



Proactive Beam Management in FR2 Open RAN for Digital Twin-Assisted Industrial 6G Environments

Niklas A. Wagner, Louay Hito, Marco Danger, Christian Wietfeld

Chair of Communication Networks, TU Dortmund University, 44227 Dortmund, Germany

Email: {niklas.wagner, louay.hito, marco.danger, christian.wietfeld}@tu-dortmund.de

Abstract—High-capacity and low latency millimeter-Wave (mmWave) communications in 5G and future 6G networks rely on directional beamforming to overcome increased path loss. Beam management in mobile scenarios requires frequent beam alignment, which introduces significant signaling overhead and latency with exhaustive search and hierarchical approaches, especially under volatile radio conditions in factory environments. This work presents a Digital Twin (DT)-assisted proactive beam management framework in FR2 Open Radio Access Network (Open RAN), implemented end-to-end with a commercial Open RAN Radio Unit (O-RU) and the OpenAirInterface (OAI) stack. The proposed approach exploits a synchronized digital representation of the physical system to proactively align beam directions using a lightweight geometric model, reducing measurement-based beam sweeping overhead while using the full beam codebook. Experimental evaluation at 28.7 GHz validates the procedure in a reproducible lab setup and in a case study within an industrial transfer environment with metallic obstructions and passive reflectors. Compared to a reactive baseline with four mobility-aware beams, the proactive approach eliminates the up to 32.8% beam-restricted resources practically observed, and thus achieves 46% higher downlink and 53% higher uplink throughput with more stable performance under mobility.

Index Terms—6G, Digital Twins, Industrial Wireless Networks, mmWave, Open RAN, Proactive Beam Management

I. INTRODUCTION

Millimeter-Wave frequencies in FR2 (Frequency Range 2), starting at 24 GHz, and future FR3 frequencies in upper mid-band from 7 GHz to 24 GHz, promise multi-gigabit data rates in 6G cellular networks by offering substantial bandwidth. In FR2 and the upper part of FR3 [1], increased path loss necessitates directional beamforming to achieve sufficient link budget [2]. Beam management, which encompasses beam selection, tracking, and recovery, becomes critical in mobile use cases, where optimal beam directions change continuously.

Traditional reactive beam management relies on exhaustive beam sweeping, where the base station transmits multiple Synchronization Signal Blocks (SSBs) on different beams. The User Equipment (UE) measures the received signal strength and reports the strongest SSBs received to enable beam selection at the base station. Within the broader SSB beams, beam refinement using Channel State Information Reference Signal (CSI-RS) can be performed for hierarchical beamforming [3]. In the following phase, the UE aligns its receiving beam. While this approach is robust, it incurs substantial signaling overhead and additional delay that can be problematic in high-mobility Non-Line-of-Sight (NLOS) scenarios with changing volatile channel conditions.

Advances in Open Radio Access Network (Open RAN) enable flexible software-defined implementations that facilitate integration of customized algorithms [4]. Here, beam management in end-to-end networks is supported through the Open Fronthaul [5]. Context-aware Digital Twin (DT) approaches, maintaining a synchronized digital representation of a physical system [6], offer a robust concept for proactive beam management, choosing beams based on propagation or predictive models instead of relying solely on measurements.

In industrial environments, Industry DTs (IDTs) are often employed to model factory layout, including machinery and robot trajectories, which can be leveraged to predict beam directions and anticipate blockages. The proposed coupling between IDT and Network DT (NDT) enables efficient proactive beam management to robustly use Intelligent Reflecting Surfaces (IRSs) in specific NLOS regions, as seen in Fig. 1.

To the best of the authors' knowledge, this work presents the first implementation of a proactive beam management framework with a commercial FR2 Open RAN Radio Unit (O-RU) and OpenAirInterface (OAI), enabling an end-to-end DT-based approach for real-world industrial environments.

The paper makes the following main contributions:

- DT-assisted beam management framework for mmWave networks with IRS based on the OAI software platform.
- First study of FR2 Open RAN with Split 7.2 using OAI deployed at industrial-environment scale.
- Evaluation of the proposed framework in terms of performance, overhead, and stability under mobility.

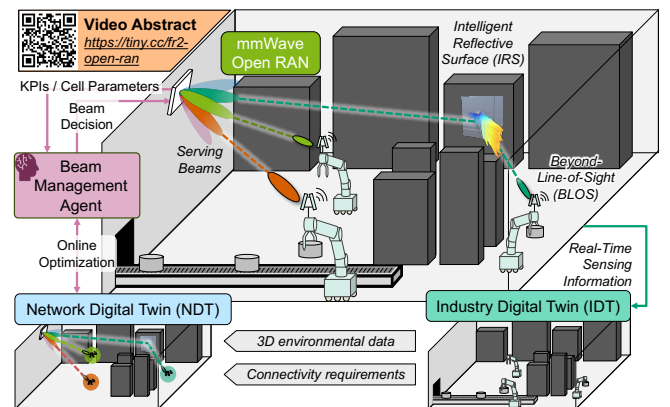


Figure 1. Overview of the DT-assisted proactive beam management framework in FR2 Open RAN. The IDT provides mobility and connectivity requirements; the NDT maintains a representation of the radio environment.

The remainder of this paper is organized as follows: Related work on context-aware beam management and Open RAN FR2 networks is reviewed in Sec. II. The proactive DT-based beam management is described in Sec. III and validated with the FR2 Open RAN setup in Sec. IV. The evaluation in Sec. V provides a case study in an industrial transfer environment. Lastly, Sec. VI concludes the paper and outlines future work.

II. RELATED WORK

Beam management in cellular 3rd Generation Partnership Project (3GPP) networks is largely measurement-driven, relying on SSB and CSI-RS-based sweeping and reporting [2]. This frequent sweeping can consume non-negligible radio resources, motivating approaches that reduce the online search space using environmental context information or AI/ML methods, as discussed for 3GPP Release 19 [2].

Context-aware beam management augments radio measurements with mobility or environmental cues to prioritize promising candidate beams. For instance, [7] utilizes vehicle context to reduce unnecessary sweeps in vehicular links. Similarly, sensing-assisted methods exploit non-RF modalities, such as LiDAR point clouds, to anticipate blockages and narrow the set of candidate beam pairs [8]. While these approaches can reduce online probing overhead, purely data-driven methods may degrade when sensed context is noisy, stale, or temporarily inconsistent with the radio environment.

Extending the sensing capabilities, DT-enabled beam management leverages continuously updated digital representations of the physical system to support proactive beam decisions. DTs are characterized by bidirectional synchronization between physical and digital representation [6]. Existing designs exploit this concept to derive spatial priors for beam selection, such as using obstacle-aware real-time ray tracing to reduce overhead in indoor scenarios [9], or combining DTs with AI methods and sparse measurements to predict narrow beams [10]. Additionally, vision-assisted creation of DTs [11] has been proposed to enhance the DT model fidelity.

With the O-RAN specification, the Open Fronthaul Interface [5] standardizes open interfaces, enabling integration of flexible beam control logic and open control. Integrating reconfigurable IRS with Open RAN, [12] demonstrates a study with Software-Defined Radio (SDR) and channel emulation at sub-6GHz frequency bands, while [16] orchestrates a custom RIS for mmWave sensing with waveforms generated by OAI. End-to-end Open RAN mmWave testbeds beyond simulation or emulation enable real-world assessment of flexible beam management under realistic conditions. Prior work on FR2 Open RAN has mainly explored testbeds with SDR. Using the OAI software platform [17], several works have implemented mmWave testbeds with SDRs and diverse beamformers [13]–[15]. Here, [14] integrates custom phased arrays with the OAI stack and SDR to study real-time beamforming control. Camera-assisted beam management has been demonstrated also on an OAI-based SDR platform, where visual sensing triggers proactive beam switching toward predefined alternative directions [15]. Table I classifies the discussed works with

Table I
COMPARISON OF RELATED WORK APPROACHES WITH RESPECT TO EVALUATION PLATFORM AND OPEN RAN INTEGRATION.

Ref.	Context	Platform	Freq.	Split	IRS	Mob.	E2E
<i>Context- and sensing-aided beam management</i>							
[7]	Vehicle state	Simulation	28 GHz	–	–	✓	–
[8]	LiDAR + pos.	Simulation	60 GHz	–	–	✓	–
<i>Digital-twin-assisted beam management</i>							
[9]	Ray tracing	Simulation	–	–	–	(✓)	(✓)
[10]	DT + AI/ML	Testbed/DT	28 GHz	–	–	(✓)	–
[11]	Vision DT	Sim./Dataset	–	–	–	–	–
<i>SDR-based Open RAN / IRS testbeds and studies</i>							
[12]	–	SDR + IRS	<6 GHz	8	em.	(✓)	–
[13]	Camera	SDR (OAI)	28 GHz	8	–	(✓)	✓
[14]	–	SDR (OAI)	28 GHz	8	–	–	✓
[15]	Camera/LiDAR	SDR (OAI)	28 GHz	8	–	(✓)	✓
[16]	–	SDR + IRS	39 GHz	8	✓	–	–
This Work	Geom. DT + Ray Trac.	COTS FR2 O-RU	28.7 GHz	7.2	✓	✓	✓

Split: functional split (7.2: intra-PHY; 8: PHY/RF); IRS: passive or reconfigurable reflecting surface in the loop; Mob.: mobility evaluated with measured KPIs; E2E: end-to-end deployment including core network.
✓ fully supported, (✓) partially or emulated, – not addressed; em.: emulated.

respect to evaluation platform and Open RAN integration. Concepts of real-time control loops in Open RAN enable future modular integration of proactive and AI-driven multi-dimensional scheduling [4].

Building on these directions, we implement and evaluate the DT-enabled proactive beam management within OAI via O-RAN Split 7.2 with a Commercial Off-The-Shelf (COTS) FR2 O-RU and UE instead of previous lower-power SDR testbeds, enabling evaluation of beam management strategies under mobility in larger-scale industrial environments.

III. DIGITAL-TWIN-ASSISTED PROACTIVE BEAM MANAGEMENT FRAMEWORK

In this section, we describe the architecture and design of the proposed DT-assisted proactive beam management framework in the Open RAN architecture. We first present the overall system architecture, including the components of the NDT and its interaction with the physical system and IDT. Then, we detail a first proactive geometry-based beam management procedure that leverages the DT model to determine optimal beam directions for both Line of Sight (LOS) and NLOS scenarios via IRSs.

A. System Architecture of the DT-Assisted Beam Management

For proactive beam management, we develop a coupled IDT and NDT framework as depicted in Fig. 2, operating in near-real-time. The NDT maintains synchronized representations of the Open RAN, UE, and environment. Meanwhile, the IDT provides connectivity requirements and live environmental information about vehicles and machinery layout.

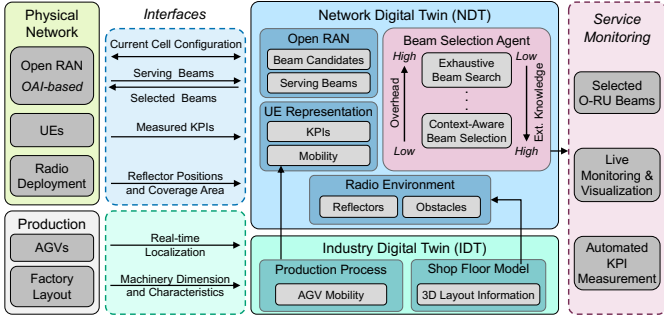


Figure 2. System architecture of the DT-assisted beam management framework. The NDT supports the proactive beam management procedure. Environmental information from the IDT is ingested for real-time adaptation.

Using this information, the beam selection agent in the NDT provides the DT-assisted beam selection. The Open RAN representation within the NDT is comprised of the following parameters provided by the Open Distributed Unit (O-DU):

- SSB frequency and position parameters from the currently applied configuration in the Open RAN.
- Beam candidate set with center directions in azimuth-elevation domain of the O-RU.
- Current serving beams and associated SSB indices.
- Channel State Information (CSI) reports from the UEs including the reported SSBs and their Synchronization Signal Reference Signal Received Power (SS-RSRP).

The UE representation includes mobility information based on external tracking systems like a robotic arm or an optical reference system coupled via the IDT. Additionally, the NDT can ingest passive and active measurements, like SS-RSRP, and bi-directional throughput for service-level monitoring. The radio environment is represented by obstacles and IRSs. Reflectors enable Beyond-Line of Sight (BLOS) connections and are characterized by their position and coverage region. Information exchange between the physical systems and DTs is realized via ZeroMQ publish-subscribe messaging.

B. Proactive Geometry-Based Beam Management

In the following, we detail the geometric beam selection process. The proactive beam management combines information from the IDT with the NDT's geometric model as seen in Fig. 3 to predict the serving beam without exhaustive probing. For calculating the relative LOS path $\mathbf{v}$, the UE position $\mathbf{p}_{\text{UE}} = [p_x, p_y, p_z]^T$ is transformed into the local O-RU reference frame through inverse rotation $\mathbf{R}^{-1} = \mathbf{R}^T$:

$$\mathbf{v} = \mathbf{R}_{\text{RU}}^T (\mathbf{p}_{\text{UE}} - \mathbf{p}_{\text{RU}}) \quad (1)$$

where $\mathbf{R}_{\text{RU}}$ is the rotation matrix representing the orientation of the O-RU in a common global frame. Similarly, the positions of reflectors $\mathbf{p}_{\text{IRS}}$ are integrated (cf. Fig. 3) for potential BLOS beam selection. The respective beam azimuth ϕ and elevation θ angles are:

$$\phi = \text{atan2}(v_y, v_x), \quad \theta = \text{atan2}\left(v_z, \sqrt{v_x^2 + v_y^2}\right) \quad (2)$$

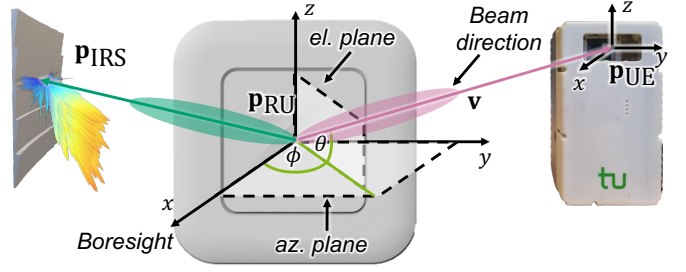


Figure 3. Geometric relationship between the O-RU, UE, and reflector positions in the O-RU spherical beam coordinate domain inside the NDT.

Within the NDT, the beam selection agent selects the best serving beam $b_{\text{serv}}^* \in \mathcal{B}$ of the beam set $\mathcal{B}$ by minimizing the Euclidean distance in the azimuth-elevation domain:

$$b_{\text{serv}}^* = \arg \min_{b \in \mathcal{B}} \|\mathbf{d}_{\text{UE}} - \mathbf{d}_b\|_2 \quad (3)$$

where $\mathbf{d}_{\text{UE}} = [\phi, \theta]^T$ denotes the direction from O-RU to UE in the local azimuth-elevation domain, and $\mathbf{d}_b$ denotes the center direction of a candidate beam b . Hence, for single or clustered users, only a single SSB aligned with the dynamic serving beam has to be transmitted, substantially reducing overhead. If the NDT detects a UE in an NLOS region, its beam is configured toward a suitable reflector position $\mathbf{p}_{\text{IRS}}$.

IV. VALIDATION OF THE FR2 OPEN RAN SETUP

This section describes the Open RAN FR2 testbed to validate the proposed proactive beam management framework within OAI. The testbed is deployed in lab and indoor industrial transfer environments as seen in Fig. 4a and Fig. 4b, respectively. While this section focuses on a systematic lab-scale validation, Sec. V provides a case study in a transfer environment with typical factory conditions including metal obstacles, IRSs and dynamic UE mobility.

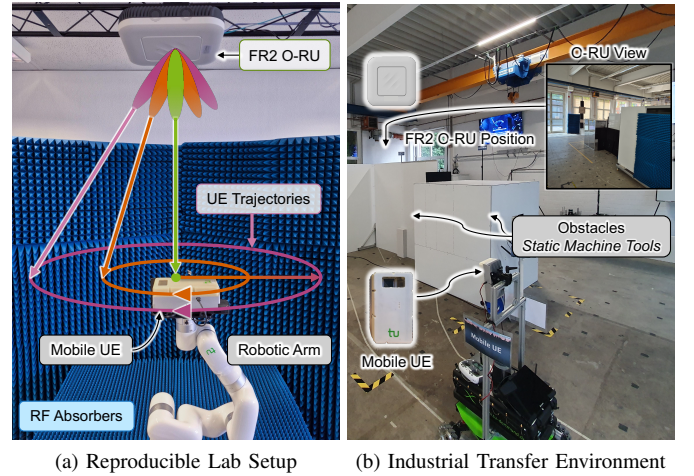


Figure 4. Evaluation testbeds at lab-scale and industrial transfer environment. While the controlled lab setup enables reproducibility for algorithm validation, the industrial environment provides real-world propagation conditions.

A. Hardware Platform and Cell Parametrization

The subsequent measurements in the Open RAN mmWave testbed are conducted at 28.7 GHz with 100 MHz of bandwidth. Detailed specifications of the end-to-end testbed components are provided in Table II. The COTS O-RU, which is also suitable for larger halls due to its output power, integrates an 8×8 planar antenna array with a vendor-fixed 65-beam codebook. It interfaces with the OAI O-DU via the O-RAN Split 7.2a [5]. Time synchronization between O-DU and O-RU is realized via Precision Time Protocol (PTP) with a GNSS-disciplined grandmaster clock. The Open RAN OAI stack is deployed including core network in New Radio (NR) Standalone mode, enabling end-to-end measurements with COTS mmWave UEs.

B. Validation of the Proactive Procedure in the Lab Setup

For beam characterization and DT model validation, we employ a COTS FR2 UE (cf. Table II) in the lab environment, mounted on a robotic arm as shown in Fig. 4a to perform automated measurements. The robot executes a trajectory of concentric circles at a starting radius of 530 mm and arc step 25 mm, yielding 28,000 samples, traversing 21 of 65 beams.

First, we assess the SS-RSRP without active beam management, using only a static boresight beam. The resulting measurements in Fig. 5-left show a strong power gradient with a peak of -44 dBm at the center and rapid decay to below -65 dBm at the edges. The observed half-power beamwidth of the main lobe of less than 20° shows a narrow beam with limited sidelobes. Next, we apply the proactive beam management procedure to select the optimal beam based on the DT model, as visualized by the Voronoi cells around the beam centers. The resulting beam selection and corresponding SS-RSRP in Fig. 5-right show that the procedure applies a suitable beam at each position, yielding a nearly constant power level of -44 dBm, which corresponds to the maximum RSRP value the UE can report [3] due to the close distance.

Table II
DETAILS ON THE FR2 OPEN RAN TESTBED COMPONENTS

	Parameter	Description/Value
Open RAN	Radio Unit	LITEON FlexFi FR2 (O-RAN Split 7.2a)
	Antenna Array	Aethertek IRIS (8×8, cross-polarized)
	Max. Beam Angle	$\pm 60^\circ$ in azimuth and elevation
	Fronthaul Switch	Fibrolan Falcon RX
	CU / DU Platform	AMD Ryzen 9 7950X, 64 GB RAM,
	CU / DU Software	OAI [17], base commit: 5fcd456a
	Operating Frequency	28.7 GHz, 100 MHz Bandwidth
	MIMO Configuration	2x2 DL (2 layers) / 2x2 UL (2 layers)
	Max. TX Power	47 dBm EIRP
	Modulation Order	Max. 64-QAM (UL and DL)
	Slot Structure	120 kHz SCS, TDD pattern: 7D1S2U
	Deployment	3GPP NR Standalone with 5GC [18]
UEs	Device Model	Quectel 5GDM01EK with RG530F-EU
	mmWave Antenna	Quectel RA530T with four QTM547 (8×8, cross-polarized)
	Max. TX Power Capabilities	ca. 48 dBm EIRP (Power Class 1) Release 16, incl. NR Standalone

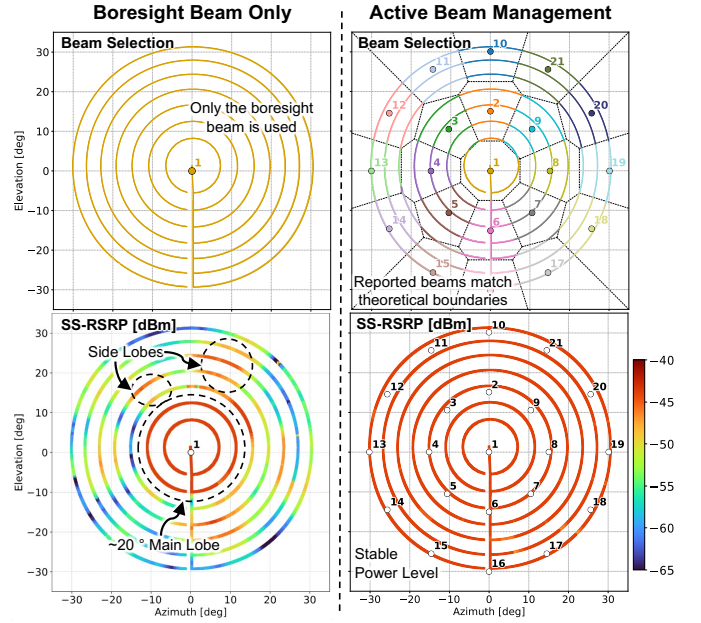


Figure 5. Validation of the beam management procedure in the laboratory testbed. Measurements are shown with boresight beam only (left) and active beam management (right) for applied beam (top) and SS-RSRP (bottom).

C. Signaling Overhead by Beam Management in OAI

Analyzing the signaling overhead with analog beamforming and the current slot-based beam scheduling in OAI, the baseline reactive approach with n SSBs requires n downlink slots with different beams for SSB/System Information Block 1 (SIB1) transmission, totaling $(n - 1)$ beam-restricted slots not available for data transmission on another beam. In uplink, with standard Physical Random Access Channel (PRACH) configuration index 135, each tenth slot contains PRACH in each beam direction successively, leading to $14/32(1 - 1/n)$ of available uplink symbols being beam-restricted. For 4 SSBs and 10 ms burst periodicity, this results in ca. 5% of the available slots in downlink and 32.8% in uplink. Dependent on the number of SSBs beams, the beam-restricted slots increase, e.g., for 8 SSBs 11.8% of downlink and 38.3% of uplink slots get beam-restricted. The proactive approach with single SSB per active serving beam eliminates beam-restricted slots, as only beam directions with users are active, still enabling selection from the full beam set. With the proactive procedure validated and practical reactive constraints analyzed, we next assess their performance.

V. CASE STUDY IN AN INDUSTRIAL ENVIRONMENT

This section presents the case study for evaluation of the proposed proactive beam management framework in a real-world industrial transfer environment using the developed Open RAN FR2 testbed in a mobile scenario.

A. Scenario in the Indoor Hall Environment

The industrial measurements are conducted in a transfer hall environment with a layout dominated by large metallic

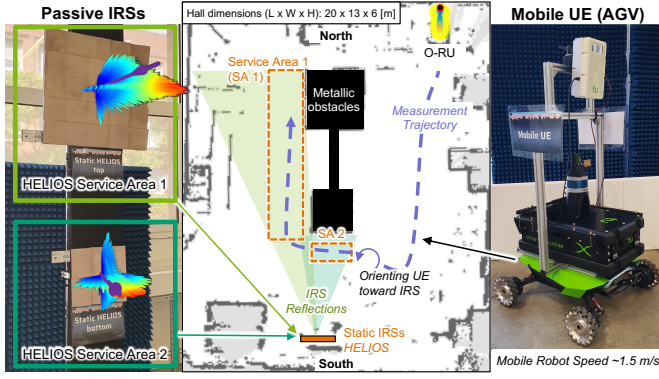


Figure 6. Overview of the industrial transfer environment with O-RU and HELIOS IRS deployment as well as the mobile UE measurement trajectory.

structures that strongly affect mmWave propagation, as shown in Fig. 6. Central obstacles separate the accessible assembly area into two elongated corridors merging at the southern end. In the deployment, the O-RU is mounted 2 m above the floor in the northern corner of the hall and operates at an EIRP of 23 dBm, below its maximum of 47 dBm, to suit the hall dimensions. For the IRSs, we employ two customized HELIOS [19] passive IRSs. Both IRSs are mounted on the south side of the hall, with the upper IRS creating a broader reflection toward the western side of the hall, serving BLOS Service Area 1 (SA1). Meanwhile, the lower HELIOS is optimized for Service Area 2 (SA2). This general scenario was also employed in a previous study with a *closed-source* FR2 network and is further described in [20].

In this environment, the IDT receives position updates from an optical tracking system and combines them with the machinery layout of the hall. Subsequently, the NDT estimates future blockage conditions and computes suitable beam directions for the O-RU by incorporating the characteristics of the passive IRSs from ray-tracing via their radar cross-sections (cf. Fig. 6 on the left). The resulting Radio Environment Map (REM) for the NDT is shown in Fig. 8.

The following measurements are performed with the UE mounted on a mobile robot (cf. Fig. 6-right) representing an Automated Guided Vehicle. During the high mobility measurement campaign, it traverses the hall at a speed of up to 1.5 m/s representative for industrial logistics applications, but challenging for FR2 beam management as rapid channel variations and frequent propagation path transitions occur.

B. HELIOS Coverage Areas and Beam Selection

To identify BLOS service areas inside the NDT, the deployment is characterized by ray tracing of the hall geometry with O-RU and both passive HELIOS IRSs [19], using their distance-resolved near-field reflection patterns [21]. The resulting REMs in Fig. 7 separate the individual contributions. Deploying only the O-RU leaves both corridors uncovered behind the central metallic structures, while the upper and lower HELIOS illuminate the western corridor (SA1) and central corridor (SA2), respectively. The per-position maximum

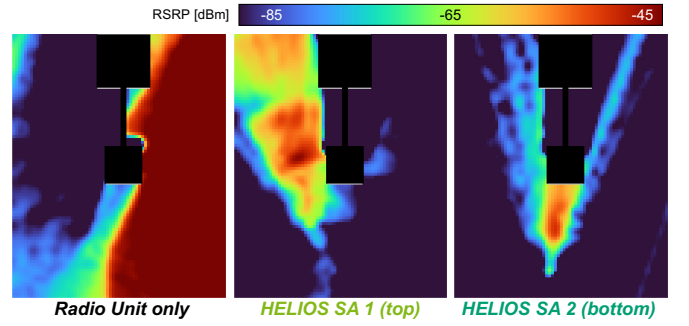


Figure 7. Individual propagation characteristics of the radio components including IRS near-field patterns. O-RU only (left), and via the upper (center) and lower (right) HELIOS IRS.

yields the REM in Fig. 8-left, from which the NDT derives the BLOS regions as polygons annotated with the anchor position of the associated IRS. Serving a UE via an IRS thus becomes a controlled network planning decision instead of a potentially volatile opportunistic choice.

C. Connectivity and Throughput Performance

Measuring the SS-RSRP across the hall with active proactive beam management and all 65 beams, as shown in Fig. 8-right, confirms the expected coverage pattern with strong signal in the LOS region and BLOS coverage in SA1 and SA2 via the upper and lower HELIOS, respectively. Comparing the measurements to the DT-based ray tracing in Fig. 8, integrating data from the network planning phase shows that the model captures all major propagation characteristics.

Throughput measurements with iPerf3, UDP and a static UE at different positions in the scenario (cf. Table III) confirm the expected overhead analyzed in Sec. IV-C, with the reactive approach yielding lower data rates compared to the

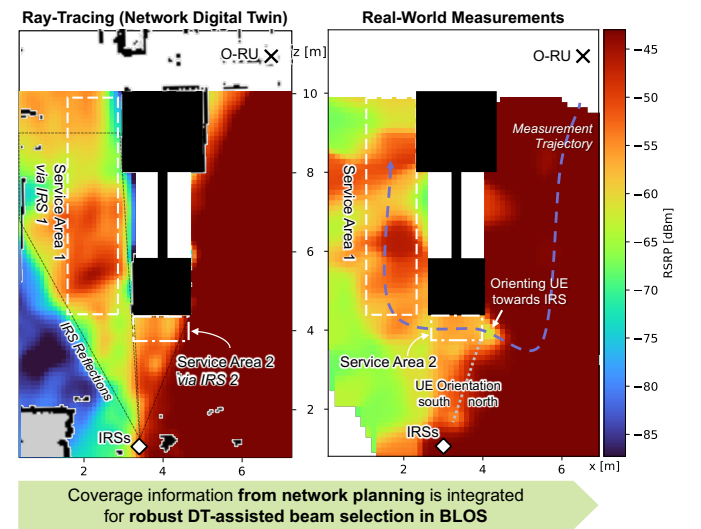


Figure 8. REM of the industrial environment from ray-tracing and actual measurements with the mobile UE. The NDT leverages accurate information about the BLOS areas of the IRSs for beam decisions from network planning.

Table III

PEAK DATA RATES FOR THE BEAM MANAGEMENT APPROACHES AT DIFFERENT REGIONS OF THE INDUSTRIAL TRANSFER ENVIRONMENT.

Region	React. DL	React. UL	Proact. DL	Proact. UL
LOS	307 Mbps	49.4 Mbps	449 Mbps	75.8 Mbps
SA1	278 Mbps	50.9 Mbps	449 Mbps	74.6 Mbps
SA2	293 Mbps	50.3 Mbps	449 Mbps	75.0 Mbps

proactive approach, mainly due to the need for multiple SSB transmissions and corresponding PRACH occasions. Uplink throughput improves by 53% from 49.4 Mbps to 75.8 Mbps, consistent with the around 50% gain expected from eliminating uplink beam restrictions. Downlink throughput increases from a peak value of 307 Mbps with 4 SSBs in the reactive approach to 449 Mbps with a single SSB in the proactive approach, improving by 46%. This improvement is higher than the theoretical value and caused by the reduced uplink resources available for signaling in the reactive approach, which also influences the achievable downlink throughput. Importantly, the proactive approach offers 65 beam-direction options without the additional beam-restriction overhead, while the reactive approach with 4 SSBs can only serve the 4 beams chosen in a mobility-aware manner. This limitation could be mitigated by hierarchical beam management with additional broader beams. However, the employed O-RU does not yet support this approach at the time of writing. The identical 449 Mbps proactive peak in all three regions of Table III shows that the reflector paths deliver strong connectivity and no additional cost in terms of peak throughput once beam-restriction overhead is removed.

The absolute data rates achieved are not yet on the level of carrier-grade FR2 systems [20], which has multiple reasons: First, the COTS O-RU version employed supports only up to 64-QAM modulation instead of common 256-QAM. Second, the used bandwidth during evaluation is limited to 100 MHz, which also constrains the peak data rates. However, higher bandwidths are expected with the ongoing integration of FR2 O-RU within the OAI Open RAN stack.

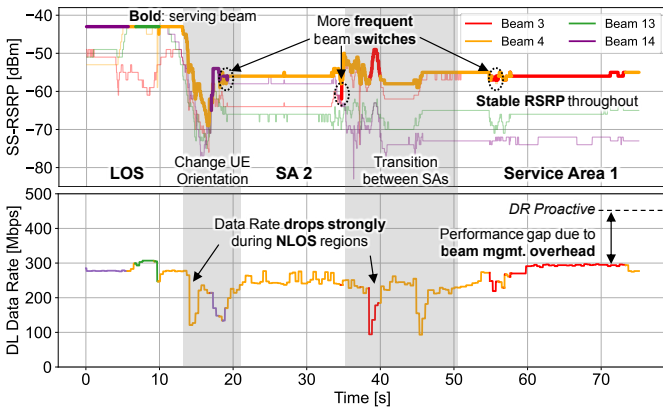


Figure 9. SS-RSRP and downlink data rate of the **reactive** approach over a trajectory in the industrial environment. The color of the plot indicates the selected beam, changing more frequently compared to the proactive approach.

D. Evaluation of Beam Management Under High Mobility

To compare the reactive and proactive beam management approaches under mobility, we measure the performance over a trajectory covering different regions of the hall. The trajectory starts in the LOS region, moves through SA2 with BLOS connectivity via the lower IRS, then enters SA1 via the upper IRS. As the UE reports the four beams with strongest SS-RSRP for the reactive procedure, all reported beams relevant to the beam selection are shown in Fig. 9 over time. While the reactive approach momentarily yields higher SS-RSRP compared to the proactive approach (cf. Fig. 10) as it uses the *measured* strongest beam, its mean SS-RSRP is comparable, yielding -53.6 dBm compared to -52.5 dBm, while frequent beam changes can be observed. Each serving beam change leads to reconfiguration and beam alignment at the UE, which can cause temporary drops in throughput and increased latency. In contrast, the proactive approach in Fig. 10 shows a more stable beam selection with fewer changes, as the NDT selects the beam based on the trajectory, environment model and desired stable reflections from network planning, reducing frequent beam switching and associated overhead. The observed data rates in Fig. 9 and 10 confirm this analysis, with the proactive approach maintaining higher and more stable throughput across the trajectory, especially in the BLOS regions, however, requiring external knowledge. In Fig. 11, the selected beam is visualized over the trajectory, showing that the proactive approach directs beams toward the UE or IRS in line with theoretical expectations.

Both procedures serve the UE through the same four beams, two in LOS and one per IRS, restricting the difference to switching dynamics. Over the trajectory, the reactive procedure performs 38 beam changes and severe oscillations, against three changes for the proactive procedure, which switches only on region transitions intended during network planning. The gain in performance is conditioned on IDT data quality. Here, stale updates or erroneous positioning information in the IDT would misalign the beam undetected, unlike the reactive procedure's implicit SS-RSRP-based awareness.

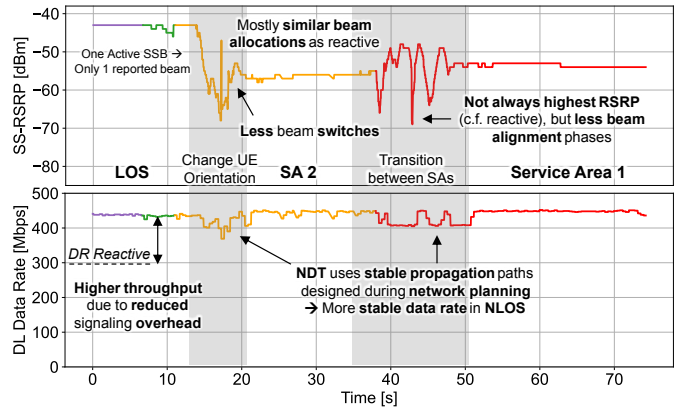


Figure 10. Measurements over the trajectory with the **proactive** DT-assisted approach. Color indicates the beam applied by the DT prediction, resulting in fewer beam switches than the measurement-driven reactive procedure.

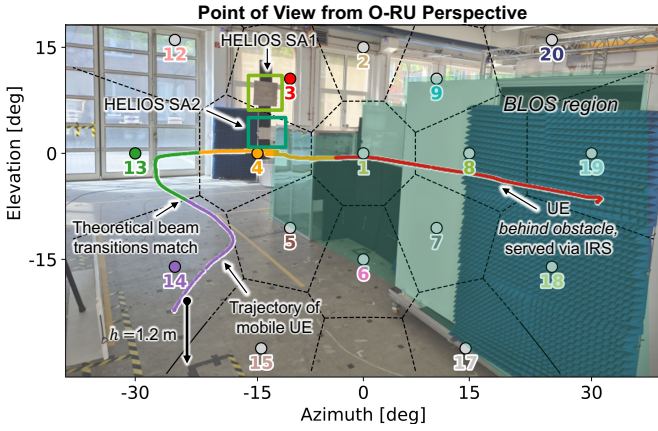


Figure 11. Mobile UE Trajectory from O-RU view of the proactive approach. The color of the trajectory indicates the selected beam, which changes as the UE moves. In the obstructed BLOS regions, the UE is served via the IRSs.

However, with a measured half-power beamwidth of approximately 20° (Sec. IV-B), the dense 65-beam codebook provides overlapping coverage. Moderate positioning errors therefore typically lead to the selection of an adjacent beam that still maintains connectivity, not leading to a link outage.

VI. CONCLUSION AND OUTLOOK

This paper presented a DT-assisted proactive beam management framework for FR2 Open RAN networks. The end-to-end evaluation with a COTS Split 7.2 FR2 O-RU and the OAI software platform in lab and industrial environments represents, to the best of our knowledge, the first study of this kind. The proposed framework integrates an NDT with real-time Open RAN metrics and mobility and environmental information from an IDT to proactively determine serving beam directions using a lightweight geometric model with reflector-aware selection for BLOS operation via passive IRSs. In the experimental evaluation, the proactive procedure eliminates measurement-driven beam sweeping by decreasing the number of transmitted SSBs from one per beam in the reactive baseline to one per co-located UE group, while still selecting from the full beam candidate set. This reduction is reflected in the observed throughput, with the proactive approach achieving 46% higher downlink and 53% higher uplink throughput than the reactive approach. Furthermore, the proactive approach reduces beam oscillations and increases stability, with only three beam changes over a robot trajectory with BLOS areas, compared to 38 for the reactive baseline.

Future work will address multi-user beam coordination and hybrid proactive-reactive refinement with sparse probing. In addition, we will evaluate the approach with O-RUs supporting higher-order modulation and higher bandwidth as well as study its transfer to FR3 and sensing applications for future adaptive multi-band 6G deployments.

ACKNOWLEDGMENT

This work has been funded by the Federal Ministry of Research, Technology and Space (BMFTR) via the 6GEM+ transfer hub under grant

no. 16KIS2412, the GEM-X project under grant no. 16KISS005 and the VICTOR6G project under grant no. 16KIS2549. The authors would like to thank Simon Häger for providing the HELIOS passive IRS design and the corresponding detailed reflection patterns.

REFERENCES

- [1] D. Shakya, M. Ying *et al.*, "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 J. Commun. Soc.*, vol. 5, pp. 5192–5218, 2024.
- [2] 3rd Generation Partnership Project (3GPP), "Technical Specification Group Radio Access Network; NR; NR and NG-RAN Overall Description; Stage 2," 3GPP, TS 38.300, 2026, release 19.
- [3] —, "Technical Specification Group Radio Access Network; NR; Physical layer procedures for data," 3GPP, TS 38.214, 2026, release 19.
- [4] N. A. Wagner and C. Wietfeld, "O-RACES: proactive AI-driven scheduling in Open RAN for 6G-networked humanoid robots," in *IEEE Conference on Computer Communications (INFOCOM)*, 2026.
- [5] O-RAN ALLIANCE, "O-RAN Working Group 4 (Open Fronthaul Interfaces WG): Control, User and Synchronization Plane Specification," Tech. Rep. O-RAN.WG4.TS.CUS.0-R005, Feb. 2026.
- [6] A. Fuller, Z. Fan, C. Day, and C. Barlow, "Digital Twin: Enabling technologies, challenges and open research," *IEEE Access*, May 2020.
- [7] H. Ding and K. G. Shin, "Context-aware beam tracking for 5G mmWave V2I communications," *IEEE Trans. on Mobile Computing*, Jun. 2023.
- [8] M. Zecchin, M. B. Mashhadi, M. Jankowski, D. Gündüz, M. Kountouris, and D. Gesbert, "LIDAR and position-aided mmWave beam selection with non-local CNNs and curriculum training," *IEEE Transactions on Vehicular Technology*, Jan. 2022.
- [9] K. Heimann, J. An, L. Hito, S. Saidi, and C. Wietfeld, "Obstacle-aware proactive beam management based on real-time ray tracing for mmWave networks," in *2025 IEEE 101st Vehicular Technology Conference (VTC2025-Spring)*, Jun. 2025.
- [10] P. Garrett, T. Osman, and A. Alkhateeb, "Digital-twin aided spatial beam prediction," in *2025 IEEE International Conference on Machine Learning for Communication and Networking (ICMLCN)*, May 2025.
- [11] M. Arnold, B. Major, F. V. Massoli, J. B. Soriaga, and A. Behboodi, "Vision-assisted digital twin creation for mmWave beam management," in *IEEE International Conference on Communications*, Jun. 2024.
- [12] M. Tsampazi, M. Polese, F. Dressler, and T. Melodia, "O-RIS-ing: Evaluating RIS-assisted NextG Open RAN," in *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, 2025.
- [13] 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 *IEEE 5th International Symposium on Joint Communications & Sensing (JC&S)*, Jan. 2025.
- [14] 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 *Proc. of the 30th Annual Int. Conf. on Mobile Computing and Networking (ACM MobiCom)*, New York, USA, Dec. 2024, pp. 1820–1822.
- [15] A. Schott, B. Acikgöz, O. Massoud, M. Petrova, and L. Simić, "Unleashing sensor-aided environment awareness for beam management in beyond-5G networks: an Openairinterface experimental platform," in *IEEE Wireless Communications and Networking Conf. (WCNC)*, 2026.
- [16] A. Madnaik and K. Sundaresan, "Practical design and orchestration of frequency-shifting RIS for NLoS mmWave sensing," in *Proceedings of the Int. Symp. on Theory, Algorithmic Foundations, and Protocol Design for Mobile Networks and Mobile Comput.* ACM, Oct. 2025.
- [17] OpenAirInterface Software Alliance, *OpenAirInterface5G*, 2026. [Online]. Available: <https://gitlab.eurecom.fr/oai/openairinterface5g>
- [18] S. Lee *et al.* (2025) Open5GS. Open Source implementation for 5G Core v2.7.5. [Online]. Available: <https://open5gs.org/open5gs/docs/>
- [19] S. Häger, J. Ferreira, S. Böcker, D. Schreurs, and C. Wietfeld, "Passive intelligent reflecting surfaces for efficient 6G mmWave networks: Design, validation, and field trials," *IEEE Open Journal of the Communications Society*, vol. 7, pp. 3222–3252, 2026.
- [20] M. Danger, S. Häger *et al.*, "Reflection instead of densification: Experimental insights into IRS-aided industrial 6G mmWave," in *VDE-ITG Conference on Mobile Communications (MKT)*, May 2026.
- [21] S. Häger, M. Kaudewitz, and C. Wietfeld, "Near-field extension of analytical reflection model for large-scale mmWave IRS geometries in 6G," in *IEEE Int. Conf. on Communications (ICC)*, May 2026.