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Is It Running? Unveiling 6G-Driven System-of-Systems Testbeds using Visual Metaphors

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***Abstract*—The rapidly evolving new concepts of the 6G technology raise the challenge of assessing how well 6G-enabled system-of-systems architectures perform in real-life situations beyond theories and simulations. To facilitate this, a new Visual Metaphor layer is presented in this paper to add the visualization feature for a system-of-systems Digital Twin (DT). Visual metaphor plays a crucial role in assisting network engineers to comprehend complex 6G concepts through intuitive visual representations. Powered by an immersive Augmented Reality (AR) based on laser projection system, the metaphor framework seamlessly projects the simulated environments into reality and vice versa. Thus, it bridges the gap between theoretical development and practical implementation. Furthermore, it features a plug-and-play solution to accommodate the validation of integrated systems and applications easily. To validate the performance and show the flexibility of the visual metaphor layer, we perform three case studies from the application contexts of teleoperation, platooning, and intralogistics. The results show that the visual metaphor can visualize internal network states, such as communication links, as well as virtual objects and other environmental features. The metaphor can accomplish these diverse and modular tasks while preserving an overall system response time of 55 ms in large-scale scenarios with up to 40 robots.**

***Index Terms*—System-of-Systems Architecture, Digital Twin, 6G Testbed, Mobile Robots, Augmented Reality**

I. Introduction

In recent years, the 5G mobile network has been rolled out worldwide, although its accessibility varies in certain regions. Meanwhile, researchers have started investigating the next sixth generation (6G) of mobile networks. This step is essential to meet the anticipated communication and networking demands in 2030. The International Telecommunication Union Telecommunication (ITU-T) foresees 6G supporting novel concepts and applications, such as holographic-type communications, multi-sense experience, and DT [1]. These applications revolutionize communication and interaction with the digital world through immersive visualization and ultra-low end-to-end latency [2]. As these innovations take shape, a crucial need arises to explore the 6G capabilities to the fullest extent by experimenting under dedicated 6G testbeds. A seamless integration of the 6G testbed and DT enables the researchers to replicate and simulate real-world scenarios in a dynamic environment, making experiments more straightforward and affordable.

The Digital Network Twin (DNT) is one component in the system-of-systems architecture that we propose in Fig. 1, bringing the capability to monitor, emulate, and predict the channel properties of real world scenarios. However, there remains to be a significant gap in assessing the impact of such DNT applications on the testbed during runtime [3]. Thus, it is not surprising that Internet Research Task Force (IRTF) [4] suggests a network visualization component as part of the DNT. With this concern, this work presents the immersive network visualization in the real world by introducing a new Visual Metaphor layer within our system-of-systems architecture coupled with the DNT. Accordingly, the interactive mapping between the physical 6G testbed and the DNT can be visually and intuitively illustrated using immersive AR, based on a laser projection system. This system is designated to seamlessly project the communication link quality and the environments generated from the DNT into reality. Building upon our prior research [5], this work delves into a comprehensive exploration of system-of-systems development while introducing novel concepts not previously covered. The contributions are summarized as follows:

- Proposal of a **system-of-systems architecture** to **integrate the visual metaphor** with the real world and DNT.
- **Development** of the **immersive Visual Metaphor** to intuitively support **network debugging and optimization**.
- **Comprehensive case studies** in diverse test fields and **validation** of the visual metaphor performance.

The remainder of this paper is structured as follows. In Section II, we discuss the related works. Consecutively, we provide a brief overview of the 6G scaled testbed in Section III. Section IV specifies our system-of-systems architecture. Accordingly, Section V explains the overview of our experiment setups before demonstrating the results in Section VI. Finally, Section VII formulates a future research outlook and the conclusions of this study.

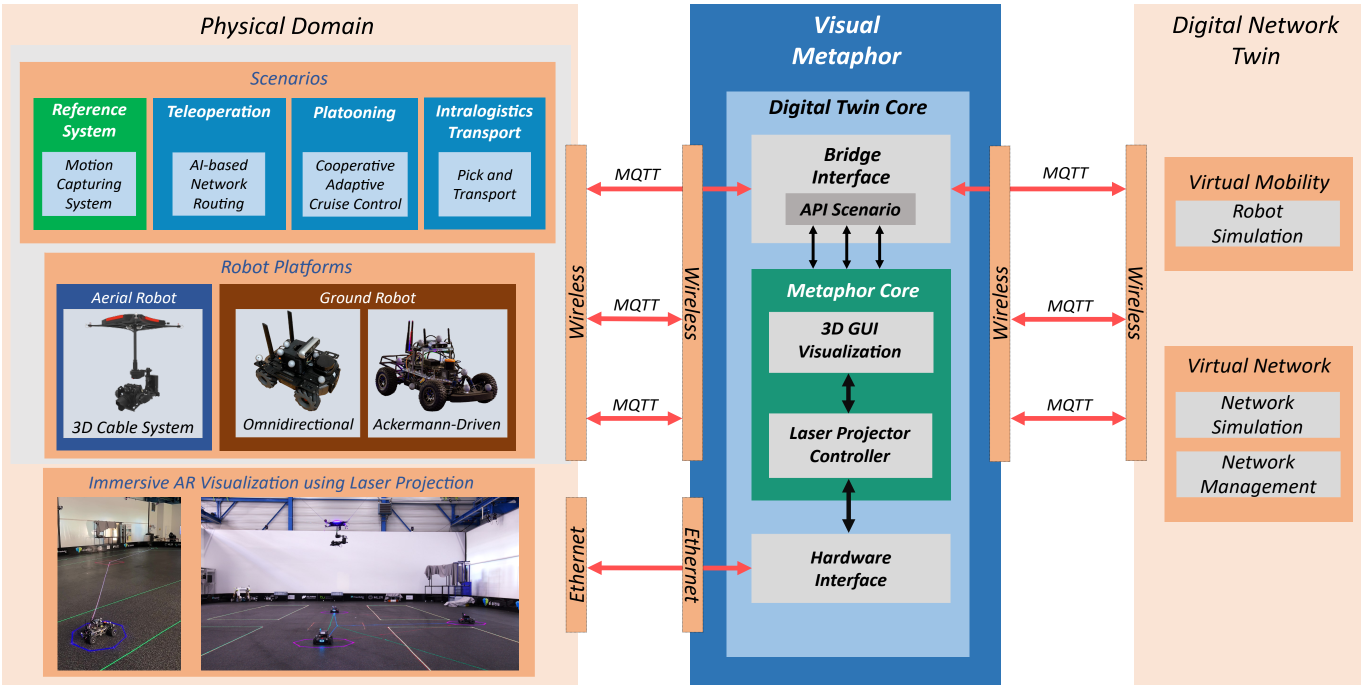

Fig. 1: Proposed plug-and-play system-of-systems architecture for different use-cases including visual metaphor layer. The Message Queuing Telemetry Transport (MQTT) protocol accommodates wireless communication of different systems which are distributed in different locations in the research hall.

II. Related Work

With 6G development on the horizon, it is crucial to investigate the key enablers of 6G testbeds, which are pivotal in accelerating the assessment process of 6G networking solutions. In the surveys of Kuruvatti et al. [3] and Wang et al. [6], mainly the digital twinning concept is presented as the key enabler for 6G testbeds. The authors [6] highlight the usage of the DNT to provide comprehensive 6G system verification. The most recent DNT state-of-the-art [7]–[10] reveals the trend of applying data-driven intelligent network optimization and *what-if* analyses. Notably, the works in [3], [4] emphasize the necessity of DNT offering visualization tools to depict network traffic, infrastructure, and end users. Hence, the network analysts and planners are supported in profoundly comprehending the 6G network functions.

In terms of visualization, the work of [7] proposes a comprehensive strategy for developing a centralized Graphical User Interface (GUI) that manages and monitors the flow of the DNT operation in all life cycle stages. Recent studies [8], [10], [11] have further extended these visualization tasks, predominantly within the virtual domain, employing special GUI and AR-based Head Mounted Devices (HMD). Notably, motivated by the goals of cost efficiency and improved ergonomics for human operators in terms of using Virtual Reality (VR)- or AR-based HMD, Finke et al. [12] introduce an innovative solution using a laser projection system to improve the efficiency of order picking in intralogistics. Roo et al. [13] present a spatial augmentation projector system in a hybrid Mixed Reality (MR) framework. This system overlays digital information onto physical objects in the real world, showcasing the broad applications of MR in collaborative learning and hardware maintenance. Both systems [12], [13] prove that the spatial-based projection system enhances the user experience for domain-specific tasks.

In software development field, Züllighöven et al. [14] propose theoretical concepts of guiding metaphors and design metaphors. The guiding metaphor emphasizes a shared perspective for all involved parties during the entire development process. These concepts present practical applications such as the expert workplace, where the guiding metaphor empowers experts by creating a work environment with adequate equipment and tools. In this context, the design metaphors serve as tools, with each guiding metaphor translated into intuitive design metaphors to offer detailed guidelines for refining the design of the application domain [14]. Therefore, guiding and design metaphors must fit seamlessly to aid in understanding and analyzing new design concepts of a specific application domain. Design guidelines in Human-Computer Interaction (HCI) [15] focus on system latency, known as System Response Time (SRT), to ensure an optimal user experience by defining maximum acceptable delays. Prominently, Doherty and Sorenson's HCI latency guidelines [16] emphasize that latency should stay below $300\,\mathrm{ms}$, enhancing the sense of direct user control.

III. Scaled 6G Research Testbeds

This section provides a brief overview of our previous research [5] on use cases of scaled 6G research testbeds and the key enablers. Fig. 1 describes the different systems that will be integrated into our visual metaphor framework. The focus of this section is to introduce scenarios and robot platforms of the physical domain as well as the DNT parts.

A. Autonomous Robotic Platforms

The physical domain part in Fig.1 shows the robot platforms for the real-world scenario: the Ackermann-driven or car-like robot, omnidirectional robot, and 3D aerial cable robot system. Overall, the ground robot platforms have three main parts: The drive layer using Robot Operating System 2 (ROS2), the computing layer, and the communication layer. The computing layer in the Ackermann-driven car includes a computing unit, LiDAR, camera, and the Inertial Measurement Unit (IMU), while an omnidirectional robot has a computing unit and the IMU. Both robot platforms feature communication layers supporting Wi-Fi6, mesh technology, and can be extended for future 6G technology. For the drive layer, the vehicle uses ROS2, allowing both remote control and autonomous driving. Additionally, the Autonomous Navigation System Simulator (AuNa) framework provides a Cooperative Adaptive Cruise Control (CACC) controller for platooning with the Ackermann-driven cars [17] and a path-following controller for following trajectories with the intralogistics omnidirectional robots. Moreover, a 3D aerial cable robot securely mimics the mobility of a Unmanned Aerial Vehicle (UAV) and covers the whole hall area. With its wide coverage range, this cable robot enables 3D networking solutions for obstructed situations by equipping it with a mobile base station.

B. Case Studies

1). Teleoperation: Teleoperation is a scenario when a car-like robot or Ackermann-driven platform is driven remotely by a human teleoperator. This use case demonstrates a decreased connection quality as the car is closer to the cell edge, primarily because of physical propagation restrictions. To overcome this, a UAV acts as an aerial relay node and integrates PARRoT - Artificial Intelligence (AI)-enabled predictive routing [18]. PARRoT autonomously selects optimal network routes for the live video stream of the teleoperator to improve the data transmission rates.

2). Vehicles Platooning: Platooning is the scenario in which Ackermann-driven robots drive in a convoy to minimize inter-vehicle spacing, based on ultra-reliable low latency Vehicle-to-Vehicle (V2V) communication. In this scenario, various numbers of Ackermann-driven robots, physical and virtual robots participate in cooperative platooning by communicating using CACC.

3). Intralogistics Transport: We introduce a 3D automated intralogistics environment in this use case. In the automated intralogistics setting, depicted in Fig. 5, virtual and physical omnidirectional robots navigate through various pickup stations to transport packages to a central drop-off location. DNT is used here to assess the shadowing effect due to different virtual shelf heights and their impacts on robot communications. To resolve this, we introduce a 3D aerial cable robot as part of a 3D Network Management application in intralogistics. This robot improves connectivity in low-signal areas and intelligently re-establishes connections between the robot fleet and the base station.

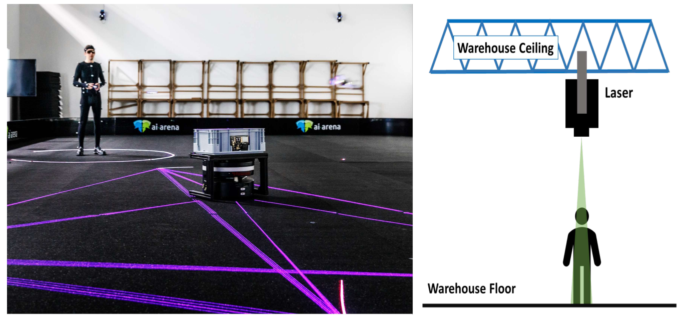

Fig. 2: Laser projection system setup and example.

C. Digital Network Twin

First of all, the so-called Lightweight ICT-centric Mobility Simulation (LIMoSim) [19] is proposed as the DNT to emulate the virtual network. The features of LIMoSim correlate to the virtual network and virtual mobility functionalities in Fig. 1. LIMoSim incorporates the map of specific environments as the input, generates virtual obstacles, and scales data to model distances realistically [5]. By employing the Motion Capturing (MoCap) system, all marked logistics entities and robots can be tracked and localized. Then, the positions and orientations of each entity are monitored by LIMoSim. The channel model calculates the path loss, considering obstacles in the Non-Line-of-Sight (NLOS) situation. A radio technology model translates this into reception power and data rate parameters. This highly flexible model can be adapted for emerging 6G models. The resulting link matrix ($\boldsymbol{L}$) contains network constraints for each link in the scenario [5]. Consecutively, these constraints are distributed as network challenges to robots that use the AuNa [17] framework.

IV. Proposed System-of-Systems Architecture

As explained in section II and highlighted in recent research [8], [10], [11], a significant research gap exists in the current DNT technology. This gap specifies the immersive network visualization in the physical world, specifically for enhancing the experience of 6G assessments. Fig. 1 highlights our plug-and-play system-of-systems architecture, consisting of three domains: the physical, visual metaphor, and DNT application. This section delves into the key enablers and the architecture of visual metaphor, which is developed as a DT framework in a game engine.

A. Physical Domain - 6G Testbeds

The physical domain accommodates various 6G-driven scenarios, depicted in Fig. 1. In each scenario, immersive AR visualizations and diverse autonomous robot platforms are utilized for the hybrid experiment of virtual and physical domains. We conduct our experiments in the Inovationlab[1] research hall of the Technical University of Dortmund, which is a logistics warehouse testbed with a size of 570 m^2.

[1]https://www.innovationlab-logistics.com/research-centre/

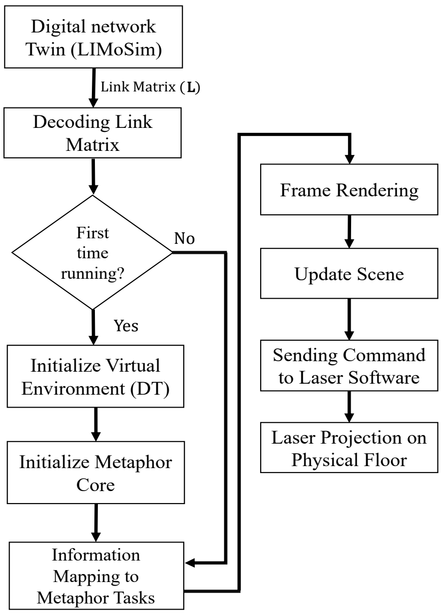

Fig. 3: Brief overview of visual metaphor flowchart.

The laser projection system in Innovationlab is responsible for the static and dynamic visualization of the communication processes between robots and simulated and physical environments. Direct projection mapping over real-world surfaces is the key technology of the laser system that offers immersive AR. Eight laser projectors are attached to the ceiling of the hall with a height of six to seven meters, as illustrated in Fig. 2. We can project the laser to a particular location on the warehouse floor through the laser Application Programming Interface (API) embedded in our 3D GUI of visual metaphor. The laser API sends particular commands to the laser projector software, which is connected directly to the laser hardware through an Ethernet connection as depicted in Fig. 1. The laser projection has the capacity to project up to ≈ 1600 laser points in a frame. The scan rate of the laser projection is the percentage of the default sample rate from the manufacturer that ranges from $60\% - 400\%$.

B. Visual Metaphor

The novel feature of the proposed system-of-systems architecture is the development of a visual metaphor for network behaviors. This visualization layer is motivated by the IRTF visualization idea [4] and the framework of Züllighöven [14] emphasizing guide metaphors and design metaphors. In this paper's scope, the guide metaphors act as a guide for the network experts and offer a shared perspective throughout the complex world of digital networks. The design metaphors serve as plug-and-play tools that are adjustable to the specific requirements of diverse DNT applications and real-world scenarios. In current development, the visual metaphor behaves as the guide metaphor, while system-of-systems architecture represents the tool of design metaphors. This subsection emphasizes the backbone of visual metaphor, the DT core which consists of the bridge interface and metaphor core. The DT is the software stack encapsulating various functionalities from the application to the physical layers.

1). Bridge Interface: This layer connects the real-world scenarios, DNT services, and the 3D GUI visualization or the DT of visual metaphor. A MQTT network protocol plays a vital role in establishing this communication bridge between domains. The interface features a 2D GUI to select certain scenarios and set up the connections to MoCap, laser system, and MQTT broker. Once a scenario is selected, the corresponding API scenario receives and decodes the MQTT message in a JavaScript Object Notation (JSON) format from the DNT, which in this paper is the link matrix $\boldsymbol{L}$ from the LIMoSim. The consumption of the link matrix $\boldsymbol{L}$ is also presented in the first two processes in Fig. 3.

2). Metaphor Core Layer: The metaphor core layer utilizes the link matrix $\boldsymbol{L}$ obtained from the DNT in subsection III-C. This layer transforms the decoded messages into meaningful information, i.e., communication link quality, prediction of network routes, and real-time positions and orientations of the robots. In this paper context, the 3D GUI is the main DT interface for the visual metaphor, representing the virtual twin of the research hall's physical environment. Fig. 3 illustrates the brief flowchart of this layer.

First of all, the metaphor core receives the decoded link matrix $\boldsymbol{L}$ from the API scenario. The visual metaphor initializes the virtual environment of DT according to the selected scenario as well as creates the metaphor objects of communication links depending on the number of endpoints in the decoded information. Once the metaphor objects and environment are initialized, the information is mapped to the corresponding visual metaphor task to produce a frame. The resulting consecutive frames will be rendered as a scene in the DT. The updated scene generates the visual metaphors of network communications as specific shapes, not only in the 3D GUI but also in the physical domain.

The 3D GUI is coupled with an immersive AR-based laser projection system. Therefore, laser functions send commands to the laser software in parallel with the scene updating. Consequently, the metaphor core displays real-time network communications from the physical network and robots, as well as simulated networks and robots of the DNT. Instead of visualizing the network in a virtual environment, we project the simulated environments, including virtual objects, robots, and network infrastructures, into the real world. Our research emphasizes projecting metaphors based on V2V links, which the DNT generates for each use-case depicted in Fig. 1. The metaphors include visualizing aspects such as the present link quality and the network routing. Moreover, we seamlessly project virtual elements like the vehicle track and warehouse shelves into the physical world.

This layer is adapted from the proven visualization concept in spatial projection systems [12], [13], offering immersive MR experiences for operators. Thus, the visual metaphor aligns with the main goals of IRTF visualization [4] and the guide and design metaphors [14]. First, this approach enables network experts to obtain a versatile set of resources

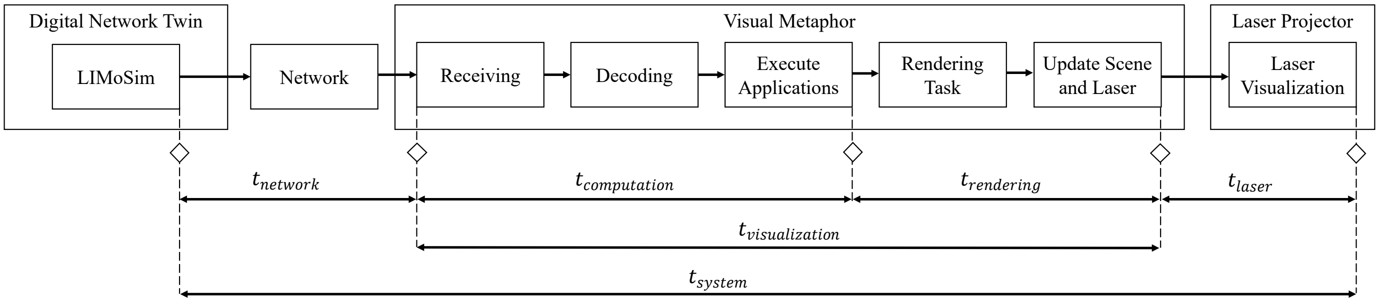

Fig. 4: Overview of the overall system latency contributors based on [20], where the physical network is emulated by the DNT.

by using an interactive and intuitive visualization in the physical domain. Consequently, it can help them navigate and troubleshoot the 6G-driven DNT applications in a more user-friendly experience, holistic, and ergonomic manner during the evaluation phase. Second, visual metaphor makes the concept of visualizing the DNT applications more comprehensible. Those goals provide valuable insights and decisions regarding optimizing real-world network infrastructure during the evaluation of 6G applications.

V. Experiment of Scaled 6G Testbed

This section highlights our contributions to the integration of the system-of-systems architecture by validating the new visual metaphor layer in particular scaled 6G study use cases in section III. In this experiment, we primarily focused on validating the visual metaphor using the SRT performance metric that represents the overall latency between the DNT and the laser visualization. We exclude the internal latency of DNT since it acts as the emulated data source of the physical network. This metric plays a crucial role in assessing the performance of interactive systems and their impact on the HCI experience. The SRT provides insights into the system's responsiveness to the input from LIMoSim and its efficiency in projecting the desired visual metaphor on the physical floor.

TABLE I: Visual Metaphor PC Specification

Specification	Value
Operating System	Windows 10
Processor	Intel Core i9-7980XE CPU @2.6 GHz
Number of Cores	18
Memory	96 GB
Graphics Processing Unit	NVIDIA GeForce RTX 3080 Ti

The measurement setup for each scenario is carried out as depicted in Fig. 5 and takes place in visual metaphor with the provided specification in Table I. LIMoSim in DNT PC emulates the link matrix $\boldsymbol{L}$ periodically according to the real-time network constraints and transmits the link matrix $\boldsymbol{L}$ via MQTT protocol to the visual metaphor. The visual metaphor stores the end-to-end network latency between the DNT and the visual metaphor, including the computation statistics like rendering time and computation time for each scene.

The measurement pipeline for SRT metric is depicted in Fig. 4, consisting of DNT, visual metaphor, and laser projector hardware. The SRT metric or t_{system} shows the overall system latency from the transmitted link matrix $\boldsymbol{L}$ in DNT PC until the laser is projected and visualized on the physical floor. It includes the sum up of the network latency $t_{network}$, visualization processing time $t_{visualization}$, and the latency of laser projection t_{laser}.

First of all, both the clocks of DNT and visual metaphor are synchronized using Network Transport Protocol (NTP), where the DNT is the time server and the visual metaphor is the time client. This step is required to ensure there is no time offset between them. Hereafter, the network end-to-end latency $t_{network}$ is measured using the time delay between the transmitted timestamp from link matrix $\boldsymbol{L}$ of LIMoSim and the timestamp when the message is first received on the API of the visual metaphor. Sequentially, the visualization processing time $t_{visualization}$ is measured using the built-in rendering statistics function of the game engine software.

Visualization processing time emphasizes the graphics rendering of visual metaphor that comprises the Central Processing Unit (CPU) time $t_{computation}$ and the rendering thread time $t_{rendering}$. This process represents the elapsed time since the API of visual metaphor receives the link matrix $\boldsymbol{L}$ message until the new scene is rendered. We consider the CPU time $t_{computation}$ as the time duration for receiving and decoding a message, extracting the information, and executing the corresponding applications, like updating the positions of the robots and rendering the visualization of communication links in 3D GUI. Meanwhile, the rendering time $t_{rendering}$ describes the time that elapses from the application to render the scene view

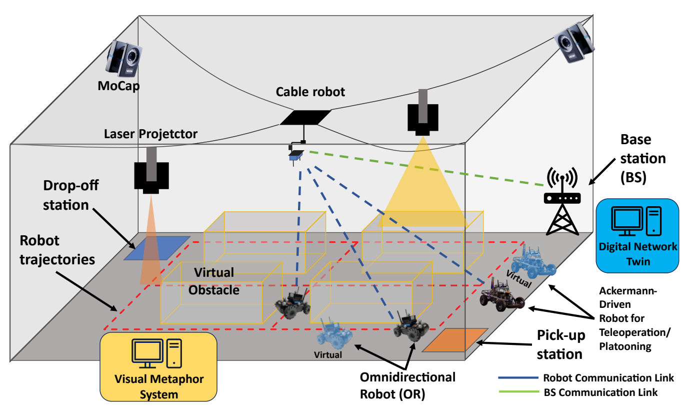

Fig. 5: Testbed setup for scenario evaluation that integrates the proposed system-of-systems architecture.

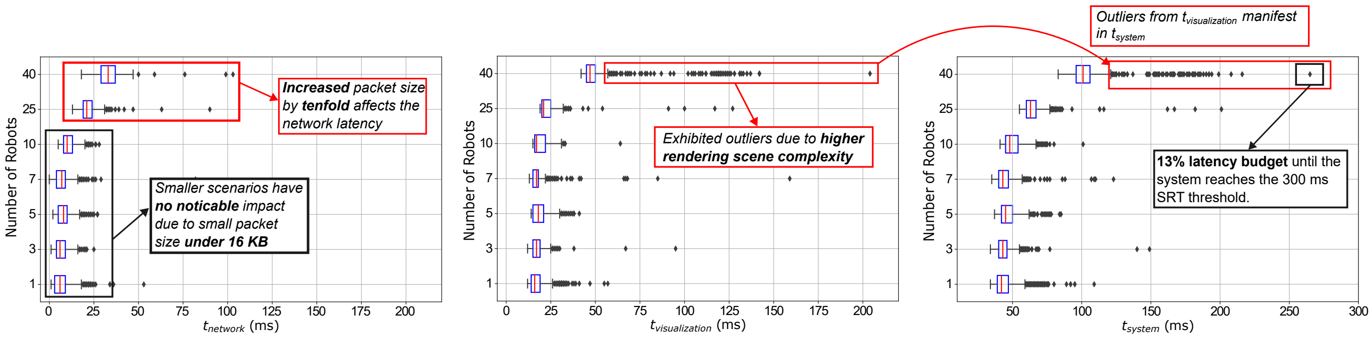

Fig. 6: Scalability analysis of different performance metrics for various numbers of robots.

until the new scene and laser network visualization are updated in the 3D GUI. In parallel, once the laser visualization in the 3D GUI is rendered, the signal control to the laser projector software is sent. Consequently, t_{laser} is measured and defined as the time delay between the sending signal control and the laser is projected in the physical world.

In the case of the visual metaphor validation, we focus on the visualization of the Received Signal Strength Indicator (RSSI) between network participants and the predicted network routes. This validation stage aims to obtain a comprehensible visualization of the link quality from the generated link matrix $\boldsymbol{L}$ from LIMoSim. Table II describes the LIMoSim simulation parameters for every scenario we want to measure.

In the teleoperation, we observe the behaviors of the PARRoT [18] by visualizing the predicted network route as the laser line linked between either the Ackermann-driven car to the cable robot or the base station. The visual metaphor subscribes to both MQTT topics of PARRoT and LIMoSim link matrix $\boldsymbol{L}$ in this scenario.

We evaluate two critical parameters in the platooning scenario: the quality of V2V communication between robots and the signal strength to the base station. The platooning measurements are carried out using a different number of robots, up to 40 vehicles, that run for several laps. For the measurements with up to three robots, we use physical robots. Beyond three robots, we employ only virtual robots.

In the 3D automated intralogistics scenario, we emphasize the validation of visual metaphor visualization for 3D network management application. This involves projecting the virtual environments to the physical floor and the visualization of V2V communication link quality due to the shadowing effects of the virtual obstacles. In this experiment, we employ three physical omnidirectional robots.

TABLE II: LIMoSim Network Simulation Parameters

Parameter	**Value**
Update Interval	0.1 s
Alpha (α)	2.6
Speed of light (c)	299 792 458 m s^{-1}
Center Frequency (f)	2.4 GHz
Transmission Power (P_{TX})	20 dBm
Noise Floor	−85 dBm
Bandwidth	20 MHz
Constraints	Data rate, loss, limit, RSSI

VI. Results

A. Scalability Analysis for Visual Metaphor Performance

The scalability analysis in Fig. 6 evaluates several performance metrics of latency, visualization processing time, and SRT for diverse numbers of robots solely in the platooning scenario. This scenario is chosen due to LIMoSim's ability to simulate various virtual robots accurately. As illustrated in Fig. 6, the trends observed in most performance metrics clearly indicate an increase in system response time as the number of robots in the scenario grows. This performance trend is partially influenced by the multiplied latency time, which is averaging $\approx$10 ms up to 25 robots, and the latency is tripled to $\approx$32 ms for the 40 robots scenario. The exhibited situation arises from the increased packet size of the link matrix $\boldsymbol{L}$ message due to the rising constraint information for each robot key in the JSON message.

The second contributing factor is the escalated visualization processing time, which averages around $\approx$23 ms. Moreover, some outliers are also noticed in some measurements. The shown behaviors depend on the availability of the computer's processing resource and the complexity of the rendering task. These observations highlight the impact of scalability on the assessed performance metrics and contribute to the more significant delay of SRT as depicted in the rightmost plot of Fig. 6. Lastly, the laser projection time also contributes to the SRT, with an average of $\approx$20 ms, which is determined through laser software measurements.

The combination of every latency contributor in Fig. 4 results in the overall average SRT of the visual metaphor,

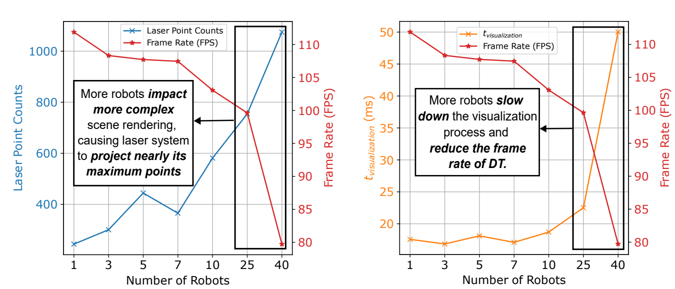

Fig. 7: Frame Per Second (FPS) comparison against laser point counts and FPS comparison against visualization time.

which is $\approx$55 ms for overall showcases. The current result is still within the boundaries of the HCI guidelines threshold [15], [16] of 300 ms. Hence, the visual metaphor potentially enables the network engineer to be still in control of perceiving the evaluated DNT applications.

Furthermore, we analyze the visual metaphor in terms of DT graphical performance and its correlation with projected laser points in Fig. 7. This analysis still relates to the scalability of simulated robots, where the x-axis for both plots in Fig. 7 shows the number of robots. The left-side plot compares the frame rate against laser point counts. It is evident that an upward trajectory in laser point counts is observed with a growing number of robots. Simultaneously, the right-side plot depicts the rising trend of visualization time, aligning with the increased complexity of rendering scenes for multiplied numbers of robots. This visualization process includes generating laser visualizations for both DT and real-world laser projection. Notably, both plots showcase a discernible downward trend in frame rate as the number of robots expands. The DT frame rate experiences a decrease, primarily due to the escalating count of projected laser points, which exerts increased computational load. This surge in laser point counts directly impacts the frame rate, highlighting the challenges posed by scaling in terms of computational efficiency. These findings emphasize the intricate relationship between the number of robots, laser point counts, visualization time, and FPS, providing essential insights for optimizing the scalability of the visual metaphor system.

B. Visual Metaphor Visualization

The following evaluation is carried out to test the entire system-of-systems architecture in the 6G testbed, including the integration of LIMoSim and the visual metaphor. For all scenarios, the projected laser lines represent the visual metaphor of the communication link between network participants. In addition, in the platooning and intralogistics scenarios, the different colors of the laser line represent the varying RSSI values of a communication link. Fig. 8, 9, and 10 depict side-by-side visual metaphor results between DT and reality.

1). Teleoperation Result: The visual metaphor of the teleoperation scenario highlights the behavior of AI-based network routing in Fig. 8. The real-world setup initially shows the direct communication links of the cable robot and Ackermann-driven robot to the base station. Once the PARRoT predicts the alternative network route, the visual metaphor switches the communication visualization via the aerial node of the cable robot. In parallel, the 3D GUI displays the same robots' positions and laser visualizations.

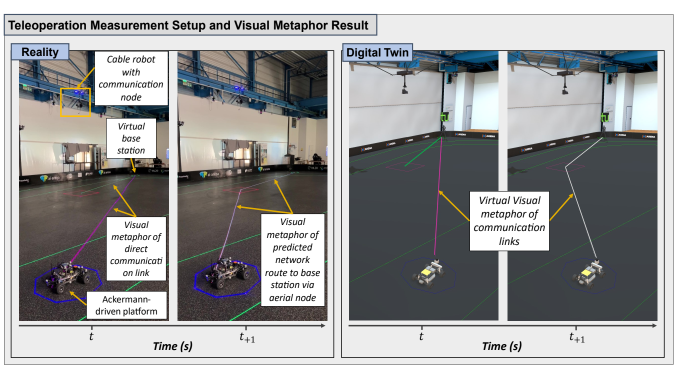

Fig. 8: Teleoperation measurement setup and the visual metaphor result for AI-based network route.

2). Platooning Result: Fig. 9 illustrates the result of the platooning scenario, showcasing the visualization capabilities of the visual metaphor. It effectively maps the scaled testbed of the vehicle track into the physical world using a laser projection system. In the platooning context, the projected laser lines connecting the Ackermann-driven cars to the base station visually indicate link quality. When the Ackermann-driven cars remain within the base station's coverage, these laser lines are visible and appear green. Additionally, distinct colors of laser lines connecting robots and the cable robot signify the presence of a V2V connection link, allowing for clear identification between these diverse connections.

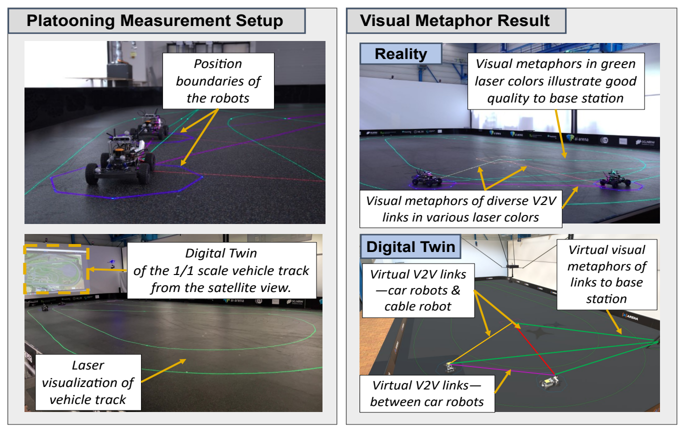

Fig. 9: Platooning measurement setup and the visual metaphor result. The DT illustrates the 1/1 scale of the vehicle track from the satellite view.

3). Intralogistics Result: Within the intralogistics scenario in Fig. 10, the laser lines serve as indicators of the V2V communication link quality among robots. A red line signifies a poor communication link, while a green line indicates a strong one. The presence of a blue line suggests that a cable robot facilitates communication as part of the 3D network management application. The emulated warehouse shelves from DNT are projected to the physical floor as the four large yellow-colored rectangles. To recap the section VI, we present a link to a video for the intralogistics transport in Fig. 11.

VII. Conclusion

In this paper, we introduce a novel feature of the visual metaphor in our 6G system-of-systems testbeds, aimed to enhance the evaluation experience of new 6G applications in DNTs. This system significantly improves the comprehensibility of the DNT concepts and behaviors, unveiling an interactive mapping between the physical 6G testbeds and DNT. It provides network operators with visually and

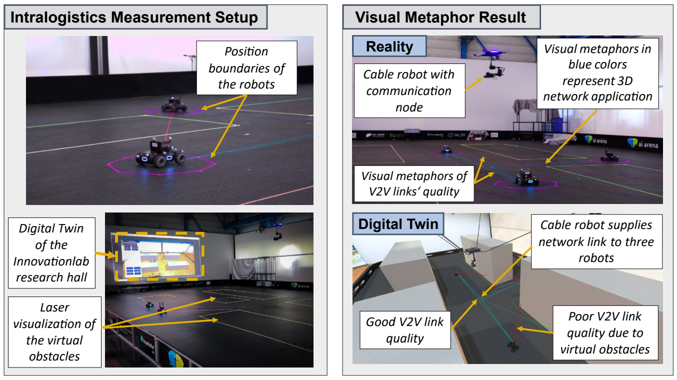

Fig. 10: Intralogistics measurement setup and the visual metaphor result for 3D network management. The DT replicates the Innovationlab research hall and visualizes the virtual obstacles from DNT.

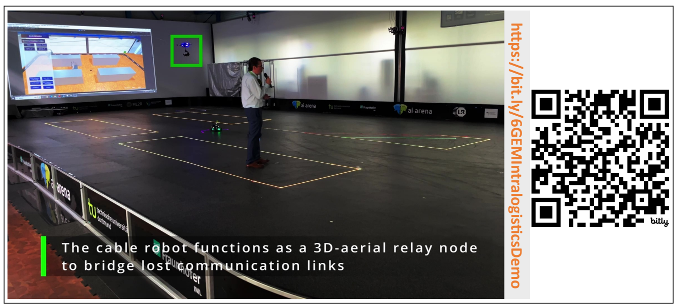

Fig. 11: For the demonstration of the visual metaphor in the intralogistics scenario, scan the QR-code or use the following link: https://bit.ly/6GEMIntralogisticsDemo.

intuitively illustrative experiences through immersive AR technology powered by a laser projection system. We have further demonstrated the integration of the different systems: teleoperation and platooning in a scaled environment and intralogistics transport scenario in a real-world sized environment, into the visual metaphor system. As a result, this novel method seamlessly projects V2V communication link quality and three-dimensional network environments generated by DNT into reality, providing a holistic context for assessing 6G applications. The demonstrations show that the visual metaphor behaves according to the defined functionalities with the average system response time of 55 ms. Essentially, the visual metaphor closes the gap between the real-world network and the digital network environment. Visual metaphor provides insights beyond what conventional simulations offer and facilitates a cost-effective testbed through scalability for increased numbers of users and scenarios unlike in VR- or AR-based HMD. The system also improves the ergonomics of the network operators. Future work involves the development of a simulator for swarm robots in the virtual mobility domain.

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