Accepted for presentation in: 2023 IEEE Globecom Workshops (GC Wkshps), Workshop on Intelligent 6G Architecture: towards network simplicity and autonomy (Int6GArch)

Integration of Scaled Real-world Testbeds with Digital Twins for Future AI-enabled 6G Networks

Cedrik Krieger[1], **Harun Teper**[2], **Julia Freytag**[3], **Irfan Fachrudin Priyanta**[4], **Philipp Schulte**[3],
Moritz Roidl[4], **Jian-Jia Chen**[2], **and Christian Wietfeld**[1]
[1]Communication Networks Institute, TU Dortmund University, 44227 Dortmund, Germany
[2]Department of Computer Science, TU Dortmund University, 44227 Dortmund, Germany
[3]Fraunhofer Institute for Material Flow and Logistics, 44227 Dortmund, Germany
[4]Chair of Material Handling and Warehousing, TU Dortmund University, 44227 Dortmund, Germany
e-mail:[1,2,4]{Cedrik.Krieger, Harun.Teper, IrfanFachrudin.Priyanta, Moritz.Roidl,
Jian-Jia.Chen, Christian.Wietfeld}@tu-dortmund.de
e-mail:[3]{Julia.Freytag, Philipp.Schulte}@iml.fraunhofer.de

Abstract—**Future 6G communication systems need to be carefully evaluated under near real-life boundary conditions to prove their performance beyond theoretical considerations and simulations. In this work, we propose a new, lean approach to integrate and evaluate future 6G network architectures and AI-enabled approaches in scaled physical environments that emulate the full-scale communication, mobility, and environmental conditions powered by a Digital Network Twin (DNT). Our approach is enabled by the realistic modeling of the radio environmental impacts within the DNT, such as path loss, shadowing, and interference. One key contribution lies in the specific communication emulation functionality embedded in the real-time capable DNT, which allows imposing specific communication technology properties of the real-life scenario on the scaled physical environment. In this paper, we introduce a prototyping architecture and present a comprehensive case study to demonstrate the effectiveness of the approach: the AI-enabled mesh routing protocol PARRoT is evaluated in three scaled scenarios (teleoperation, platooning, and intralogistic transport). The results show that future 6G networks can be evaluated in realistic, yet safe and cost-efficient environments before moving onto the real world.**

I. INTRODUCTION

The development and research process of 6th Generation of Mobile Communication Networks (6G) is in full motion, in which sophisticated technology approaches and the integration of pervasive Artificial Intelligence (AI) play a key role. The global goal of sustainable and limitless connectivity supporting high data rates, low latency, and new services will probably not be met by focusing on a single technology branch. Rather, this goal can be reached by adding up multiple approaches [1], which are integrated into a network-of-networks [2], including terrestrial and non-terrestrial networks. With addressing such a wide spectrum of different solutions, there is an urgent need for comprehensive trials in dedicated testbeds, motivated to ensure a secure integration, robustness, and end-to-end reliability across novel approaches and to overcome simulative simpleness. Real-world trials require a lot of planning, preliminary integration, and are highly sensible for external influences (like weather or availability of locations). They in turn cost plenty of resources so that economic interests collide with technological interests. Digital Twins (DTs) are often emphasized as the key aspect of the 6G communication generation. While DTs in general describe the replication of real-world processes for monitoring and prediction purposes, a more specific subclass of DNTs has emerged, which focuses on the development of 6G communication aspects. Small-scaled vehicles [3] are known in the development of autonomous platforms [4], where new algorithms can easily be tested before migrating to a *1/1*-scale. Inspired by this paradigm, we propose the concept of a digital triplet to analyze the behavior of real-world scenarios, as shown in Fig. 1, by transferring the scene to a scaled environment with an integrated co-simulation. It features the realistic calculation of radio environments, which are imposed on the scaled-down testbed as real-time network challenges for emulation. The approach is highly extensible by its modular design and supports cost-efficient scalability analyzes. Furthermore, robotic platforms can be equipped with current, but also with future, although not yet available 6G communication technologies to comprehensively evaluate novel concepts and validate their robustness and performance in real time under near real-life conditions.

Our key contributions are summarized as follows:

- Proposal on **scaled research testbeds** with **imprinted real network effects** for cost-efficient real-world development of **6G-ready communication platforms**.
- Flexible and modular testbed with a **real-time capable Digital Network Twin** to emulate future 6G technologies **prior to their availability** on physical robotic platforms.
- Comprehensive **case studies** on diverse testbeds with **variable scaling** to demonstrate the end-to-end analysis of 6G approaches, including the real-world deployment of an **AI-enabled mesh routing** protocol.

The remainder of the paper is structured as follows. After discussing the related work in Sec. II, we present the key enablers for the conducted testbeds in Sec. III. We continue with an overview of the system architecture in Sec. IV before showing the case studies in scaled testbeds in Sec. V. Finally, we review the findings and give an outlook on future improvements in Sec. VI.

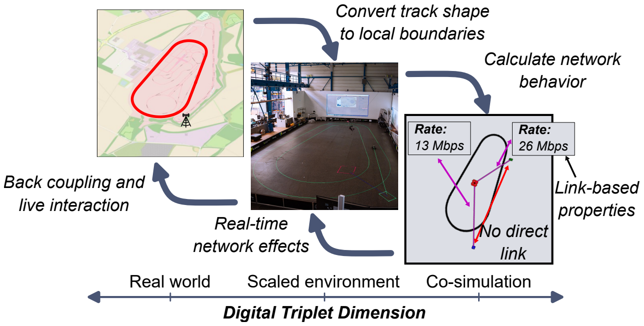


Fig. 1. Concept of a digital triplet to integrate real world, scaled, and simulated environments and evaluate novel 6G approaches in reproducible and safe scenarios. (Map: © OpenStreetMap Contributors, CC BY-SA).

II. Related Work

Digital twinning is one of the frequent keywords that comes along with the development of 6G. Mihai et al. [5] summarize various aspects and provide an outlook on potential use cases of digital twins. Sanz Rodrigo et al. [6] provide an architecture for a DNT to monitor and evaluate a 5th Generation of Mobile Communication Networks (5G) network. Dakic et al. [7] derive error models for system-level Vehicle-to-Everything (V2X) Hardware-in-the-Loop (HiL) testing. In [8] and [9], end-to-end testing of remote operations is performed with a focus on the Quality of Experience (QoE). Requirements for vehicular teleoperation and platooning are provided by the 5G Automotive Association (5GAA) in [10]. Having these covering the aspects of real-world integration, the frameworks Lightweight ICT-centric Mobility Simulation (LIMoSim) [11] and Autonomous Navigation System Simulator (AuNa) [12] act as DNTs on the simulative side, combining virtualized mobility with network simulation.

III. Key Enablers for Small-Scaled Testbeds

In this section, we describe the key enablers to build a scalable, flexible, and modular 6G testbed in our universal testing environment[1]. We integrate cost-efficient robotic platforms to have real mobility, being equipped with Commercial off-the-Shelf (COTS) solutions as Communication-under-Test (CuT). This allows the proposed approach to cover near-realistic situations in a *1/10*th-scaled highway as well as a *1/1*-scale intralogistic environment with the ease of switching scenes. Novel approaches for 6G communication can thus be prototyped and optimized for real-world deployment prior to the availability of novel communication equipment. The environment additionally features an immersive visualization system to further assist in understanding and illustrating the behavior and system states of new 6G concepts.

A. Autonomous Robotic Platforms

1) F1/10 Vehicular Platform: The F1/10 platform [13] is an open-source, Robot Operating System 2 (ROS2)-based *1/10*th-scale autonomous vehicle testbed. The platform is based on an RC car chassis, as shown in Fig. 2. The base platform features a drive layer and a computation layer. The drive layer consists of the motors and the chassis, while the computation layer holds an embedded PC, a LiDAR, a camera, and an Inertial Measurement Unit (IMU). We extend the platform with a communication layer, supporting Wi-Fi 6 and mesh technology and being extensible with future 6G communication devices. The vehicle uses the ROS2 navigation stack, supporting teleoperated and autonomous driving, and a Cooperative Adaptive Cruise Control (CACC) controller for platooning, as implemented in the AuNa framework [12].

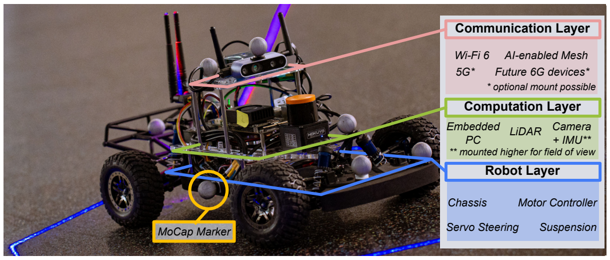
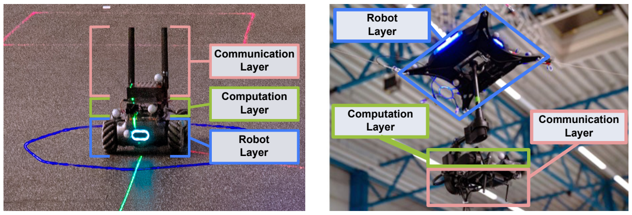


Fig. 2. The F1/10 vehicular platform is a 1/10th-scaled version of a real race car with a modular extensible communication stack for future 6G technologies.



(a) Omnidirectional Robot

(b) Cable Robot

Fig. 3. Our 6G testbeds can flexibly support diverse robotic platforms for versatile mobility on the ground, but also aerial mobility for 3D networking.

2) Omnidirectional Robot Platform: Our flexible testbed can handle various robots. Fig. 3 shows an omnidirectional robot, offering the advantage of moving in confined spaces and following complex trajectories. Omnidirectional mobility is especially useful for intralogistic environments, as more space is available for shelves. It is equipped with the aforementioned modular communication layer.

3) Three-dimensional Aerial Cable Robot: The testing environment offers a three-dimensional aerial cable robot as shown in Fig. 3 (b), which can dynamically follow trajectories. Cable robots can be installed in industrial halls and hold mobile base stations, enabling novel approaches for three-dimensional networking. Further, the cable robot allows to mimic Unmanned Aerial Vehicle (UAV) mobility from full-scale scenarios in the scaled environment without safety concerns. Future 6G topologies will leverage AI-enabled placement of communication-equipped UAVs [14] to overcome Non Line-of-Sight (NLOS) situations. Our testbed is therefore able to assist in early stage real-world deployments of such approaches and evaluate beyond simulations.

---

[1] Innovationlab at TU Dortmund: https://www.innovationlab-logistics.com

B. Small-scaled Network Emulation in Dynamic Environments

The main challenges for the evaluation of new approaches under real-life conditions are the high costs and effort required. Our small-scaled testbeds support the end-to-end evaluation of novel 6G approaches, offering reduced spatial requirements, cost-efficient scalability, higher flexibility for diverse scenarios, and controllable boundaries across several runs. Although this is a big advantage compared to the existing method of performing test runs in the *1/1*-scale world, the ultimate drawback is that the smaller distances do not pose the same challenges to the communication system as experienced in the *1/1*-scale real-world scenario. We therefore propose a novel approach to reflect the testbed scaling in a real-time capable DNT co-simulation and achieve realistic end-to-end properties. In Fig. 4, we show our architecture. It consists of two parts, which are responsible for the small-scaled network emulation. First we have the DNT, which is LIMoSim in our case, being a real-time network co-simulation of the scaled environment. It receives position information from a Motion Capturing (MoCap) system to monitor the environment and offers the possibility to include virtual obstacles in order to compose the feature vector $\boldsymbol{x}$ containing the virtual environment data. The vector $\boldsymbol{x}$ is scaled up by a factor of s to model the distances between the F1/10 cars as they would be in the real world. A channel model calculates a distance-based path loss and optionally adds wall loss in case of NLOS situations due to obstructions from virtual objects to produce a loss vector $\boldsymbol{l}$. This loss vector is further consumed by a technology model. Exemplary, the calculated reception power can be converted to a resulting Modulation and Coding Scheme (MCS) according to standard-compliant threshold specifications of the CuT, which in turn leads to data rate limitations. The technology model is highly modular and can be adapted to novel 6G models. Eventually, end-to-end constraints are calculated this way and the DNT broadcasts a link matrix $\boldsymbol{L}$, containing network constraints for each individual link existing in the scenario. Secondly, Fig. 4 also shows the further concept to apply the calculated constraints as network challenges in a distributed fashion to each of the robots. During the scenario, LIMoSim shares the link matrix $\boldsymbol{L}$ periodically over a dedicated Message Queuing Telemetry Transport (MQTT) interface. The robots use the relevant links and apply the network challenges in the manner of a virtual physical and data link layer, which limits packet reception on top of the real layers directly on the device. Applications and implementations from network layer and above are therefore unaware of being operated in a scaled environment and show their usual behavior. This enables our testbed approach to be flexible in testing and validating diverse 6G applications.

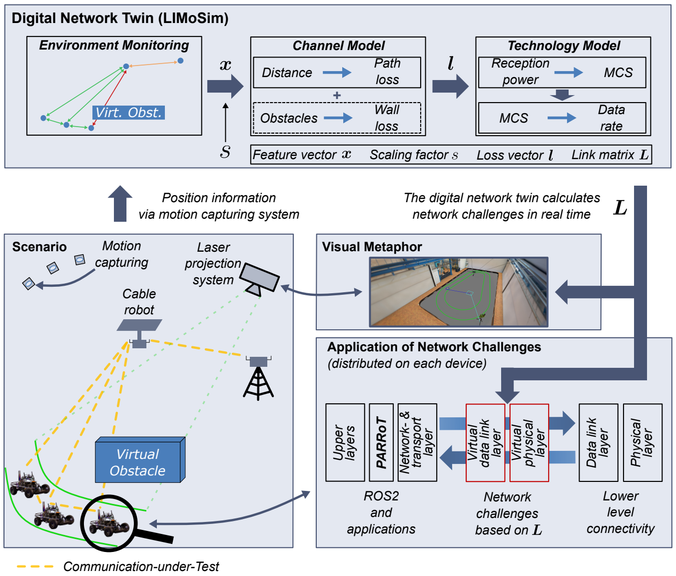


Fig. 4. Coupling between the real-world and DNT. LIMoSim processes the position data to calculate the link loss, which is directly applied to the network stack and affects the communication between the testbeds.

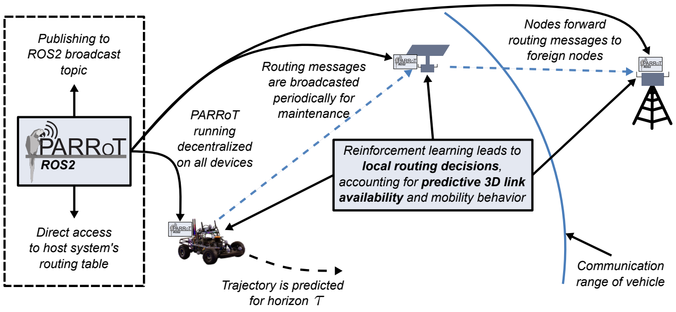


Fig. 5. A per-device decentralized ROS2 implementation of PARRoT processes cooperative information to directly modify the host's routing table.

C. PARRoT: AI-enabled Predictive 3D Routing

Natively integrating AI into the architecture of 6G networks can be leveraged to design flexible network architectures running autonomous protocols, thus being comparably lean in terms of their configuration complexity. One such protocol is the cooperative multi-agent Reinforcement Learning (RL) approach Predictive Ad-hoc Routing fueled by Reinforcement learning and Trajectory knowledge (PARRoT) [15], which combines the ability to generalize network states from its RL functions and proactively accounts for three-dimensional link availability. PARRoT has shown its performance in comprehensive simulations. We have realized PARRoT's first real implementation using ROS2. It runs decentralized on ground vehicles, on a base station site, and on a computing unit attached to the aerial cable robot. Fig. 5 visualizes the PARRoT concept: each node distributes status information on a broadcast topic in periodic intervals to cooperatively update other nodes in order to maintain a local view of the network topology. Shared information is threefold and can be classified into identification data, mobility information, and RL metrics. A trajectory prediction allows to cooperatively assess the network topology and predict 3D link availability to finally utilize the RL process for local routing decisions. This leads to multi-hop connections that extend the communication range of a node beyond its physically limited range. The implementation directly accesses the routing table of the host system, enabling performance evaluations based on real data.

D. *Visual Metaphor: AR-enhanced Network Visualization*

The Internet Engineering Task Force (IETF) stated network visualization [16] as a requirement of DTs and to act as an intuitive guidance system for network optimization. We create a visual metaphor, which adds a laser-based projection system as an immersive Augmented Reality (AR) component to the common 3D-rendered visualization as a DT (c.f. Fig. 6). It can visualize trajectories and vehicle track boundaries in the scaled research environment, and it also offers the opportunity to create visual metaphors and illustrate internal network states. In this work, we focus on the projection of Vehicle-to-Vehicle (V2V) link-based metaphors, which are provided by the DNT during the scenario. For example, we visualize the current link quality and the selected routes of the routing protocol.

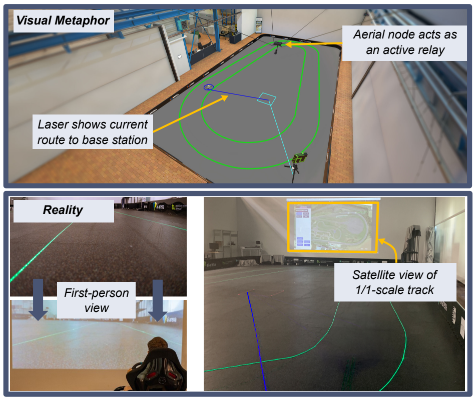


Fig. 6. The visual metaphor couples data from the digital network twin with the testbed and environment states to visualize link quality and network routes.

IV. LEAN SYSTEM ARCHITECTURE INTEGRATION FOR END-TO-END TESTS

In this section, we briefly describe our high level system architecture as illustrated in Fig. 4. It consists of the DNT, a visual metaphor, a distributed stack to apply network challenges, and diverse robot platforms to include real mobility in the scenario. The DNT is the core component, receiving real-time position data from a MoCap system to calculate a link matrix as described in Sec. III-B. The visual metaphor (c.f. Sec. III-D) consumes and visualizes scenario-specific information, such as the link matrix $\boldsymbol{L}$. It processes the link-based information and converts them to visualizations which can be seen in a detailed 3D model, but are also projected to the scaled environment's ground by the laser projection system. The link matrix $\boldsymbol{L}$ represents the network challenges which affect the communication-based applications running on the robots. Consequently, these applications influence the mobility and generated data within the scenario, to close the loop in our system architecture. We distinguish between a control link (e.g. Wi-Fi 6) supporting a MQTT broker to share control data to the robots, and a Communication-under-Test (CuT), which can for instance be a mesh network as used in Sec. V. The network challenges are only applied on the CuT interface to ensure a secure backbone control link while simultaneously not loading control traffic over the CuT.

V. CASE STUDIES IN SCALED 6G TESTBEDS

A. *Reliable Teleoperation enabled by Predictive Networking*

Fig. 7 shows a scenario in which a human teleoperator experiences deteriorating link quality when approaching the cell edge. A single base station cannot sufficiently cover the whole area due to physical propagation properties. Future 6G approaches can overcome such issues by the integration of meshed concepts into infrastructure-based architectures. To resolve the situation, we bring a well-placed UAV into the scene which acts as an aerial relay and exemplify how AI-enabled protocols, such as PARRoT, can autonomously choose available routes for the first-person view video stream. We evaluate by sending real data with 50 Mbit/s and measure the throughput over time (c.f. Fig. 8). It can be seen that the direct communication from the vehicle to the base station fails in a black spot beyond the cell edge. However, when having the PARRoT-UAV integrated, an alternative route is found and the gap is closed. This proof-of-concept trial shows that our scaled testbed approach is capable of posing realistic network challenges to create cost-efficient scenarios. This allows the modular end-to-end validation of real implementations of future AI-enabled protocols for 6G communication approaches.

B. *Scaled CACC-enabled V2X Platooning*

6G will have an impact on the energy efficiency of traffic by enabling cooperative driving techniques, such as platooning, where vehicles drive in a convoy to reduce the inter-vehicle distance, relying on robust ultra-low-latency V2X communication. In this scenario, we demonstrate platooning with three F1/10 vehicles (see Fig. 9), where the vehicles communicate with each other for cooperative platooning via CACC. In a first step, we observe the Cooperative Awareness Message (CAM) [17] generation process according to European Telecommunications Standards Institute (ETSI) specification for a vehicle platoon, operating at a speed of 8 m/s, resulting in a testbed speed of 0.8 m/s ($s = 10$), for which we modify the generation rules to reflect the scaling factor s. The vehicles check the following generation rules every 100 ms and trigger the generation of a CAM if one of them applies:

- The position changed by more than $^4\!/_s$ m.
- The velocity changed by more than $^{0.5}\!/_s$ m/s.
- The heading changed by more than 4°.
- Elapsed time since last CAM is $\geq$ 1000 ms.

Fig. 10 (a) shows the distribution of CAM inter-message times. The measured data is mostly consistent with the work of [18], addressing a comparable highway platooning scenario with the same target velocity. As our test drives are continuously driven, all CAMs are generated no later than 600 ms, because the position rule applies roughly after this elapsed time. We further analyze the different CAM trigger conditions based on the location where the CAM is generated (c.f. Fig. 10 (b)). On the straights, the position condition triggers the V2X traffic. Due to the constant velocity, the messages are equally distributed over these areas (see histogram on x-axis in Fig. 10 (b)). In the curves, the heading condition mainly causes message

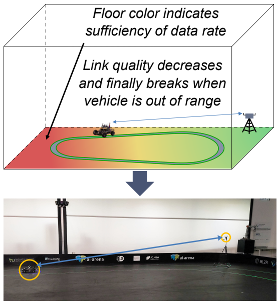


Fig. 7. A vehicle is teleoperated at high speeds in a motorway scenario, requiring high data rates. The limited communication range disrupts the video stream and forces a full stop. We operate a UAV to close communication gaps by offering alternative routes and continue the teleoperation.

generation due to steering. After reaching the apex, the vehicle accelerates to reach the target speed, creating CAMs due to the velocity and heading condition (labeled as $V + H$). This shows that our application stack can be used on scaled vehicles to evaluate real vehicular mobility. Furthermore, our testbed enables the development of safe and reliable protocols under varying radio conditions in V2X scenarios.

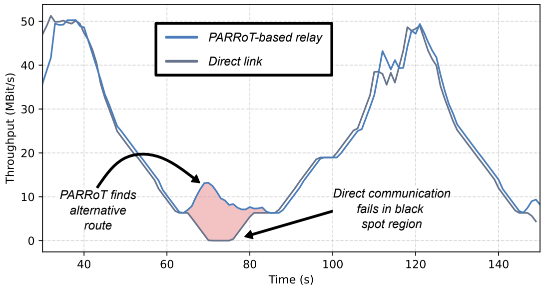


Fig. 8. In a proof-of-concept trial, an aerial node running PARRoT shows to overcome a black spot region by being used as a relay node.

C. Dynamic Intralogistic Environment with Virtual Objects

Intralogistic environments are challenging in terms of radio propagation. The efficient placement of shelves counteracts total communication coverage. In this case study, we demonstrate how DNTs can play a key role in the optimization and analysis of network performance. Besides the theoretical consideration, our DNT also allows performing test runs with the robot fleet prior to placing the shelves, and thus without risking crashes in case of uncovered areas. In our scenario, we simulate different shelf heights and their effects on the radio propagation, as shown in Fig. 11. We calculate the Radio Environmental Maps (REMs) shown in Fig. 12 which are threefold per scenario. The top REM shows the data rate coverage provided by the base station if the robot uses the direct link for data transmission. The middle REM shows the available data rate if the robot uses the relay link over the centrally placed UAV. It shows the combined data link from the robot to the UAV and from the UAV to the base station. Although the robot has a strong link to the UAV in some places, the link from the UAV to the base station limits the whole relay link to a maximum of 19 Mbit/s in our scenario. The bottom REM shows the best available data rate for the robot if it chooses the best link. This calculation is particularly useful to identify black spots in the scenario and to optimize the placement of the shelves. Fig. 13 shows the complementary Empirical Cumulative Distribution Function (ECDF) of available data rates using PARRoT compared to a direct link connection. We see that even a static placement of the UAV increases the quality of links. We consider this a proof-of-concept prediction using the DNT, indicating promising performance improvements by using three-dimensional networking in combination with predictive mesh routing. As a subsequent step, the DNT simulation needs to be scaled to consider V2V links for the predictive mesh routing to further increase available data rates and coverage. For future approaches, DTs can assist with developing AI-enabled placement strategies [14] and improving the network coverage.

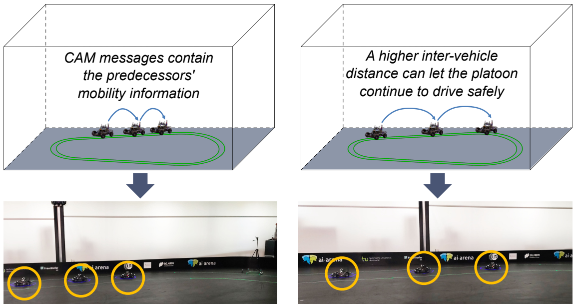
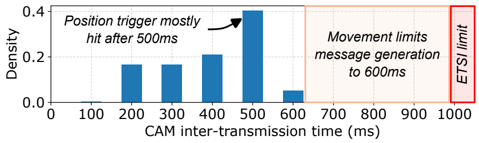
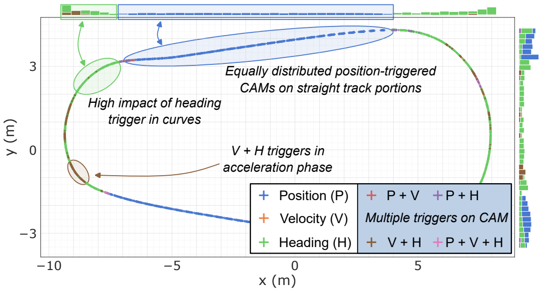


Fig. 9. Platoons require robust information exchange for safe operation. Our approach allows to evaluate the effects of deteriorating channel conditions.



(a) Distribution of CAM inter-message times



(b) Spatial view of CAM trigger conditions

Fig. 10. Analysis of CAM properties during runs in proposed scaled testbed.

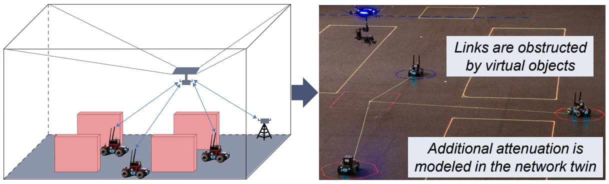


Fig. 11. Intralogistic robots require a constant connection to an edge computer for path planning. We can determine the network conditions and effects of obstacle placement and scaling, like high-bay warehouses, using our DNT to predict and emulate the end-to-end latencies in advance.

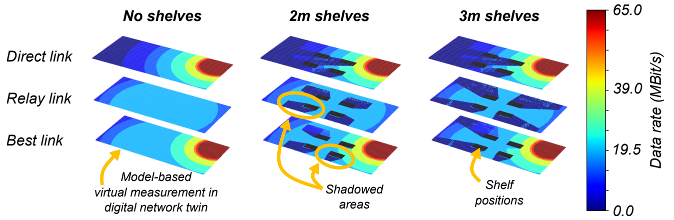


Fig. 12. REM plots showing the available data rate per link from robot to base station (direct link) or by relaying via a centrally placed UAV in 4.5 m height. The top REM merges these two REMs and shows the best available link with respect to the available data rate between UAV and base station.

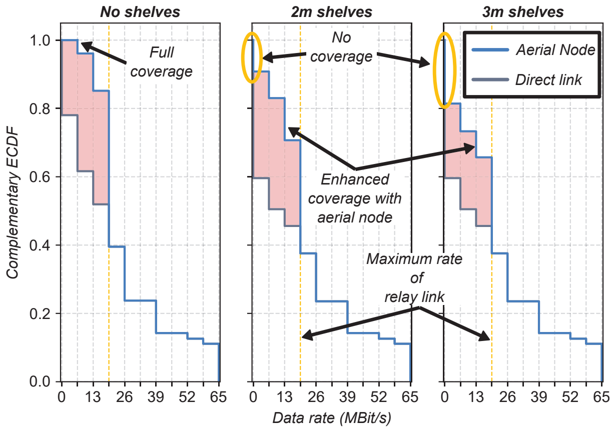


Fig. 13. Complementary data rate ECDF between the base station and mobile robot considering the direct link or the relayed route via the aerial node.

VI. CONCLUSION

In this paper, we present scaled physical research testbeds with emulated network effects to allow near real-world tests with real mobility beyond simulation and in advance of available 6G equipment. Our case studies show first proof-of-concept prototypes and a lean end-to-end integration that benefits from the flexible, modular, and cost-effective nature of our implementation and is complemented by an immersive visualization. We demonstrate our testbeds using V2X and three-dimensional network communication and show their capability to integrate and evaluate future 6G AI-enabled communication approaches. In future work, we will leverage our DNT to perform more extensive studies and compare the scaled results with measurements from full-scaled real-world experiments. Furthermore, we will add advanced models to our scaled network emulation to run comprehensive trials of future 6G technologies. Finally, we refer to Fig. 14, which links to a video of the automotive case studies.

ACKNOWLEDGMENT

This work has been partly funded by the German Federal Ministry of Education and Research (BMBF) in the course of the *6GEM* research hub under grant number 16KISK038 as well as supported by the Ministry of Economic Affairs, Industry, Climate Action and Energy of the State of North Rhine-Westphalia (MWIKE NRW) along with the *Plan & Play* project under the funding reference 005-2008-0047 as well as supported by the Federal Ministry of Transport and Digital Infrastructure (BMVI) in context of the project Virtual integration of decentralized charging infrastructure in cab stands under the funding reference 16DKVM006B.
We also thank Lukas Thurow for assisting with the implementation and integration in the course of his activity as a student assistant.

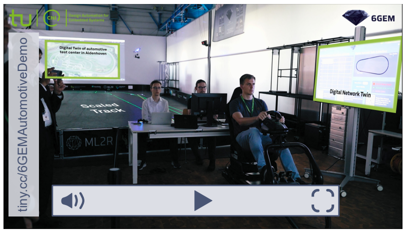


Fig. 14. To watch the automotive testbed showcase video, scan the QR-Code or use following link: http://tiny.cc/6GEMAutomotiveDemo

REFERENCES

[1] M. Giordani, M. Polese, M. Mezzavilla, S. Rangan, and M. Zorzi, “Toward 6G networks: Use cases and technologies,” *IEEE Communications Magazine*, Mar. 2020.

[2] Hexa X, “Expanded 6G vision, use cases and societal values,” Tech. Rep. D1.2, Apr. 2022.

[3] H. Lee, J. Park, C. Koo, J.-C. Kim, and Y. Eun, “Cyclops: Open platform for scale truck platooning,” in *International Conference on Robotics and Automation (ICRA)*, May 2022.

[4] J. Betz, H. Zheng, A. Liniger, U. Rosolia, P. Karle, M. Behl, V. Krovi, and R. Mangharam, “Autonomous vehicles on the edge: A survey on autonomous vehicle racing,” *IEEE Open Journal of Intelligent Transportation Systems*, Jun. 2022.

[5] S. Mihai, M. Yaqoob, D. V. Hung, W. Davis, P. Towakel, M. Raza, M. Karamanoglu, B. Barn, D. Shetve, R. V. Prasad, H. Venkataraman, R. Trestian, and H. X. Nguyen, “Digital twins: A survey on enabling technologies, challenges, trends and future prospects,” *IEEE Communications Surveys & Tutorials*, Sep. 2022.

[6] M. Sanz Rodrigo, D. Rivera, J. I. Moreno, M. Àlvarez Campana, and D. R. López, “Digital twins for 5G networks: A modeling and deployment methodology,” *IEEE Access*, Apr. 2023.

[7] A. Dakić, M. Hofer, B. Rainer, S. Zelenbaba, L. Bernadó, and T. Zemen, “Real-time vehicular wireless system-level simulation,” *IEEE Access*, Feb. 2021.

[8] M. Patchou, J. Tiemann, C. Arendt, S. Böcker, and C. Wietfeld, “Realtime wireless network emulation for evaluation of teleoperated mobile robots,” in *IEEE International Symposium on Safety, Security, and Rescue Robotics (SSRR)*, Nov. 2022.

[9] C. Schüler, T. Gebauer, M. Patchou, and C. Wietfeld, “QoE evaluation of real-time remote operation with network constraints in a system-of-systems,” in *IEEE International Systems Conference (SysCon)*, Apr. 2022.

[10] 5GAA, “C-V2X use cases and service level requirements volume II,” Tech. Rep., Feb. 2021.

[11] B. Sliwa, M. Patchou, K. Heimann, and C. Wietfeld, “Simulating hybrid aerial- and ground-based vehicular networks with ns-3 and LIMoSim,” in *Proceedings of the 2020 Workshop on Ns-3*, Jun. 2020.

[12] H. Teper, A. Bayuwindra, R. Riebl, R. Severino, J.-J. Chen, and K.-H. Chen, “AuNa: Modularly integrated simulation framework for cooperative autonomous navigation,” in *43rd IEEE Real-Time Systems Symposium (RTSS)*, Dec. 2022.

[13] M. O’Kelly, V. Sukhil, H. Abbas, J. Harkins, C. Kao, Y. V. Pant, R. Mangharam, D. Agarwal, M. Behl, P. Burgio *et al.*, “F1/10: An open-source autonomous cyber-physical platform,” *arXiv preprint*, Apr. 2019.

[14] T. N. Guo, “Robust Q-learning for fast and optimal flying base station placement aided by digital twin for emergency use,” in *IEEE 96th Vehicular Technology Conference (VTC-Fall)*, Sep. 2022.

[15] B. Sliwa, C. Schüler, M. Patchou, and C. Wietfeld, “PARRoT: Predictive ad-hoc routing fueled by reinforcement learning and trajectory knowledge,” in *IEEE 93rd Vehicular Technology Conference (VTC-Spring)*, Apr. 2021, Best Student Paper Award.

[16] C. Zhou *et al.*, “Digital Twin Network: Concepts and Reference Architecture,” Internet Engineering Task Force, Tech. Rep., Oct. 2022.

[17] ETSI, “Part 2: Specification of cooperative awareness basic service,” Tech. Rep., Jan. 2019, version 1.4.1.

[18] B. Vieira, R. Severino, E. V. Filho, A. Koubaa, and E. Tovar, “COPADRIVe - A realistic simulation framework for cooperative autonomous driving applications,” in *IEEE International Conference on Connected Vehicles and Expo (ICCVE)*, Nov. 2019.