one6G

Taking communications to the next level

TOWARDS 6G-ENABLED DIGITAL TWINS

Technical Recommendations

WHITE PAPER

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one6g.org

Scope

Digital Twins are generally defined as virtual representations of physical systems with bidirectional data exchange [1]. The use of Digital Twins has been widespread throughout recent years in industrial automation and process engineering, where Digital Twins can provide insights in to system performance and likely failure rates, among other metrics. However, the uptake of Digital Twin technology is now expanding to encompass other vertical industries and domains, such as smart cities, network modeling, and in particular increasingly to applications within the rapidly progressing fields of Robotics & AI. The one6G association believes that many key application areas of the future 6G communication system will be enabled by Digital Twins.

For mobile communication networks, two somewhat distinct types of Digital Twin are of the most significant interest. First, the perhaps more common scenario of digital twins of physical systems, i.e. “Application-level Digital Twins”, which can represent a city, a robot, a smart farm, or many other systems; and 2) a digital twin representing components of the network itself, i.e. “Network-level Digital Twins”.

Notably, research from the literature on the simultaneous simulation of physical and networked systems indicates that it is important to consider the combined dynamics of the system as a whole rather than considering each component in isolation. However, the current landscape of Digital Twin technology typically focuses on either physical or network twins separately, meaning that holistic Digital Twin solutions must themselves connect these virtual representations “ad-hoc” – a task which can often be challenging due to fundamental differences in representation between network and application-level digital twins. In other words, there is a distinct lack of Digital Twin solutions for efficiently mirroring the behavior of networked physical systems. The one6G association recognizes the importance of Digital Twins as a key technology for future wireless communication systems and vertical industries and therefore considers the development of a combined Digital Twin platform to be of high importance for ongoing 6G research & technical development.

The goal of this white paper is to drive the development of such a platform by presenting a set of technical recommendations for a combined application/network-level digital twin platform, derived from the state-of-the-art Digital Twin technology, and in consultation with the wider cohort of one6G members and stakeholders. Although general in nature and not limited to the scope of the one6G association, these recommendations will be further considered within one6G WG4 as part of an ongoing process to develop a combined network/physical Digital Twin platform.

First, we define and outline the key characteristics of Digital Twins and the current landscape of Digital Twin tooling, broadly characterizing Digital Twins as application-level or network-level as defined above. Then, we present the results of a survey on Digital Twin Tooling & Requirements which was distributed to one6G members, and summarize the key conclusions relevant for the combined Digital Twin. Next, we present a series of recommendations for a combined physical/network Digital Twin platform based on the key characteristics, current landscape, and survey results, broadly characterized as “high-level” recommendations and “technical” recommendations. Finally, we conclude with an outlook towards the next steps for the development of the one6G Digital Twin platform, including integration between Digital Twins and generative AI.

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1. Definitions of terms

Digital Twin: A virtual representation ("twin") of a system with bidirectional, online data exchange between the system and twin. Note: examples of underlying systems can include physical hardware, software systems, process, etc.

Simulation: A virtual representation of a system, typically used for making predictions about future states given known input data. Crucially, simulations lack the online, bidirectional data exchange needed for digital twin representations.

Application-layer Digital Twin: A form of digital twin which represents a system within the application layer. An example could be an industrial factory, a robot, a smart city, etc. Typically deals with application-layer metrics such as factory throughput, robot performance KPI's, etc.

Network-layer Digital Twin: A form of digital twin which represents the communication network between multiple entities. Typically deals with network-layer metrics such as quality of service, up/downlink rates, etc.

Digital Twin Federation: A term which encompasses techniques for interoperability between Digital Twins, for example by sharing data and functions between DT entities.

2. Digital Twin Tools & Systems

2.1. Anatomy of a Digital Twin

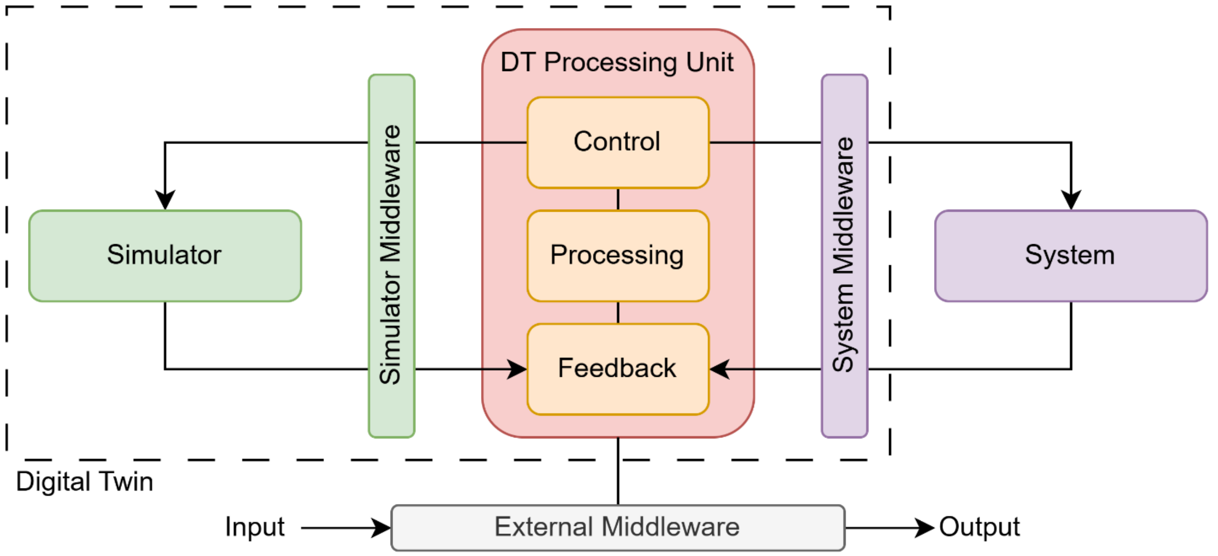

Figure 1: A block diagram illustrating the anatomy of a typical Digital Twin system. Feedback from a system and its simulated representation are transmitted (via middleware as necessary) to the Digital Twin processing unit. Control or update signals may then be transmitted back to the system(s) as needed. The DT processing unit be connected to external IO via a suitable middleware. Note that this is a high-level architecture and specific Digital Twin implementations may differ[1].

Digital Twins (DTs) are virtual replicas of physical entities, systems or processes that maintain continuous synchronization with their real-world counterparts through bi-directional data exchange [1]. Digital Twins can be used to augment a system with enhanced capabilities of monitoring and prediction. This enables use-cases such as predictive maintenance, process optimization, or model-based control, to name but a few examples. In general, DTs provide system operators with an enhanced level of decision-making and control in complex cyber-physical systems & environments.

The high-level anatomy of a DT is illustrated in Figure 1. Note that we have been quite general in our approach to categorize the key constituent elements of DTs, since in practice DT systems can be complex and extremely domain dependent. First, note that typically a DT represents a physical or software defined entity or collection of entities, which we will name generically a 'System'. The key elements of a DT are then as follows:

1. System Middleware: A communication layer that allows for communication between the System and the DT entity. The specific choice of middleware is use-case dependent, for example industrial automation DTs may use a system based on the OPC-UA standard, ROS may be used for robotic systems, or in general ad-hoc solutions could be used. In addition, the DT may require real-time and/or accurate/high-resolution sensing of System entities, which may be performed by entities within the System or alternately by the communication signals themselves, i.e., via Integrated Sensing and Communications (ISAC). In the above

[1] For example, a DT designed for predictive maintenance is unlikely to send control signals directly to the physical system or digital counterpart, and rather may simply update a database entry or use an external API to update maintenance statistics.

abstraction, ISAC can be implemented as a component or feature of the system middleware[2].

2. Simulator: A key component of DTs is the virtual representation of the system. This is achieved through use of an appropriate simulator, which should simulate the System to a level of accuracy dependent on the use-case. The complexity of the simulator and its individual feature set are full use-case dependent. For example, a robotic simulator could be used, or a custom simulation could be written for a chemical process in a plant.
3. Simulator Middleware: We define an additional middleware entity as a bridge between the simulator and the "DT Processing Unit (DPU)", defined later. Although in practice this may not be needed for a standalone DT which uses a single simulator "backend", it is a desirable property to enable interoperability between simulators for different use-cases.
4. External Middleware: We define a further and final middleware entity which acts as a bridge between the DPU and external input & output signals. This communication bridge enables, for example: a DT to prompt an external service based on the System and/or Simulator state, or for an operator of the DT to modify some parameters online. The ISAC capability discussed in Point (1) may alternatively be considered or implemented as a constituent part of external middleware.
5. DT Processing Unit (DPU): This is the "brain" of the DT, which receives input signals from the System, the underlying Simulator, and potential external interfaces, via the appropriate communication interfaces. The DPU processes these signals

Note that to maintain generality, we do not assume that the communication interfaces between the Simulator, System and external I/O utilize are based on the same middleware. Neither do we overly constrain the operating parameters of any of the described entities (such as Simulator frequency, DPU processing frequency, etc.) since in practice these parameters will be highly use-case dependent. Rather, the defined description of a DT is intended to indicate the key features of DTs while supporting the wide variety of DT use-cases which are currently seen in industrial applications as well as elsewhere. In particular, some special cases of DT may include:

- Real-time DTs which utilize low-latency communication middleware to enable real-time synchronization between the system and its virtual counterpart
- "Edge-enabled" DTs which offloading the processing of the information to via the external I/O middleware where expensive computations and Artificial Intelligence (AI)-driven analytics can be applied

The specified architecture is well designed to define a Digital Twin of a single entity or process, or of a group of systems with similar properties, operating in the same domain (i.e. industrial automation, or a robot swam). However, for complex systems which are composites of multiple entities or entities with disparate properties, such as a physical system and an associated communication network, the current architectural decision of a single simulator back-end and associated middleware can be problematic. In other words, the current architecture mean it is difficult to create "cross-domain" DTs.

A concrete example of this is a DT which represents both a physical entity and its underlying communication network. Implementing such a DT would have real benefits: by integrating a cyber-physical system DT, which provides input in to both the system and network dynamics, the advantages of DTs in terms of elevated predictive and analysis capabilities would be granted for the combined system as a whole, allowing for greater ability to dynamically adjust it to operational requirements, and adapt to the available resources (be they physical or network resources). To expand further on this point, we explore the definition of sub-types of DTs in the forthcoming section.

[2] This layer of capability is envisaged to be combined in the future (6G) ecosystem with the communication layer.

2.2. Application-layer digital twins

Application-layer Digital Twins (AppDTs) are virtual models that replicate the behavior, environment, and operational state of physical entities such as mobile robots, industrial systems, and autonomous vehicles. These Digital Twins are essential for enabling real-time monitoring, predictive analytics, and intelligent control, providing a synchronized virtual representation that allows users and AI systems to interact with physical systems more efficiently.

The Simulator back-end for AppDTs typically is often physically-based, continuous time simulators, which can accurately represent the dynamics of the system. For example, AppDTs in the robotics domain may use robotics simulators such as MuJoCo, Gazebo or Nvidia Isaac Sim, which offer fast computation speeds and high accuracy.

A common requirement (or feature) of AppDTs is their ability to operate with low-latency, high-throughput communication to ensure seamless synchronization between physical and virtual entities. This is particularly important in mobile robotics, where sensor data from cameras, LiDAR, GNSS, and IMUs must be processed in real-time to enable remote control, autonomous navigation, and predictive decision-making.

In addition, a key aspect of certain AppDTs is the ability to offload complex computational tasks to external computing resources, such as cloud servers or on the Edge of a communication network. This allows for the robots to operate efficiently without being constrained by onboard processing limitations. In highly dynamic environments, such as industrial facilities or logistics centers, the execution of AI models for object recognition, trajectory planning, and sensor fusion requires significant computational resources that cannot always be provided by embedded systems. Offloading these computations over a communication network introduces additional challenges, as latency, jitter, and packet loss, which can have knock-on effects which impact the responsiveness of the control system.

To summarize, three key characteristics of AppDT's are as follows:

- Typically use a Simulator which prioritizes physical accuracy and operates at high frequency in continuous time
- Real-time (or at minimum "online") communication rates are typically needed for the middleware entities, to enable real-time and accurate sensing and/or fast control rates, according to the needs of the application
- The DPU is typically hosted on an external server (i.e. not directly on the System), or otherwise the DPU offloads expensive computations via the external I/O middleware

Next, we will explore the disparate characteristics of DTs intended to represent communication networks.

2.3. Network-layer digital twins

Network-layer digital twins (NetDTs) are concerned with virtually representing the complex dynamics and operational state of communication networks. Due to the high complexity of communication networks, which may involve numerous interconnected devices (i.e. User Equipment or UE's) communicating over various protocols (5G, WiFI, IoT), NetDTs can be useful to carry out design or analysis of communication networks ahead of time, without requiring significant hardware resources and complex, hard-to-recreate experimental setups. They can also be used to replicate network infrastructure components, including Radio Access Networks (RAN), Edge computing resources, and Core network functions.

NetDTs have various real-world industrial use-cases, including:

- Real-time monitoring of network statistics, i.e. to ensure a minimum level of service or make predictions on network congestion.
- Real-time control of network parameters, based on conditions in the real network & twin.
- Network optimization, i.e. based on predictions on traffic flow.
- Network design and planning

NetDTs can themselves operate at various layers, or in other words levels of abstraction. This is often evident by the choice of underlying network simulator. For example, "system-layer" NetDT simulators such as NS3 [2] are designed to model the flow of information (as packets) in communication networks, while "physical-layer" NetDT simulators such as Nvidia Sionna [3] instead model the physical propagation of radio waves. Either (or both) of these approaches can be useful, depending on the nature of the problem to be solved by the digital twin.

A crucial difference between AppDT's and NetDT's, is that the simulator back-end of NetDT's are often event-based, meaning that their execution is based on discrete events (such as delivery of a packet) rather than continuous time. In practice, this can prove problematic for the integration of systems which involve virtual representation of both a physical system and a communication network.

2.4. State of the art

2.4.1. Digital Twin Standards & Solutions in Industry

Digital Twins are widely used in industry, with commercial solutions or services available from a variety of companies and institutes, such as Fraunhofer IPK [4] and Siemens [5]. The exact treatment of DT technology varies according to the industry, company, and application requirements. For example, Siemens illustrates a variety of DTs in their portfolio, including DTs for Products, DTs for Production, and DTs for Performance. They also make a distinction between DTs which are "passive" and those which are "active", where active DTs have the potential to respond to inputs and make autonomous decisions, which they refer to as "Executable Digital Twins (xDTs)". Note that both active and passive DTs are encompassed by the DT anatomy set out in Section 2.1.

Efforts are ongoing to standardize the usage of DTs in industry to promote interoperability and reuse of technology. More specifically, in collaboration with Platform Industrie 4.0 [6], the IDTA has defined a standardized interface to enable the Digital Twins in industry, which it terms the Asset Administration Shell [7]. This standard defines an "asset" as being represented by an "asset administration shell", which contains *identifying information*, one or more *submodules* whose content contain the features and capabilities of the underlying asset, and a *semantic communication mechanism* for conveying information to and from assets. The unifying aim of the Asset Administration Shell is to greatly simplify the process of incorporating Digital Twins in to industrial processes, and to reduce business costs for companies. To this end, the envisaged use cases and technologies include features such as automatic asset identification, automatic configuration of communication between registered assets, integration with various industrial communication protocols such as OPC-UA, and more.

2.4.2. Co-Simulation of Physical Systems & Communication Networks

As real-world deployments of robotic systems continue to become more commonplace, specifically outside of controlled lab or industry settings with hard-wired or finely tuned wireless communication systems, mobile communications networks will play an increasingly necessary role in supporting robot operations. This is because robotic systems operating in real-world settings will necessarily involve:

1. Intra-system Communication: communications between embodied agents (robots) in multi-agent systems
2. Inter-system Communication: communications between individual embodied agents (robots) with each other, or between robots in separate multi-agent systems
3. Computational Offloading: communications between agents and offboard processing units or data storage entities

In the robotics domain, the communication signals transmitted between agents are likely to be extremely multimodal with highly varying characteristics based on the specific scenario. For example, a robot could be transmitting small data samples (e.g. control signals) to its neighboring agents at a high frequency, or large data samples (e.g. sensor data) to an offboard server at a low frequency, or some combination of these two extremes.

Furthermore, certain subcases of networked robotics may involve other communication modes, such as:

- Real-time communication between *wireless* sensors and robotic hardware (e.g. EMG electrodes on a wearable robotic system)
- Real-time communication between robots and human operators/overseers for e.g. remote maintenance tasks

Evidently, the performance of robots operating in real-world scenarios is tightly coupled to the performance of their underlying communication networks. Despite this, existing Digital Twin platforms or architectures typically address these domains separately due to the discrepancy between the underlying simulator back-ends of these systems, leading to a fragmented approach that does not exploit the full potential of Digital Twins. Therefore, it is desirable to utilize a DT which is able to represent the coupled dynamics of both the physical system and communication network. As alluded to in Section 2.3, this can be challenging with typical AppDT's/NetDT's. However, a number of research works have explored mechanisms to bridge these different forms of DT.

1. RoboNetSim [8] implemented an interface between a network and robotic simulator to account for the discrete/continuous time discrepancy. However, this required low-level changes to both simulators, and thus was of limited extensibility.
2. Cornet [9] implemented a specific network-robot simulator for multi-UAV systems. ROS was used as a middleware between the systems, however the solution is specific to two simulator backends (Gazebo and NS3), again lacking extensibility. Furthermore, the introduction of ROS2 has brought significant architectural changes to the middleware, and ROS1 is no longer supported.
3. Ros-netsim [10] outlined a more general framework which utilized a middleware entity, also designed in ROS, to bridge the disparate architectures of the network & physics simulator back-ends. Although Ros-netsim is more extensible, it still relied on a ROS1 based implementation, and was unproven in terms of scalability to large robot systems or data packets.

These frameworks, especially (3), provide an indication on how AppDT and NetDT technology can be combined to produce a holistic DT system, which is a desirable tool for those working on the design & application of 6G robotic solutions & systems.

2.4.3. iTEAM-UPV 6G-Enabled Digital Twin Platform

The iTEAM-UPV 6G-enabled Digital Twin Platform for Immersive Robotics is designed to explore these challenges by integrating Digital Twins with real and simulated mobile robots over a private 5G network, serving as a precursor to 6G-based control architectures. By leveraging ROS-based robots, immersive interfaces, AI-driven analytics, and real-time network configurations, this testbed provides a realistic environment to evaluate the latency, reliability, and scalability of robotic applications. The iTEAM-UPV testbed is designed to characterize the network requirements of Digital Twins by testing different Quality of Service (QoS) conditions, including variations in packet loss, network congestion, and latency. By measuring the resulting Quality of Experience (QoE) at the application level, researchers can assess how network conditions influence human-robot interaction, reaction times, and real-time control accuracy.

The integration of immersive interfaces such as VR, AR, and haptic feedback within Digital Twins is another critical component of the iTEAM-UPV testbed. Traditional robotic control interfaces often rely on screens, joysticks, and conventional HMIs, which may not provide the level of situational awareness required for real-time operation in complex environments. By using VR-based 360 video streaming, immersive cockpits and haptic suits, operators can achieve a more intuitive and precise interaction with remote robotic systems. The iTEAM-UPV testbed incorporates devices such as the Meta Quest 3, Apple Vision Pro, and haptic feedback systems like the BHaptics Tactglove and OWO Vest, allowing for detailed analysis of how haptic and immersive technologies enhance robotic teleoperation.

To better understand the requirements and limitations of Digital Twins in real-world industrial and logistics applications, the iTEAM-UPV testbed defines two primary use cases. The first use case involves an immersive race between two mobile robots, where the robots are remotely driven through a Digital Twin environment while interacting with virtual objects in real-time. This setup tests the impact of network reliability, latency, and bandwidth constraints on remote operation, while also analyzing how immersive interfaces improve user perception, reaction time, and control efficiency.

The second use case features a race between a remotely driven mobile robot and an autonomous AI-driven robot. The autonomous robot is initially trained within a Digital Twin environment using AI-based trajectory planning and sensor fusion algorithms, before being deployed in a real-world race. This experiment evaluates how well AI models trained in virtual environments transfer to real-world applications, while also examining the role of Digital Twins in optimizing autonomous robotic behavior. Since the AI-driven robot relies on sensor fusion from LiDAR, GNSS, and RGB-D cameras, this testbed provides an opportunity to study the latency and accuracy of sensor data streaming over a 5G network, particularly under challenging conditions where real-time AI inference must be performed at the Edge.

The iTEAM-UPV testbed focuses on real-world ROS-based mobile robots such as the Robotnik Summit XL, Robotnik Theron, and Unitree Go2. By combining real-time network monitoring, AI-based robot control, and immersive operator interfaces, this platform aims to contribute to the definition of the Key Performance Indicators (KPIs) required for 6G networks, particularly for low-latency, high-reliability applications in mobile robotics. Through the characterization and optimization of network parameters, media streaming protocols, AI-based sensor fusion techniques, and immersive control mechanisms, this research initiative will provide insights for the convergence of Digital Twins, immersive technologies, and 6G communications.

Figure 2: Images illustrating the iTEAM-UPV 6G-enabled DT testbed. (Top): 5G networking infrastructure. (Bottom left): a human operator controlling a mobile robot via an immersive interface with VR, AR and haptic elements. (Bottom right): two Robotnik Summit XL robots, linked via 5G to human operators.

3. Digital twin requirements, KPI's and use cases

In order to further elucidate the relationship between the requirements of DT use-cases and the choice or development of DT solutions or supporting tools, the one6G WI104 working group designed and distributed a survey on DT's to the wider cohort of one6G members. The survey was additionally intended to identify key existing DT technologies or specific tools, highlight any gaps in the current landscape where the needs of one6G members are not being met, and to provide insights on the technical feature-set that should be supported by a possible one6G DT platform, that has support for both application-layer and network-layer digital twin tooling. To summarize, the goals of survey were as follows:

1. Identify the relationship(s) between digital twin use-cases, requirements, and tooling[3]
2. Identify gaps in the current landscape of DT tools & systems, and the corresponding use-cases
3. Provide insights on the technical feature-set to be supported by the one6G Digital Twin platform

The DT survey was circulated via one6G WG3 to the wider one6G cohort using an approved survey platform. Responses were selected to be anonymous to preserve the data privacy of responders. The survey was first circulated on 14th October 2024 and was kept open until 25th November 2024 to allow adequate time to collect responses. In total, responses were received from representatives of 9 one6G members. Note that some of the questions in the survey were multiple choice, and therefore the total vote count in the subsequent analyses can exceed the total number of votes in some cases. Moving forward, the survey may continue to be distributed at future events in order to receive more feedback and update this analysis for future volumes of this white paper.

For reference, the full text of the distributed survey is provided in Appendix 0, while the answers received from the survey are summarized in Appendix 0 in tabular format. In the remainder of this section, the detailed results of the one6G Digital Twin member survey are presented and analyzed qualitatively with respect to the goals outlined above.

3.1. Digital Twin Survey Results

3.1.1. Participant Backgrounds

The first question of the survey was intended to poll on the backgrounds of the survey participants. This was important due to the wide variety of one6G members, and the intention to redistribute the poll to further audiences at future occasions. The results from this question are presented in Figure 3.

The majority of the survey participants came from a robotics background (55.9%), with the remaining working in radio optimisation (31.6%) or a self-selected area. The self-selecting participants worked directly with digital twins or network optimisation.

The largest cohort of participants with a robotics background selected 'Factory of the Future' as their background, which can be interpreted as the next-generation of industrial automation. Industrial automation in general is an industry which has already implemented real-world applications (and the associated benefits) of Digital Twins to some extent. However, there remain numerous areas in which the use of AppDT's with more advanced features can improve outcomes,

[3] To see why this is important, consider that a Digital Twin of an outdoor scenario may require different tooling to a Digital Twin of an indoor scenario.

for example by improving interoperability, supporting larger sizes of robotic fleets, and allowing for predictive analytics to optimise industrial processes design.

The remaining participants from the robotics domain selected either 'Service Robotics' or 'Disaster Robotics'. These sub-domains of robotics involve different challenges to the industrial automation setting, specifically typically featuring more unstructured, unpredictable interactions (with humans), a far less structured environment, and fewer guarantees in terms of the communication infrastructure. Functional Digital Twins may be a necessary condition in order to achieve the real-world use-cases of these sub-domains.

Participants from a networking background are largely from the field of radio optimisation, whereby characteristics of network infrastructure (e.g. UE antennas or base stations) is fine-tuned to optimise the quality of service (in terms of latency, data-rate, or other relevant parameters) which is experienced by UE's. Such a process is crucial in particular for realising the robotics-related use-cases of next generation mobile communication networks, where high numbers of robotic UE's with multimodal data transfer pipelines and varying communication requirements will present significant challenges for current communication standards.

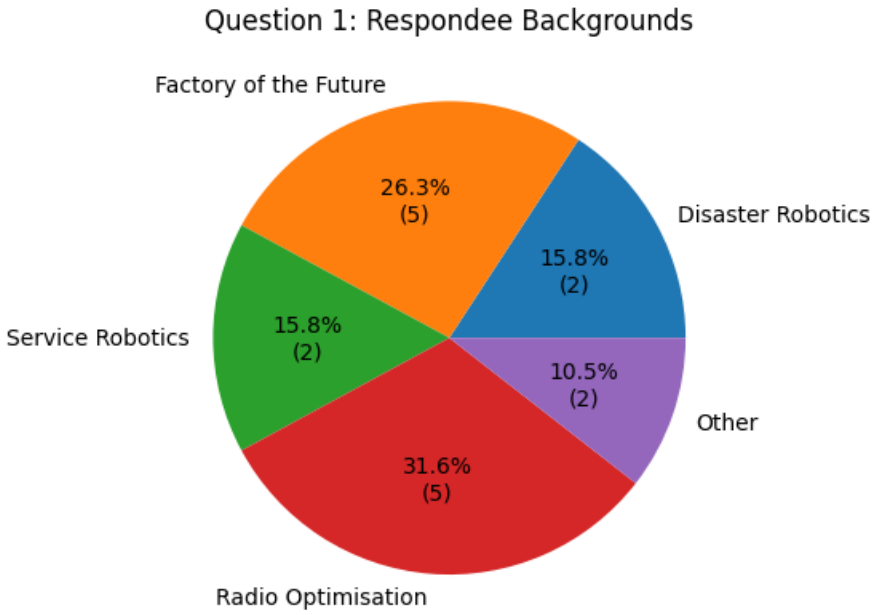

Figure 3: Results from the one6G Digital Twin member survey on the background (i.e. field or area of interest) of participants.

3.1.2. Application-Level Digital Twins

The survey polled participants on various aspects of AppDT's, with the intention to elucidate a connection between use-cases and DT tooling. Towards this, responders were asked for input in to:

1. Which AppDT tools they had used or planned to use
2. The use-cases they had or planned to address with the chosen tools
3. The requirements which lead them to select the chosen tools
4. Challenges which they have faced with the chosen tools & AppDT tooling in general

The responses from this portion of the survey are presented in Figure 4.

The AppDT tooling either being used or under investigation by the survey participants was relatively evenly distributed between robotics simulators, gaming engines, DT-specific software, and other solutions (including ad-hoc solutions). This fragmentation suggests that there is no "one-size-fits-all" solution for AppDT software, and users instead choose based on a trade-off between their individual requirements. For example, robotic simulators are a natural choice for AppDT's in the robotics domain, but users may instead choose a gaming engine if photorealism is important for their application, or a DT-specific software for support for specific factory automation use-cases.

In terms of use-cases, the majority of participants target use-cases involving model-based planning & control of systems. This suggests an "active" form of AppDT, which is able to predict & make decisions to influence the operation of the attached system, in contrast to an AppDT which is intended for offline or passive analysis of a running system. Referring back to the anatomy of a Digital Twin presented in Figure 1, "active" AppDT's can be seen as those which are actively either sending control signals directly to the physical system (model-based planning/control) or to an external service/operator for immediate action (predictive analytics).

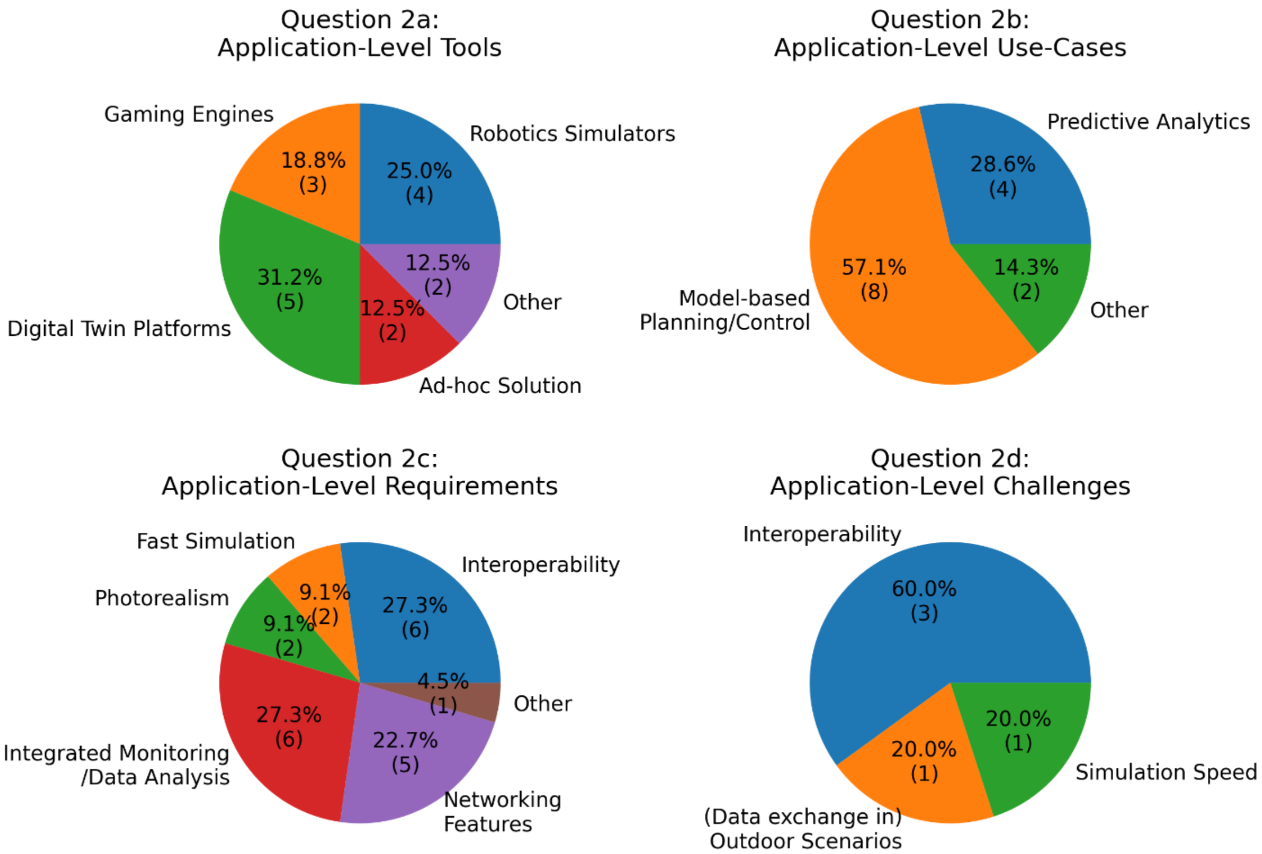

Figure 4: Results from the one6G Digital Twin member survey related to application-level Digital Twins.

The requirements specified by participants were varied, with the three most important requirements being interoperability, integrated monitoring & data analysis capabilities, and networking features. Photo-realism and fast simulation, which are important properties for synthetic data generation for AI model training, were also noted as important, though by fewer participants (possibly indicating that these requirements are tied to slightly less common use-cases). Interoperability and integrated monitoring features are important for digital twin applications, especially in next-generation scenarios where an AppDT may be responsible for representing large groups of heterogeneous robots (or other UE's), and a wide variety of data types. It is notable that networking capabilities were considered important even in AppDT's, which suggests that the "co-simulation" approach discussed in Section 2.4.2 has value even within AppDT's, which provides some motivation for a combined approach to DT systems.

Regarding the challenges faced when using AppDT tools, interoperability was noted as the most significant challenge, with simulation and the specific scenario of outdoor scenes also being noted. Outdoor scenes present a number of specific challenges, both in terms of communications (more difficult in outdoor scenarios and over long distances) and application-level challenges like environment mapping. Interoperability is a challenging problem and perhaps a strength of ecosystem based on open standards like ROS – though it is firmly targeted towards the robotics domain and may lack the rigid standardization and provable safety characteristics required by certain industrial use-cases. Identifying or building an AppDT system which adequately supports interoperability remains an open problem.

3.1.3. Network-Level Digital Twins

In a mirror of the previous question, participants were also queried on their usage of NetDT tooling and how that related to their use-cases and associated requirements. The questions posed to the participants were intended to determine:

1. Which NetDT tools they had used or planned to use
2. The use-cases they had or planned to address with the chosen tools
3. The requirements which lead them to select the chosen
4. Challenges which they have faced with the chosen tools & NetDT tooling in general

The responses from this portion of the survey are illustrated in Figure 5.

Similarly to the responses for the AppDT tooling, the response to this question indicates that choice of NetDT tooling is fragmented depending upon the use-case or field of interest. The boundary between NetDT use-cases is clearer to see, since often a use-case aligns with a specific layer of network communication (i.e. system, link-level). However, it is notable that a high proportion of responders choose ad-hoc NetDT solutions, suggesting that the feature sets of "off-the-shelf" NetDT solutions or network simulators is not yet robust, or caters more towards pure simulation than Digital Twin use-cases.

The predominant use-case selected for NetDTs was for use-case & requirement analysis (of next generation communication networks), with 25% of responders also indicating that prototyping next-generation features was their key use case for NetDTs. This is suggestive of an approach to use a NetDT for prediction and analysis, and highlights the necessity of a next-generation (i.e. 6G) digital twin platform which can enable this level of analysis to support technical R&D towards communication network design. The remaining responders indicated that robustness analysis was their primary use-case, which again can be related to the need to investigate next-generation communication use-cases which involve novel UE's (i.e. robots) with associated increases in the quality of service and robustness requirements on current communications infrastructure.

A high proportion of respondees noted easy of use as a key requirement when choosing NetDT tools, perhaps indicating that the current landscape of tooling requires a high degree of specialist knowledge to integrate. Other requirements included scalability, support for real-time feedback, and specific networking features such as network slicing. Meanwhile, the challenges recognized as facing current NetDT tooling were related to interoperability between NetDT & AppDT tools or releated to specific NetDT features such as support for multiple forms of wireless communication protocols or TCO estimation.

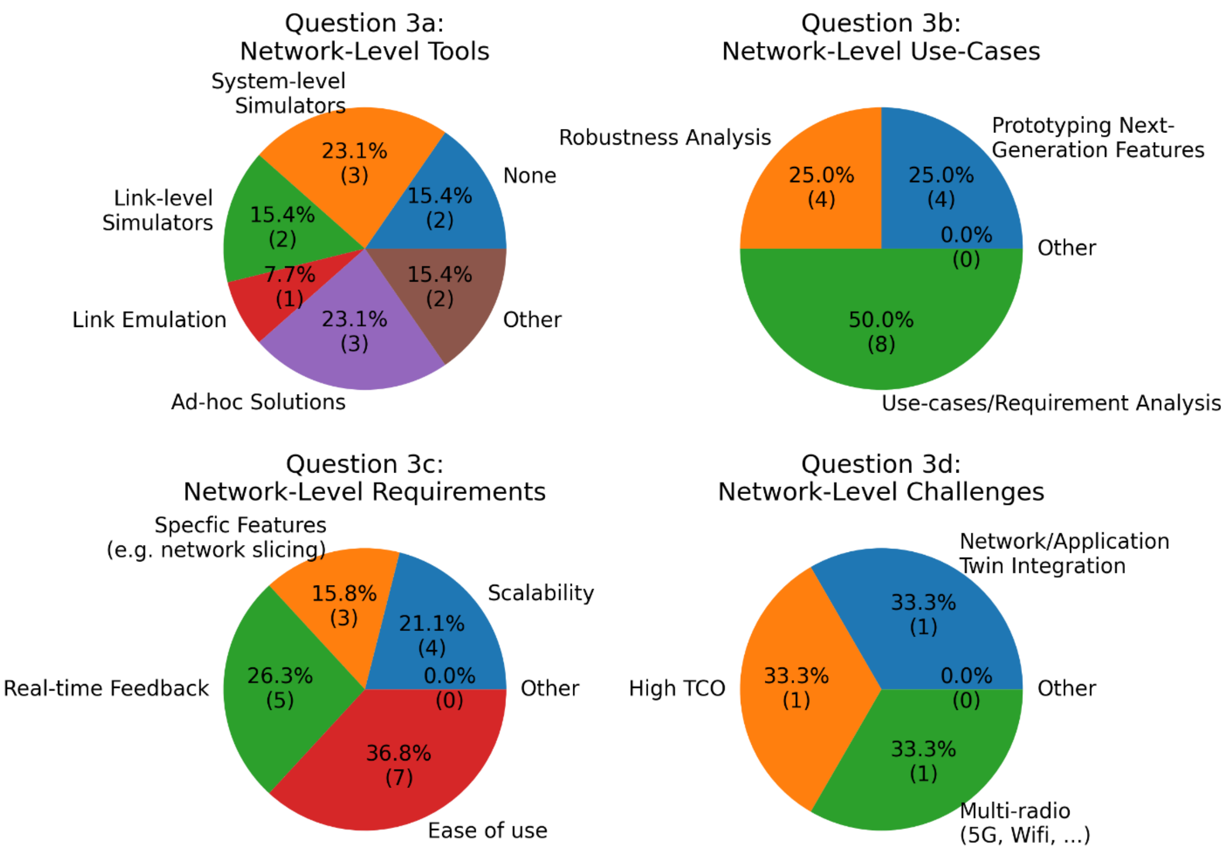

Figure 5: Results from the one6G DT member survey related to network-layer digital twins.

3.1.4. one6G Digital Twin Platform

The final question of the survey polled participants on their interest in, and ability to contribute to, a new Digital Twin platform focused on 6G research, use-cases and applications. The intention was to gauge interest in a collaborative effort towards a new 6G digital twin platform (6G-DT) by members of the one6G association. In addition, participants were also asked to suggest specific tools, either for AppDT's or NetDT's, which would be a good fit for such a platform.

The majority of responders indicated interest in contributing to the 6G-DT initiative, though in some cases this interest was linked to a specific functionality, such as a consideration of outdoor scenarios. Outdoor scenarios would certainly be a targeted feature of the 6G-DT platform, given the breadth of use-cases in robotics and other areas which take place in outdoor environments. The tools suggested by survey participants covered a range of DT tooling ranging including both AppDT simulators (MuJoCo, Gazebo) and a NetDT simulator (Sionna). The range of choices here is indicative of the lack of a "one-size-fits-all" solution, particularly in the AppDT space, and perhaps suggests that the 6G-DT platform should support multiple simulation options (or "backends") depending on the specific use-case.

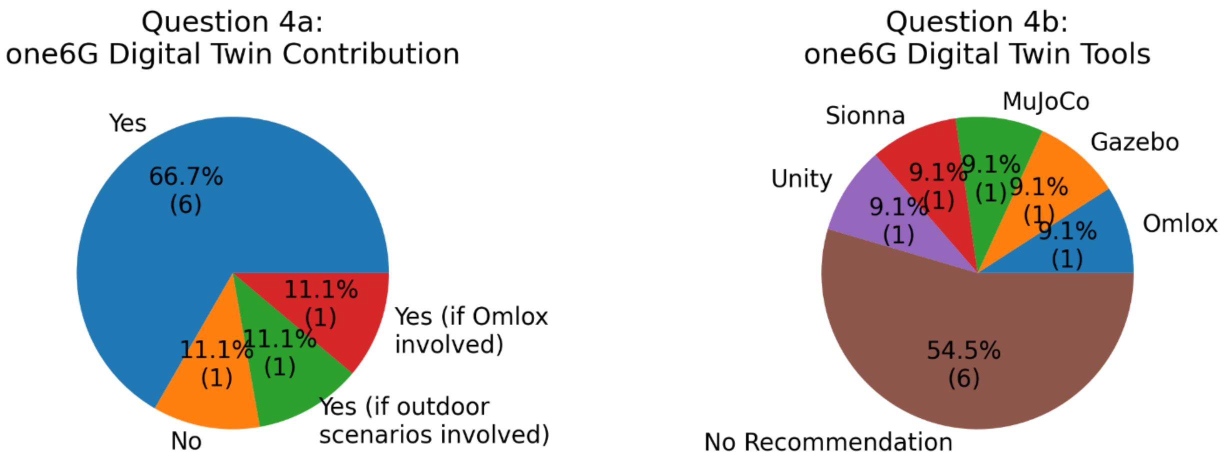

Figure 6: Results from the one6G DT member survey on interest and tooling suggestions for a one6G Digital Twin platform.

3.2. Survey Conclusions & Gap Analysis

Overall, the results from the one6G Digital Twin survey are indicative of a landscape of Digital Twin tools, across both AppDT's and NetDT's, that is fragmented according to use-case. The value of DT technology is recognized across both application-level domains (e.g. factory of the future, service robotics) and in network optimization, but users of DT's often have to create ad-hoc DT solutions using specific underlying simulators depending on their requirements. In addition, it can be difficult to find one simulator backend that supports the full set of complex requirements of a domain – for example, a simulator that supports a combination of fast processing, realistic rendering, and networking features.

A limitation of the survey presented here is the low sample side of participants, which prohibits a fuller statistical analysis of the correlations between use-cases, requirements and tooling. Nevertheless, the survey results can be interpreted as an indication of interest in contributing to a one6G 6G-DT platform, and provides hints to gaps in the current landscape of DT tooling in the context of 6G.

With the above conclusions and apparent gaps in the current landscape off AppDT and NetDT tooling in mind, as well as some additional input based on recent developments in the AI space, we will next highlight architectural considerations and high-value features for a 6G Digital Twin software platform in the next section.

4. Recommendations for a 6G-Enabled Digital Twin Platform

4.1. High-level Features

In Section 2, the definition and state-of-the-art of DT's were explored. In Section 3, an analysis on DT tooling and requirements based on a survey of one6G members was presented. Taking this information together, we can infer that there exist "gaps" in the Digital Twin tool landscape for 6G researchers and engineers of 6G or 6G-enabled technology. To fill these gaps, a 6G-enabled Digital Twin platform should provide the following high-level features:

- Interoperability: easy integration of different systems, unified interfaces to DT simulator back-ends, and interaction between distinct Digital Twin entities
- Extensibility: tools which easily support adding novel features, for example to test next-generation communication network features
- Co-simulation: combined network-layer and application-layer features
- Flexibility: Support for a wide variety of use-cases and technologies (e.g. outdoor scenes, multi-robot scenarios, multiple layers of network simulation, etc.)
- Adaptability: Support for variable-quality communication, sensing, and computing in dynamic environments, and adjusting the DT accordingly

Note that interoperability between distinct Digital Twins is a concept which is known as Digital Twin Federation (DTF) [11]. This is an important consideration when combining Digital Twins which are themselves optimized for different domains, such as DT's for Smart Cities compared to Industrial Automation. DTF also applies directly to the problem of combining AppDT's and NetDT's in to a holistic system.

4.2. Multi-Layer Architecture

The features specified above require that 6G Digital Twins utilize a multi-layer architecture, to enable the precise form of DT to be variable based on the specific purpose of the digital twin (i.e. for monitoring, real-time-control, design, etc.). Furthermore, it is also important that, in order to maintain scalability to systems of many entities, an appropriate structured database is used to manage the data which is collected and processed by Digital Twins. As concrete examples of the need for a multi-layer architecture, note the following three use-cases:

1. Simulation of radio performance (which may involve a combination of ray tracing, beam management, system level simulation, and sandbox evaluation of AI based network planning) [12]
2. Simulation of robot locomotion in real world scenarios (which may involve multiple sub-modules including obstacle avoidance, exploration, QoS awareness, etc.)
3. Generation of training data for AI models and Agents

Typically, Digital Twins may consist of heterogeneous data and information from a wide variety of heterogenous data sources, combined with representations of objects generated from CAD models or other description formats, often organized in multiple representation layers [13]. Taking robots as an example, they are commonly represented by a set of geometric, mechanical properties, and parameters relating to locomotion by the URDF file format. Their resulting representation is constrained by their mechanical design but also by the capabilities of the motors. Within a robotics

Digital Twin, which often use ROS as the communication middleware, the control data of the motors and sensor data from sensors will typically be published and subscribed to via ROS topics.

Within a digital twin, models of the physical environment may themselves be also derived from CAD data (e.g. using a format such as a Building Information Model (BIM)) or be based on real-time reconstruction from sensors like LiDAR or cameras.

In next generation communication networks, one additional source of functionality will include providing network connectivity information and properties via a standardized API from the radio network/module to connected entities such as robots, typically in the form of radio maps. Relevant network properties could include SNR (signal to noise ratio), receiver signal strength indicators (RSSI), effective data rate at a certain 3D coordinate, MIMO modes etc.

A ubiquitous, real-time sensing channel that can accurately sample the physical world is essential in attaining true digital twinning by establishing a link between the real and digital worlds. A core capability introduced by 6G will be the symbiosis between mobile communication and mobile sensing [14]. 6G-enabled network sensing through ISAC can also be instrumental in materializing this vision, as large geographical regions fall within the coverage area of mobile communication networks.

Mobile radio sensing technology will be available in the later releases of 5G and of course with 6G. 6G radio sensing will provide enhanced environmental perception starting with localization and tracking of objects, material characterization depending on the available spectrum and carrier frequency and to some extent also spectroscopy. Enhanced 6G sensing will provide the capability to measure the micro doppler profiles of buildings, bridges and heart beats (Figure 17).

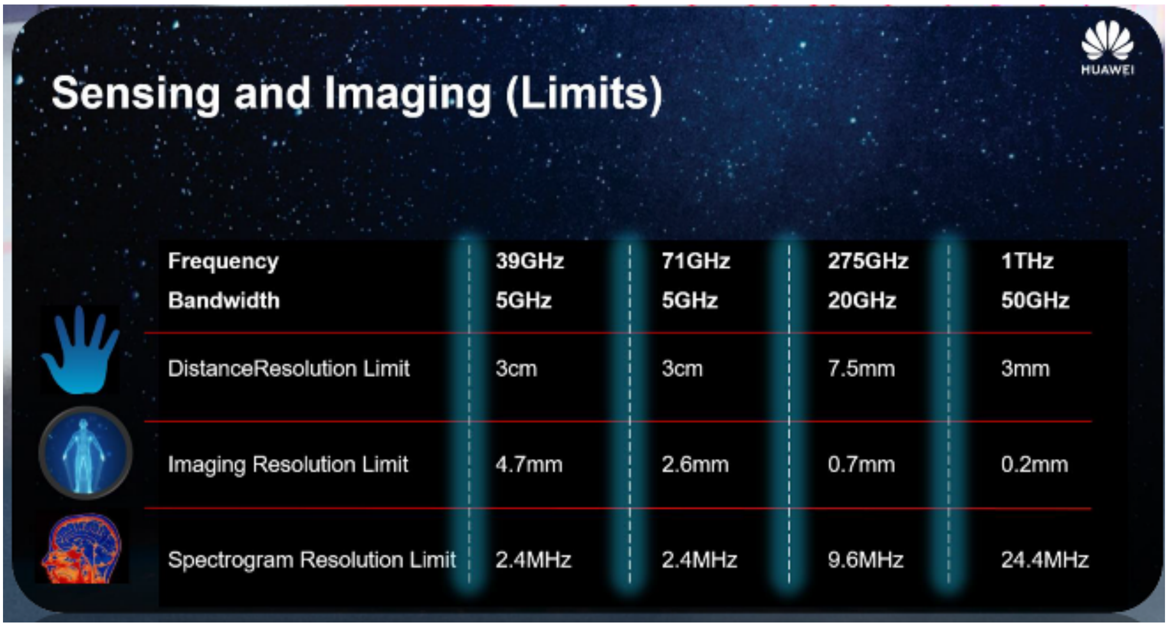

Figure 7: theoretical limits of 6G radio sensing and imaging [15]

A multi-layer architecture is proposed as the solution to enable a scalable and flexible management of data sources of a digital twin, as illustrated in Figure 18, and additionally support various simulator back-ends in order to enable interoperability as discussed in Section 4.1.1. Furthermore, a multi-layer approach is needed to evaluate and derive control commands for real world objects and systems as well as carry out management and optimization of the next generation mobile radio network.

Moreover, a multiband ISAC system can achieve near-real-time digital twins with adjustable resolution.

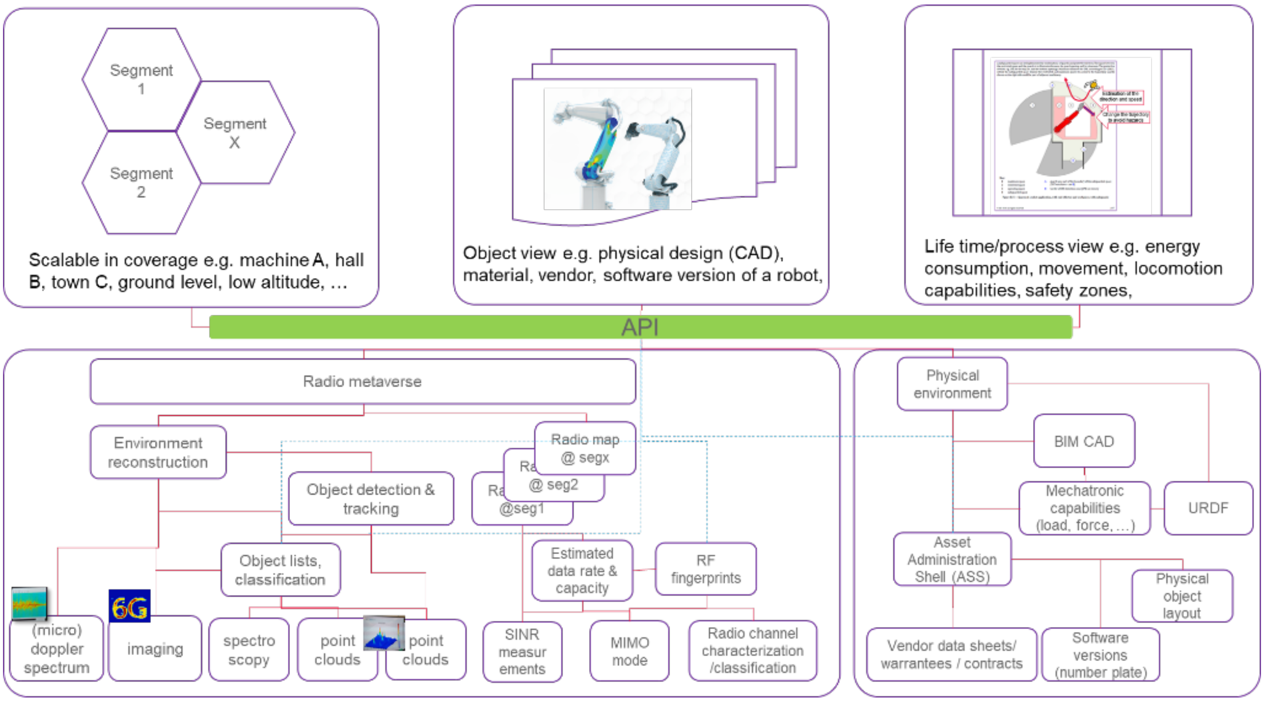

Figure 8: illustration of information hierarchies and domains

4.3. Additional Considerations: 6G & Agentic AI

In the context of next-generation mobile communications, particularly within the development of 6G networks, it is interesting to consider Digital Twins from two angles: both how 6G can be used to enhance Digital Twins (6G-4-DT) and how Digital Twins can themselves add value to communication networks (DT-4-6G).

As an example of 6G-4-DT, Digital Twins are expected to benefit from AI-native architectures, Edge-Cloud computing continuum, high reliability real-time communication, and ISAC. These capabilities will significantly enhance the real-time synchronization between the physical and virtual domains, enabling more advanced Digital Twin applications.

Meanwhile, 6G-4-DT will allow Digital Twins to be created of significantly larger, more connected systems. For example, NGMN refers in the report on 6G use cases that a large set of digital twins of separate parts of a city has to be connected to get a real-time representation of physical assets in order to form a continuous interactive map [16].

On the topic of DT-4-6G, DT entities representing components of network infrastructure, such as models of wireless antennae or base stations, could be used to investigate the impact of various design parameters on optimal RAN design & control.

Finally, it is also important to consider the interaction between Digital Twins and AI technology, including both agentic AI systems and embodied AI [17]. Digital Twins are already used as a testbed to carry out the evaluation and design of control algorithms for real systems. This makes them well suited also as a testbed for embodied AI algorithms – e.g. as a method of virtual verification before deploying trained models on real systems. Additionally, Digital Twins also have significant uses in generating synthetic data for the purpose of training AI models, as illustrated for example by Nvidia Isaac Lab [18]. For this use-case, simulator back-ends which offer a high degree of photo-realism, accuracy and speed are preferred.

Furthermore, as an extension of the multi-layered architecture proposed for 6G Digital Twins, it is important to consider how such systems can integrate with agentic AI frameworks, using standardized protocols such as MCP [19]. Some potential use-cases could include treating Digital

Twin systems as tools, allowing for DTs to be incorporated in to agentic AI frameworks. Agentic AI may additionally further enable use-cases involving DTF (Digital Twin Federation).

In addition, a key next generation feature could be to support “generative Digital Twins” i.e. Digital Twins which can be constructed ad-hoc, for example by an agentic next generation communication network, as-needed based on the intent specified by a user.

4.4. Summary

As outlined previously, a 6G-enabled Digital Twin should support the key high-level features of interoperability, extensibility, co-simulation, flexibility and adaptability. These features should be enabled by a design which is multi-layered at its core, to allow for the modular, scalable and flexible integration and management of both features and data sources. Furthermore, special consideration should be given along two further important axes: 6G integration (both in terms of DT-4-6G and 6G-4-DT) as well as the integration of AI features (including agentic and embodied AI).

5. Conclusion and Recommendations

This whitepaper has explored the use of Digital Twins, both as a technology currently used in industrial applications as well as with an outlook to the “next generation” of Digital Twin technology. The one6G association believes that next generation Digital Twins may both augment and form a key part of the services offered in next-generation communication networks, such as 6G. Therefore, a detailed consideration of “6G-enabled” Digital Twins is considered a high priority.

Beginning from the need to specify a generic definition of a Digital Twin system, the various low-level components underlying Digital Twins were introduced, including the concepts of Digital Twin systems, simulators, and various communication middleware. A brief categorisation of different types of Digital Twin was introduced – focusing for the purposes of this whitepaper on two main types of Digital Twin, namely application-layer Digital Twin’s and network-layer Digital Twin’s, and some of the key differences and typical incompatibilities between these two systems. The state-of-the-art in Digital Twins across industry, academic research, and cutting-edge industrial use-cases was also highlighted. Next, the results from a survey of one6G members on Digital Twin tooling, requirements and use-cases was presented and analysed qualitatively, so as to determine gaps present in the current, especially for those taking part in 6G research or implementation of 6G-enabled applications or use-cases. Finally, a series of recommendations was developed for a 6G-enabled Digital Twin platform, based off the survey results and analysis from previous sections of the whitepaper.

The recommendations presented in the previous section illustrate the key features that are considered important or desirable for a 6G-enabled Digital Twin. The key high-level recommendations were co-simulation (ability to represent both system and network dynamics), interoperability, extensibility (i.e. ease of adding additional features and network services), flexibility (i.e. ability to model different use-cases and application-layer industries, or to support both indoor and outdoor scenarios) and adaptability. A more thorough analysis of these high-level recommendations is provided in Section 4, alongside concrete examples of specific scenarios which should be supported by a 6G-enabled Digital Twin platform.

To follow up this on this set of recommendations, it is recommended that future collaborations between WG1 and WG4 of the one6G Association can focus on taking the first steps towards implementation of an open 6G-enabled Digital Twin platform, taking the listed recommendations as high-level goals which the platform should meet. This platform could serve to meet the needs of both one6G members as well as the wider ecosystem of researchers, engineers & other professionals working in 6G communications or in application-layer sectors which serve to benefit from 6G integration in next-generation communication networks.

Annex A - one6G survey on Digital Twin Tooling & Requirements

Survey Questions

1. Target industry/research area

Please briefly describe or list a few key words outlining your industry/research area of interest, the key technologies, and the key requirements that underpin your products/research area. For example:

i. Disaster robotics: connected robotics, communication-aware motion planning & control, secure/reliable communications for safety responders
ii. Factory of the future: connected robotics, private 5G/6G, networked control, (accurate) predictive maintenance, predictive scheduling
iii. Service robotics: AI-based human-robot interaction, cloud/network robotics, low latency AI model prompting
iv. Radio and base band optimisation: digital twins used to estimate radio maps, channel models, or other radio-related measurements
v. Other (please feel free to answer in your own format, the above are just examples)

2. Application-level digital twin platforms and tooling

a) Which application-level simulation and/or digital twin tools do you integrate/plan to integrate with your product or research pipeline, if any? For example:
   i. Robotics simulation platforms (Gazebo, Nvidia Isaac, MuJoCo, etc)
   ii. Gaming engines (Unreal Engine, Unity)
   iii. Stand-alone digital twin platforms
   iv. An ad-hoc solution (e.g combining the above with self-made solutions)
   v. Other (please describe)

b) What are the main use-case(s) that you target, or aim to target, with application-level digital twin integration?
   i. Predictive analytics e.g. operations scheduling, maintenance
   ii. Model-based planning and/or control
   iii. Other (please describe)

c) What are the main requirements that lead you to choose your desired platform? For example:
   i. Interoperability with other software or with specific hardware
   ii. Fast simulation speed
   iii. Photorealism
   iv. Integrated monitoring or data analysis functionality
   v. Networking features (radio optimisation, etc)
   vi. Other (please describe)

d) Please list and discuss any challenges faced with current application-level digital twin solutions. For example, inability for the current solutions to meet the requirements outlined in the previous question.

3. Network-level digital twin platforms and tooling

a) Which network-level simulation and/or digital twin tools do you integrate/plan to integrate with your product or research pipeline, if any? For example:

i. System-level network simulators (e.g. NS3)
ii. Link-level network simulators (e.g. Sionna)
iii. Link emulation (e.g. netem)
iv. Ad-hoc solutions
v. Other (please describe)

b) What are the main use-case(s) that you target, or aim to target, with network-level digital twin integration?

i. Prototyping next-generation features
ii. Robustness analysis
iii. Use-case/requirement analysis e.g. data-rates, latency, etc
iv. Other (please describe)

c) What are the main requirements that lead you to choose your desired platform? For example:

i. Scalable network simulation
ii. Specific features e.g. network slicing
iii. Real-time feedback
iv. Ease of use/integration
v. Other (please describe)

d) Please list and discuss any challenges faced with current network-level digital twin solutions. For example, inability for the current solutions to meet the requirements outlined in the previous question.

4. Interest in a shared digital twin platform for one6G

a) Would you consider contributing to a one6G-wide digital twin platform, e.g. in terms of specification or technical implementation?

i. Yes
ii. No
iii. If the requirements listed below are fulfilled:

b) Which tool(s) would you recommend to be integrated for a one6G-wide digital twin platform?

i. Which, if any, single tool would be suitable for this purpose?

ii. Which, if any, combination of tools do you consider suitable to be integrated in to a heterogeneous digital twin platform?

5. Please feedback any additional information relevant to digital twin tooling & requirements which you feel were not captured in the above survey.

Survey Responses

Fixed-Response Questions

Question	i	ii	iii	iv	vi	Other
1	3	5	3	6		2
2a	4	3	5	2		2
2b	4	8				2
2c	6	2	2	6	5	1
3a	2	3	2	1	3	2
3b	4	4	8			0
3c	4	3	5	7		0
4a	6	1				2

'Other' Responses

Question	Responses
1d	Network optimisation
	Data structures of the multi-layered DT
2a	Omlox
	Data from the Industrial Digital Twin Association
2b	Environmental perception
	Operational digital twin
2c	Shared DT database between multiple DT simulators
3a	Robot Simulators
	Depends on needs of outdoor DT software
4a	If outdoor scenarios are involved
	If Omlox is involved

Open-Ended Responses

Question	Responses
2d	Exchange of data between heterogeneous systems
	Low simulation speeds
	No true outdoor digital twins
	Lack of interoperability and open standardized interfaces
	Lack of standardized API for 3D location data integration
3d	Network simulators are event driven while robotic simulators use continuous time
	TCO is too high
	Multi-radio coverage – 5G, WiFi, UWB, RFID, BLE, etc
4b	Omlox, IDTA, AAS, AOUSD
	Gazebo, Mujoco, Siona, Unity
5	An open platform should be provided to exchange data and results
	DTs of outdoor scenarios are still challenging and a bottleneck
	There is a need for standardized 3D scene formats (AOUSD, Khronos, etc)

Abbreviations

DT	Digital Twin
AppDT	Application-level Digital Twin
NetDT	Network-level Digital Twin
UE	User Equipment
ISAC	Integrated Sensing and Communications
DPU	Digital Twin Processing Unit
AI	Artificial Intelligence
IoT	Internet of Things
RAN	Radio Access Network
xDT	Executable Digital Twin
EMG	Electromyography
QoS	Quality of Service
QoE	Quality of Experience
KPI	Key Performance Indicator
6G-DT	6G Digital Twin
DTF	Digital Twin Federation
BIM	Building Information Model
LiDAR	Light Detection and Ranging
SNR	Signal-to-noise Ratio
RSSI	Received Signal Strength Indicator
MIMO	Multiple-Input Multiple-Output
CAD	Computer-aided Design
ROS	Robot Operating System

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