are building a large scale testbed that closely resembles a real-world 5G deployment [2, 21]. For instance, COSMOS project [21] is being developed in New York City in collaboration with multiple universities and industry partners. However, such a large scale design comes with additional cost, high complexity, and hard to replicate elsewhere for mobile experiments. The COSMOS testbed is used for 28 GHz channel measurements [6] in NYC streets, focusing on large-area coverage. However, it lacks insights into improving the mmWave connectivity and throughput with proper beam management in mobile scenarios. In contrast, we have demonstrated that efficient beam tracking for a mobile user can significantly improve the link throughput for 5G NR. A comparison of mmWave testbeds is presented in Table 1.

[1]Details on our dataset can be found at https://wcsng.ucsd.edu/mmobile

Testbed	Cent.Freq	Ant.Type	#Ant.	Bandwidth
OpenMilli [29]	60 Ghz	Horn	1	1GHz
X60 [23]	60 GHz	Array	12	2Ghz
mm-Flex [13]	60 Ghz	Array	16	2Ghz
Millimetera [16]	60 GHz	Array	8	1GHz
MIRA [4]	24 GHz	Array	8	NA
IBM [22]	28 Ghz	Array	128	100 MHz
mMobile	**28 GHz**	**Array**	**64**	**1 GHz**

Table 1: Comparison of mmWave testbeds.

Mobility management: There is a decade of work that targets initial beam-acquisition, which incurs high overhead proportional to the number of beams [9, 26]. In contrast, beam tracking methods can predict beam direction under user mobility without scanning a large set of beam patterns. Most tracking algorithms proposed in the literature are evaluated in simulation with unrealistic channel models [24, 33, and references therein]. There are few approaches that are tested on a testbed with limited settings. For instance, [8] proposes the use of a wide beam to combat high mobility, which is not viable for long communication links in 5G NR. Beam-forecast [32] uses a narrowband channel model for beam tracking, which is also not suitable for wideband 5G NR. Most importantly, both techniques [8, 32] are evaluated on a 60 GHz testbed with trace-driven evaluation using a mechanically steerable horn antenna that does not emulate phased array beamforming well. In contrast, we demonstrate our tracking algorithm on our 28 GHz testbed with phased arrays using 5G NR waveforms. Finally, location assistant devices such as GPS or external sensors can be used for finding the user's direction from gNB [25, 28, 31]. However, external sensors are not ubiquitous and suffers from low accuracy. On the other hand, our tracking approach completely relies on mmWave radios without requiring external sensors.

3 5G NR BEAM MANAGEMENT

We first provide a primer on how 5G NR handles beam management and then propose a light-weight tracking algorithm that leverages the 5G NR waveform to improve the wireless connectivity and throughput under high mobility.

3.1 Primer on 5G NR

For downlink waveform, Synchronization Signal Block (SSB) and Channel Status Information Reference Signal (CSI-RS) are used for beam management, as shown in Figure 1. SSB plays an important role in the initial access procedure. It is an always-on signal and is transmitted periodically [1, TS 38.311]. Beam-sweeping is applied to SSB. Specifically, gNB uses different beamforming vector on each SSB so that they can periodically scan all the areas it should cover. The duration of SSB depends on the number of SSB to be sent in each period, corresponding to the number of beams that gNB tries in beam-sweeping. The user equipment (UE) will measure the received SSB and report measurement [1, TS 38.215] to gNB so gNB will know the best beam.

Although SSB is important for initial access, it takes the air time and thus brings overhead. The overhead is determined by the SSB

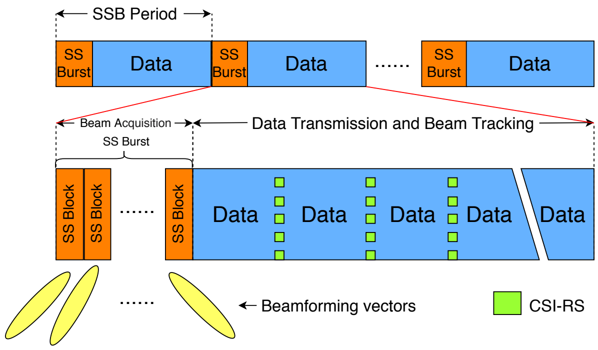


Figure 1: 5G NR downlink waveform structure.

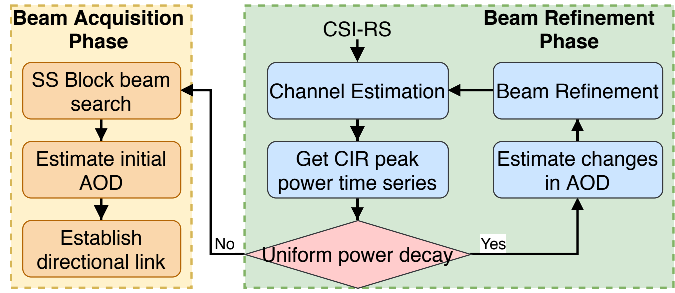


Figure 2: Design Overview: The beam acquisition phase establishes a directional link, and the beam refinement phase periodically refines the beam providing a proactive response to the user's mobility.

duration in each period and its periodicity. If gNB sends the maximum number of SSB, the duration will be 5ms. The transmission period of SSB varies from 5ms to 160ms [1, TS 38.311]. If we assume the system to be TDD so the time slots for SSB will not transmit data, SSB will take at least 1/18 of the air time and may take all of the air time (5ms out of 5ms to 160ms period). The overhead can be reduced by reducing SSB duration and increasing the period. We can reduce the duration of SSB by using efficient beam acquisition schemes rather than exhaustive searching. But there is a tradeoff to reduce the frequency of SSB. For high mobility, the link will degrade faster, and we might need SSB more frequently.

After the connection is established, CSI-RS provides the knowledge of propagation channel[1, TS 38.215] used for beam tracking, and it incurs less overhead compared to SSB. It can be transmitted periodically or aperiodically, and if periodically sent, its period varies from 4 slots to 640 slots, which is 0.5 ms to 80 ms for 120 kHz subcarrier spacing. One CSI-RS only occupies one symbol in the slot [1, TS 38.211]. So the overhead caused by CSI-RS is much less compared to SSB. If we can use CSI-RS to efficiently track the beam, we can avoid frequent SSB, thus reducing the total overhead.

3.2 Low-complexity Tracking Algorithm

5G NR provides a highly customized waveform and leaves the detailed implementation and mobility management specific to vendors. We propose a simple design of mobility management for 5G NR, as shown in Figure 2. The proposed beam refinement phase is specifically designed to reduce the high overhead of initial beam-acquisition. The beam refinement phase tracks the user movement and estimates the changes in angle of departure (AOD) over time without scanning multiple beam patterns. We leverage the high periodicity of CSI-RS to collect fine-grained channel data and use it to estimate the angle of user movement. In particular, we take the channel impulse response (CIR) for each CSI-RS measurements and observe the peak power corresponding to the direct path. Mathematically, the signal power P_R is given by

$$P_R = P_T + G_T(\theta) + G_R - P_h \tag{1}$$

where P_T is transmit power, $G_T(\theta)$ and G_R are transmit and receive gain respectively, and P_h is power decay due to channel impairments. Our key observation is that the direct path power correlates with the beam pattern at the gNB, which is a function of AOD θ as follows:

$$G_T(\theta) = \frac{\sin(N\theta/2)}{N\sin(\theta)} \tag{2}$$

where N is the number of antennas in a uniform linear array. Thus, we use an inverse function to estimate θ from the measured power. We assume the UE uses a quasi-Omni beam pattern that doesn't affect the channel with user mobility. To reduce the impact of noise and other channel impairments, we employ a Kalman filter on channel power measurements. The tracking of direct path power is not affected by multi-paths due to the sparsity of mmWave channel and the use of highly directional antennas [5, 18, 26]. Most importantly, our simple tracking algorithm achieves high accuracy in practice due to well-designed testbed with state-of-the-art phased arrays and less severe channel propagation at 28 GHz compared to other works at 60 GHz. We verified the robustness of our algorithm with indoor and outdoor channel measurement traces in Section 6.

4 REQUIREMENTS AND CHALLENGES

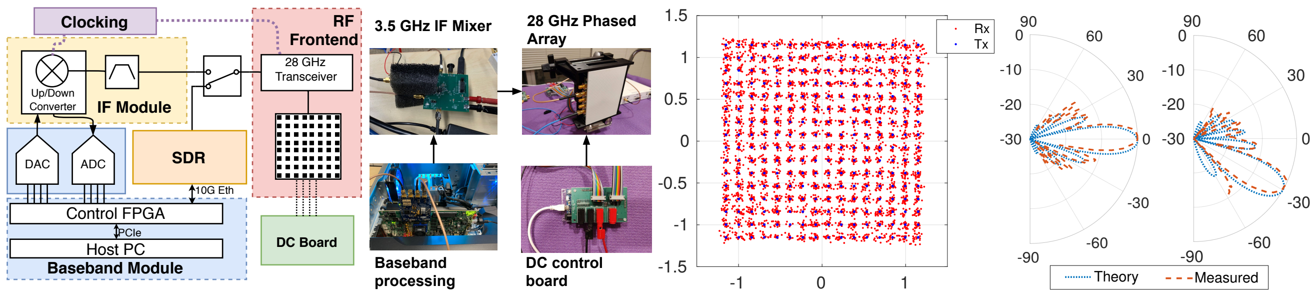
This section discusses the requirements and challenges in building a testbed oriented toward evaluating the effects of mobility in mmWave systems.

(i) Small form factor for mobile node: A form factor would allow the system to be mounted on vehicles for evaluating V2X scenarios. It requires a small and modular design of phased arrays integrated with mixers and amplifiers. Moreover, the mobile node's baseband processing should support 100 MHz bandwidth requisite by 5G NR standards. Finally, all these components have different power requirements that need to be supplied through a single battery (e.g., an available 12 V supply from a car).

(ii) High processing for gNB: The gNB needs to support up to 400 MHz of bandwidth, which cannot be met by commercial SDRs. It requires high-speed ADCs controlled by a powerful processor and FPGA. The gNB would be static and can be powered by an electric socket.

(iii) Fast control and calibration: The phased arrays need to interface with a microcontroller for fast switching between beam patterns. Moreover, some phased arrays [17] require calibration of antenna phases to generate desired beam patterns.

(iv) Clock and synchronization: The baseband sampler and up/down converter requires a stable clock to reduce system phase noise.



(a) (b) (c) (d)

Figure 3: (a) Block diagram mMobile testbed that has 2 ADC's and 2 DAC's, each sampling at 1 Gsps, which is converted to the IF stage of 3.5 GHz, and then the signal is provided to RF frontend which upconverts to 28 GHz and transmits through a phased array with 64 antennas. The node can configured to be transmit/receive with a T/R switch (b) Setup of mMobile testbed for gNB (c) 256-QAM constellation. (d) Beam patterns measured in an anechoic chamber compared with theoretical patterns.

Moreover, 5G NR uses OFDMA-based waveform, which is susceptible to frequency offsets between gNB and UE and requires tight synchronization.

(v) Experimentation and mobility dataset: While the testbed architecture itself may be useful to members of the community to build one of their own, and it would be beneficial to be able to test beam-management algorithms without the need to invest and set up hardware. Allowing remote experimentation and access is one straightforward way, but it involves a significant investment in the testbed's maintenance year-long. Added to that, limiting the testbed to remote experimentation would force the experiments to be confined to a few pre-decided scenarios, and a few users. Therefore, we believe that a well-designed dataset from multiple measurement campaigns [3] would be far more tractable and useful.

5 TESTBED ARCHITECTURE

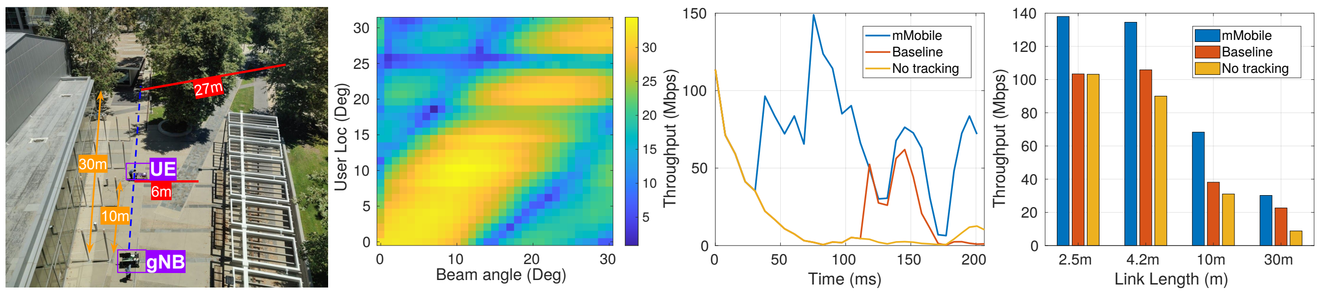
The need for 5G NR compliance sets up some requirements for mMobile. An RF bandwidth of at least 400 MHz is required for gNB class performance. Further, low phase noise and synchronization has to be ensured for OFDM performance. With large RF bandwidth, it follows the requirement of fast baseband processing to support it. Typical mmWave systems further require an IF bridge between the baseband and RF. Finally, to allow for larger flexibility, especially for mobile experiments, there is the requirement of a modular design.

Overview: mMobile uses a superhet architecture with an IF frequency of 3.5 GHz, typical to other similar systems. The baseband processing is implemented on an FPGA with a commercial Gigasample ADCs/DACs module, capable of supporting well over the required bandwidth. The wideband processing is matched at the IF and RF using wideband mixers and phased arrays. A clock distribution system supplies reference frequencies for the IF and RF mixing stages. Each module in the system may be replaced with a COTS alternative of similar specifications. The architecture is illustrated in Figure 3(a) and our set up is shown in Figure 3(b).

Configurable Baseband module: Software-defined radios (SDRs) such as USRPs are commonly used as baseband platform since they provide easy integration, experimentation, and debugging [22]. Most SDR works for a wide range of frequencies up to 6 GHz, and therefore they are suitable for directly providing the IF signal required for the 28 GHz link. However, the downside of SDRs is that they are limited by bandwidth (< 150 MHz for USRP X310). 5G NR specifications allow for up to 400 MHz of bandwidth in FR2. Such high bandwidth baseband processing requires high-performance FPGAs and ADC/DACs, but the FPGA setup may be bulky and power-hungry. To allow for both low and high bandwidth applications, we use a configurable baseband module that can be switched between a USRP or an FPGA platform. For the high bandwidth node, a Xilinx KCU105 is used in conjunction with the Analog Devices FMCDAQ2. An external mixer (Qorvo RFFC5071A) is used to upconvert the FMCDAQ2 I/Os to the required IF frequency of 3.5 GHz. The digital processing pipeline uses PCIe to link to the host computer using a reference implementation like [29]. The low bandwidth SDR-based baseband module consists solely of a USRP X300 SDR with SBX-120 daughtercard to support 100 MHz bandwidth requirements at the UE.

Phased array and Calibration: Most phased arrays pose a random phase offset due to hardware imperfections at each antenna element corrupting the desired beam pattern. We use a simple scheme to calibrate the array as follows. We fixed one of the antennas as a reference and set its phase to zero. We then take one other antenna and vary its phase for all possible values. We measure the received signal strength (RSS) using a horn antenna in an anechoic chamber for all these phase values. Mathematically, the RSS is $|1 + e^{j\phi}e^{j\psi}|^2 = 4\cos^2(\phi/2 + \psi/2)$ where ϕ is the configured phase shift and ψ is the random phase offset between the two antennas. We observe that we can estimate ψ by simply looking for which configured phase gives the highest RSS. However, looking for the highest RSS is prone to errors because of a broad maximum. We instead look for a sharp minimum and add 180^o offset to get the phase calibration factor ψ. We can repeat the process to calibrate all the antennas relative to the reference antenna. We tested and verified our calibration routine with phased arrays from pSemi [17]. We also worked with phased arrays [12, 14], which does not require calibration.

IF design and Image rejection: The IF design requires the conversion of the signal from baseband to the IF frequency. We explore two choices of IF mixer design. An IQ mixer takes the I and Q signal from the DAC and combines them using two 90^o phase-shifted LO. However, we found that most commercial IQ mixers in our desired frequency range are either passive mixers requiring high power LO and amplifiers or suffer from low bandwidth. In our current implementation, we choose another IF design that implements the



(a) (b) (c) (d)

Figure 4: (a) Outdoor experimental scenario, (b) Received Signal Strength for the outdoor 10m link, (c) Tracking time series for the 10m link, (d) Average throughput performance for different gNB-UE links.

IQ mixing in the digital domain and uses a single channel mixer. We handle the image rejection at the receiver using a requisite filter.
Clock distribution module: The clock distribution is an essential aspect of a 5G testbed. In a heterodyne architecture, we require three clocks for the baseband module, IF mixer, and the RF mixer. We use an ADF5355 based clock distribution system to generate synchronized 12.5 GHz and 3.5 GHz clocks for the IF and RF. We also connected a GPS disciplined oscillator (GPSDO) that uses GPS signals and a high-quality oscillator to provide a stable clock and remove any sampling frequency offsets.

We use a custom transceiver module to up/downconvert between the IF and 28 GHz. The transceiver module drives the 8x4 dual-polarized phased array (64 antennas) with 6 bits phase depth and 27 dB amplitude range [14]. The transceiver module contains a 4x clock multiplier and is clocked by a 6 GHz signal from a ADF5355 PLL. The transceiver uses this clock to upconvert signals from an IF of 4 GHz. We use an Artix-7 based FPGA to control the time-critical phased array beamforming weights through SPI. We also designed a power regulator board (DC Board) that takes a single 12 V supply and powers the array, up/down converters, and fan. We have tested our architecture with three different phased arrays [12, 14, 17].

6 EVALUATION

Testbed Evaluation: We show that mMobile is well designed and can support 5G NR specifications. We established a link with 240 kHz subcarrier spacing with a bandwidth of 50 MHz. The radiated transmit power is fixed to an EIRP of 30 dBm. Figure 3(c) shows that mMobile can support a high throughput link with up to 256-QAM constellation with the bit error rate as low as 0.0022 without channel coding. We have also verified that our FPGA baseband platform can be used as gNB with high bandwidth of 400 MHz required for 5G NR. Finally, we show that our phased array module can produce the desired beam patterns in Figure 3(d) when measured in an anechoic chamber.

Mobility Dataset: We collect a channel measurement dataset for a variety of indoor and outdoor scenarios. This dataset is curated to allow the development and evaluation of beam-management algorithms without requiring the testbed itself.

Table 2 describes our dataset, which consists of multiple indoor and outdoor experiments for up to 30 m gNB-UE link. In each experiment, we fixed the location of the gNB and moved the UE with an increment of roughly one degree. The table specifies the direction of user movement with respect to gNB-UE link, distance resolution, and the number of user locations for which we conduct channel measurements. Outdoor 30 m data also contains blockage between 3.9 m to 4.8 m, as shown in Figure 4(a). For each experiment, the UE starts with facing the gNB and then move in a straight line at an angle given by *MovingDir* in Table 2. At each UE location, we scan the transmission beam and collect channel data for each beam. By doing so, we can get the full OFDM channels for different locations along the moving trajectory with all the beam angles (Figure 4(b)). Moreover, we use 240 kHz subcarrier spacing, which is consistent with the 5G NR numerology at FR2, so the data we collect will be a true reflection of what a 5G UE will see.

Setting	LinkLen	MovingDir	Resol.	#pts	Blockage
Indoor	2.5m	90^o	0.1m	21	✗
Indoor	4.2m	90^o	0.1m	32	✗
Outdoor	10m	90^o	0.2m	31	✗
Outdoor	30m	120^o	0.6m	45	✓

Table 2: mMobile mobility dataset

We collected the dataset by manually moving the UE at different locations on a grid to acquire accurate ground truth location data. We emphasize that this location-based data can be analyzed for any speed of user movement. Different user speeds will have a different frequency of CSI-RS channel measurements with time. For instance, the UE moving at 30 m/s (1 m/s) will have channel data every 6.6 ms (200 ms) for the outdoor 10 m dataset. Finally, the dataset is collected with fine distance resolution to be used for CSI-RS based tracking. However, a low-resolution variant of the dataset can also be used to evaluate SSB-based beam-acquisition algorithms in practical settings. Further details on our dataset can be found at [3].

Tracking results: The gNB establishes a directional link with the UE that provides the best throughput at the time of beam acquisition. However, as the user moves, the same link will suffer from beam-misalignment and loss in throughput. In Figure 4(c), we show that the link throughput reduces significantly by the time the UE moves by 50 ms and decays further as the user moves ahead. In this example, we considered a typical V2X scenario with an outdoor 10 m link and a vehicle moving at 30 m/s. We implement our low-overhead tracking and realign the beam every 33 ms (CSI-RS periodicity). We show that our beam tracking algorithm can effectively maintain a high throughput link throughout under user mobility for 200 ms without requiring additional beam-acquisition phase. We compare our results against a baseline that implement frequent high-overhead beam-acquisition to overcome outage due to the user's mobility. The baseline implements beam-acquisition with double frequency (every 100 ms). Figure 4(c) shows that the baseline revives the link from the outage, but it cannot support a high throughput link for a long duration. On the other hand, our low-complexity tracking can sustain a stable high-throughput mmWave link without an exhaustive scan.

The throughput results for all four datasets are shown in Figure 4(d). The 2.5 m and 4.2 m results are for indoor settings, and the 10 m and 30 m results are obtained from outdoor experiments. We show our CSI-RS based tracking algorithm significantly outperforms the baseline that is solely dependent on repeating the beam acquisition with a higher frequency. In a nutshell, we obtained 1.3× throughput gain in indoor settings and 1.6× improvement outdoors compared to the baseline.

7 DISCUSSION AND FUTURE WORK

We have built a testbed for 28 GHz 5G NR and observed that propagation is fundamentally different and presented an initial algorithm by leveraging the synchronized 5G NR waveform framework to perform a fast beam acquisition and beam tracking algorithm for a single user. In our future work and potential extension, we would demonstrate the algorithm to scale to multiple users. Furthermore, given the ability to connect with a highly mobile UE, we would demonstrate that it is working in high outdoor mobility while supporting multi-users.

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