Accepted for presentation in: 30th IEEE Int. Symposium on Local and Metropolitan Area Networks (LANMAN), Boston, USA, July 2024.

On Link-level Performance of Passive IRS-boosted Indoor mmWave Communications and Road Ahead

Simon Häger, Marco Danger, Stefan Böcker, and Christian Wietfeld
Communication Networks Institute (CNI), TU Dortmund University, 44227 Dortmund, Germany
E-mail: {Simon.Haeger, Marco.Danger, Stefan.Boecker, Christian.Wietfeld}@tu-dortmund.de

***Abstract*—Private cellular network deployments are increasingly adopted globally to connect machines on industrial campuses. Millimeter-wave (mmWave) cells need to be utilized when high wireless traffic volumes are expected, e.g., owing to high application requirements in conjunction with large number of devices. However, mmWave connectivity is highly sensible to non-line-of-sight (NLOS) conditions. For cost- and energy-efficiency reasons, 6G aims to illuminate under-connected shadow regions within the targeted service area using intelligent reflecting surfaces (IRSs). We present promising indoor measurement results for the attained performance boost using commercial equipment, where the introduction of a custom-designed passive IRS seamlessly restores throughput to 2 Gbit/s with the new propagation path increasing the link margin by more than 10 dB.**

***Video Abstract*—Demonstration video is available online at: https://tiny.cc/mmWaveHeliosMeasurements.**

***Index Terms*—mmWave communications, indoor measurements, LOS/NLOS, intelligent reflecting surfaces, real-life networks.**

I. IRS-enabled Smart Radio Environments for Efficient 6G mmWave Communications

The broad available bandwidth at mmWave frequencies, e.g., 5G frequency range 2 (FR2) spanning 24 GHz to 71 GHz, facilitates scalable network capacity extension and peak data rate increase for cellular networks typically operating in sub-6 GHz spectrum. Changed propagation behavior, particularly reduced object penetration, causes severe showing such that user equipments (UEs) in NLOS experience a severely reduced link quality compared to under line-of-sight (LOS) conditions. In contrast to the deployment of additional base stations (BSs), IRS technology has emerged in 6G research to efficiently address this problem by artificially introducing strong reflection paths to shadowed users. Rather small-scale industry scenarios are very suitable for this because the physical environment and application requirements are well known, so that under-connected regions can be quickly detected. Similarly, suitable mounting positions and corresponding angular reflection ranges can be easily identified, facilitating the custom design, manufacturing, and deployment of IRSs [1, 2]. However, little to no experimental studies have exercised this process and assessed the attained performance boost on system level.

Against this background, Sec. II transfers the designed IRS from [3], previously validated using channel sounders, into an indoor environment served by a real mmWave private network. Sec. III then assesses the attained connectivity depending on LOS, NLOS, and beyond line-of-sight (BLOS) modality in extended detail over [4]. Finally, we provide insights into our ongoing 6G mmWave/IRS research activities in Sec. IV.

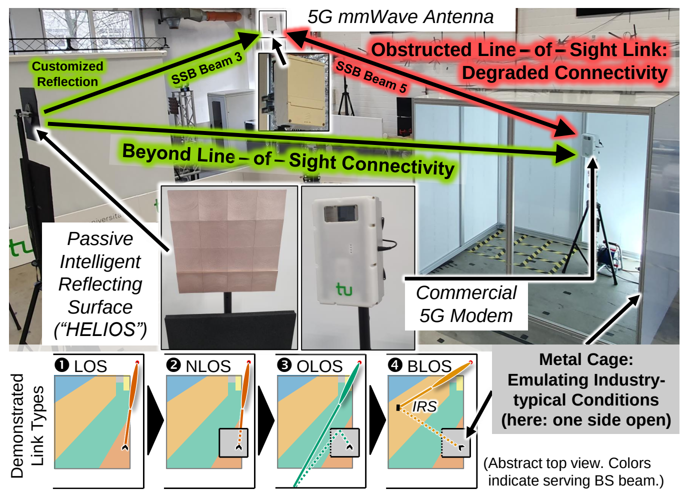


Fig. 1. Setup for systematic demonstration of mmWave link performance in LOS, Non-LOS, Obstructed LOS, and IRS-enabled Beyond LOS situations.

II. Transfering IRS into Private mmWave Network

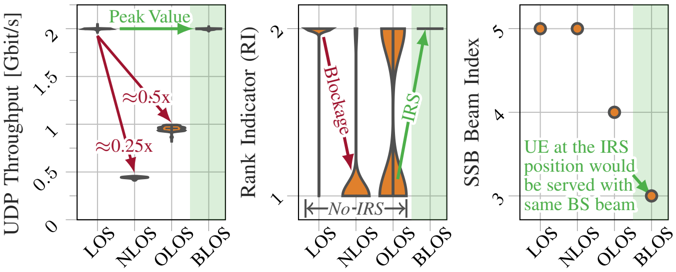
This section explains the four-step measurement procedure using the setup shown in Fig. 1. More details are given in Tab. I.

First, the UE is in *LOS* serving as a *performance reference*: Over a period of 5 min, we capture the following downlink (DL) channel parameters by periodic querying on UE and BS sides: data rate (UDP, limited to max. 2 Gbit/s for stability), reference signal received power (RSRP), max. modulation and coding scheme (MCS) of packet, transmit power, rank indicator (RI), and synchronization signal block (SSB) beam index [4].

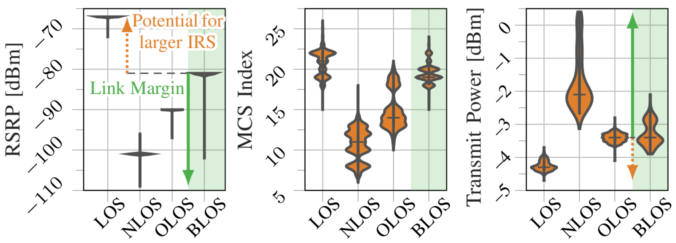
Then, *NLOS* modality is imposed by placing a cage around the UE so that its four sides plus ceiling realize the *worst-case* connectivity for the sake of this study. This setup mirrors a closable robot cell that can be found in industrial environments, such as the manufacturing floor in [5].

The safety cages of machinery are partially open in some states and typically have small windows for workers to see through. We emulate this by removing one of the sides of the cage, see Fig. 1, and refer to these channel measurements by *obstructed line-of-sight (OLOS)*.

Finally, we deploy our so-called Holistic Enlightening of bLackspots with passIve reflectOr moduleS (HELIOS) reflector, cf. [2], which was custom-designed, 3D-printed, conductive spray-coated, and finally, its reflection behavior characterized in [3]. The goal is to establish a *BLOS* communication link with it, meaning that LOS-like connectivity is provided *using the passive IRS to illuminate the shadowed UE.*



(a) Obstructed UE is served with LOS-like 2 Gbit/s data rate via IRS introducing new dominant propagation path, as attested by RI and SSB beam ID.



(b) Higher throughput with IRS attained by 10 dB power gain allowing for high MCSs. The attained BLOS link is robust with ca. 30 dB link margin.

Fig. 2. Measured mmWave downlink channel metrics with and without IRS.

III. Performance of Passive mmWave IRS

We now evaluate the measured link metrics depicted in Fig. 2 for the previously described mmWave indoor factory connectivity modalities: LOS, NLOS, OLOS, and BLOS.

In Fig. 2a, we assess the throughput in the context of multipath availability (RI) and dominant propagation path (SSB beam ID). In the LOS modality, the UE is served with 2 Gbit/s along the dominant propagation path falling into the BS-side antenna beam 5. Additionally, as illustrated by the rank indicator, the UE typically observes a second feasible path. When placing the full cage around the UE (NLOS), all propagation paths are weakened, and some become infeasible, such that the data rate drops by 75 %. If one side of the cage is opened (OLOS) to emulate an industrial machine safety cage, multipath propagation through this gap becomes dominant such that the beam orientation is switched and the throughput increases to 1 Gbit. When the HELIOS reflector is introduced, the serving beam switches again to the newly available artificial propagation path, and the DL data rate is restored to 2 Gbit/s like in LOS. If the UE were to require, say, just 1 Gbit/s, the private network still benefits from the IRS: it can either allocate 400 MHz (of 800 MHz) to other users or reduce the transmit power (and MCS) for higher energy efficiency.

The performance is studied in greater depth using Fig. 2b. Comparing the BLOS with the NLOS and OLOS measurements, mean RSRP gains of about 20 dB and 10 dB are observed, respectively. In addition, a lower transmit power is used than in NLOS. This indicates that the artificial BLOS link exhibits significant robustness as high-order MCSs similar to those in LOS are used. Nonetheless, considering the transmit and received power differences, the link margin in LOS is approximately 15 dB higher. This can be explained by the reflection-broadening HELIOS reflector, which exhibits reduced peak gain [3]. Moreover, a larger IRS can be used to achieve both maximum MCS and minimum transmit power.

TABLE I. Details on 5G mmWave Network and Passive IRS [3, 4].

	Parameter	Description/Value
BS	Radio Unit	Ericsson AIR 1281
	Frequency Band	5G band n257 (26.7 GHz to 27.5 GHz)
	TDD Pattern	DDSU, 11:3:0
	Max. Transmit Power	20 dBm / 100 mW (EIRP)
UE	Device Model	Quectel 5GDM01EK + RG530F-EU
	Modem and Antennas	Qualcomm SDX65, RA530T + 4x QTM547
	Power Class	Class 3 (max. 23 dBm / 200 mW)
	Capabilities	Release 16 compliant, 2 × 2 MIMO in FR2
IRS	Architecture	HELIOS: 3D print with conductive coating
	Design Layout	4 × 4 unit cells, 40 cm × 40 cm × 0.9 cm
	Performance Metrics	Peak reflection gain 21.1 dB (RCS) at 27.1 GHz with 20°-broadened vertical reflection
	Mounting Heights	3.2 m (BS), 1.5 m (UE), 2.2 m (Passive IRS)
	Horizontal Distances	7.2 m (BS-UE), 7.7 m (BS-IRS), 4.8 m (IRS-UE)

IV. Excerpt of Ongoing Research

The successful transfer of our HELIOS reflector into a real mmWave network marks a milestone in our 6G research. Our future work will aim to successfully serve large-scale scenarios that facilitate multiple large custom-designed IRS. This requires a faster design process than that in [3] by using an analytical reflection model instead of electromagnetic simulations. Fig. 3 depicts the reflection of an individual HELIOS module using a modified bistatic radar cross section (RCS) model [6, Ch. 11.3.2]. Another research topic is the modeling of mmWave modem power consumption, as in [7] for sub-6 GHz devices, to characterize the long-term impact of IRSs in the scope of reducing the carbon footprint of 6G systems.

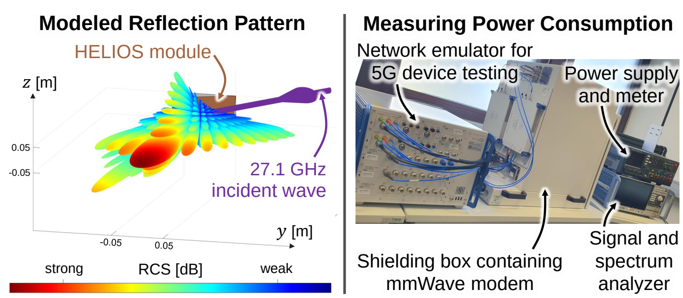


Fig. 3. Ongoing research features reflection models and power measurements.

Acknowledgment

This work has been funded by the German Federal Ministry of Education and Research (BMBF) in the course of the *6GEM Research Hub* under the grant number 16KISK038 and the *6G-ANNA* project under the grant number 16KISK101.

References

[1] M. Noor-A-Rahim *et al.*, "Toward industry 5.0: Intelligent reflecting surface in smart manufacturing," *IEEE Commun. Mag.*, vol. 60, no. 10, 2022.
[2] S. Häger, K. Heimann, S. Böcker, and C. Wietfeld, "Holistic enlightening of blackspots with passive tailorable reflecting surfaces for efficient urban mmWave networks," *IEEE Access*, vol. 11, 2023.
[3] S. Häger, M. Danger, K. Heimann, Y. Gümüs, S. Böcker, and C. Wietfeld, "Custom design and experimental evaluation of passive reflectors for mmWave private networks," in *Proc. IEEE LANMAN*, 2024.
[4] M. Danger, S. Häger, K. Heimann, S. Böcker, and C. Wietfeld, "Empowering 6G industrial indoor networks: Hands-on evaluation of IRS-enabled multi-user mmWave connectivity," in *Proc. EuCNC/6G Summit*, 2024.
[5] M. Danger, C. Arendt, H. Schippers, S. Böcker, . . . , and C. Wietfeld, "Performance evaluation of IRS-enhanced mmWave connectivity for 6G industrial networks," in *Proc. IEEE M&N*, 2024, [Online]. Video abstract available: http://tiny.cc/IndustrialmmWave.
[6] C. A. Balanis, *Advanced Engineering Electromagnetics*, 2nd ed. John Wiley & Sons, Inc., 2012.
[7] H. Schippers and C. Wietfeld, "Data-driven energy profiling for resource-efficient 5G vertical services," in *Proc. IEEE CCNC*, 2024.