# On the Integration of Digital Twin Networks into City Digital Twins: Benefits and Challenges

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***Abstract*—The concept of Digital Twin (DT) holds great potential for all sectors seeking to monitor, automate, and optimize their processes. This paper focuses specifically on Digital Twin Networks (DTNs) and City Digital Twins (CDTs), offering an analysis of the relevant literature while exploring their interrelationship, which is essential for urban planners and network operators. Although DTN is foreseen as a pillar of future 5G and 6G network architectures, it is often addressed in isolation in the existing literature (i.e., with limited consideration of other domain-specific constraints), even though it constitutes an essential asset in urban environments. In contrast, CDT is often based on the idea of infallible connectivity, which is an optimistic assumption. This study details the benefits and challenges associated with the integration of DTNs into CDTs, paving the way for further research in this field.**

***Index Terms*—Network Digital Twin, City Digital Twin, Integrated Architecture, Benefits and Challenges**

## I. Introduction

The Digital Twin (DT) concept has emerged as a promising tool to enable and support smart manufacturing initiatives, such as Industry 4.0 and Industrial Automation, based on the idea of replicating or twinning physical spaces and creating digital representations of the physical entities in a virtual space. The concept of DT can be traced back to a University of Michigan presentation by Michael Grieves in 2002 (later formalized in [1]), which describes a conceptual idea for product life cycle management that links the physical and virtual spaces throughout the entire life cycle of the product or system: from its design and manufacture, to its operation and disposal [2]. This initial concept already includes the three main elements that can be found in all subsequent DT definitions: (i) physical or real space, (ii) virtual space, and (iii) bi-directional data exchange between these two worlds.

Although defined more than two decades ago, the DT concept gained traction only after the National Aeronautics and Space Administration (NASA) proposed using this paradigm to improve its fleet management and sustainment processes in 2012 [4]. Since then, the DT concept has been revisited, with various definitions proposed over the years [5]. One of the most recent DT definitions for smart manufacturing extends the initial definition proposed by Grieves [1] with two additional dimensions: data, and services [3]. This five-dimensional DT model is shown in Figure 1. Here, the virtual space is a digital twin of the physical space and includes decision making and control of the physical space, as well as simulation models. The

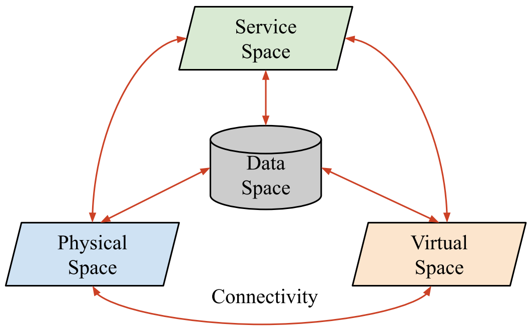


Figure 1. Five-dimensional DT model for smart manufacturing [3]. Each color represents a different dimension.

service space contains the concrete DT usages that can improve the system operation and productivity. The data part is at the center of this concept and serves the other three dimensions. Finally, the physical, virtual, and data spaces are connected using the connectivity building block.

DT is sometimes seen as a tool to perform simulations. However, the use of DT goes much beyond simulations, enabling monitoring, predictive analytics, optimization, and even control of the physical entity from a virtual space. The main difference between simulation and DT is that the former is a static representation of the physical system, while the latter is a dynamic representation based on a seamless connection and potentially continuous data streaming between the physical and virtual spaces [6]. The complexity of simulation has evolved over the years, from performing repetitive trials to validate mathematical proofs, to multidimensional and multidisciplinary simulations of complex systems [7]. DT can be seen as an evolution of traditional simulation paradigms, enabling real-time testing and evaluation of various scenarios before implementing them in reality, and throughout their life cycle.

While the concept of DT is well known in the manufacturing industry, its application to other domains such as agriculture [8], healthcare [9], mobility [10], and telecommunications [11], [12] is still in its early stages [6], [13]. There is specifically a growing interest in incorporating the DT concept as part of the future wireless network architectures. While preliminary efforts have been undertaken in the current generation of mobile networks [14], clear objectives are set for its implementation in sixth generation (6G) networks [15]. Combined with other enabling technologies, such as Artificial Intelligence (AI),



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Machine Learning (ML), and High Performance Computing (HPC), Digital Twin Networks (DTNs) – sometimes referred to as Network Digital Twins (NDTs) – have the potential to disrupt the telecommunications industry by introducing greater automation, but also by accelerating the deployment of new use cases and optimizing network planning, management and control operations.

In addition to domain-specific DTs, significant efforts are being made to define City Digital Twins (CDTs) [16]–[18], which cover larger multi-domain ecosystems such as smart cities. Many of the emerging applications and use cases enabled by CDTs, such as intelligent transportation systems, sustainable and energy efficient communications, smart grids, smart environment, and smart healthcare, overlap or target similar quality of life indicators as the use cases targeted by DTN [19]. Despite these obvious common goals, most existing CDT definitions only consider the network as a commodity, while current DTN definitions assume that other domain-specific data is readily available or do not make use of it.

In this paper, we argue that in order to efficiently support such common use cases and applications, DTN must be integrated into a larger CDT ecosystem. This integration would enable enhanced combined services targeting sustainability and efficiency. Unlike existing studies that focus on defining domain-specific DTs, we consider that in order to realize the full potential of DTN, interoperability with other DTs within a larger federated CDT is crucial.

To summarize, the main contributions of this paper are:

- To analyze the most relevant literature defining the concept of DTN for 5G and 6G networks, and describe several potential applications of DTN in other domains;
- To review the main literature defining the concept and the main initiatives around CDT;
- To propose a high-level integrated DTN-CDT architecture and discuss the main benefits and challenges of such integration.

## II. Digital Twin Networks

A DTN is a dynamic virtual representation of the physical network throughout the entire life cycle of the networked system, potentially generated in real time [15]. The International Telecommunication Union (ITU) has provided an initial high-level approach to standardizing this concept, defining the *functional* and *service* requirements of the DTN and proposing a conceptual reference architecture [12]. The functional requirements defined by the ITU include efficient data collection, efficient and unified data repository, unified data models for network applications, open and standardized southbound and northbound interfaces, and management of the DTN. Service requirements include compatibility, scalability, reliability, security, privacy, flexibility, visualization, and synchronization.

The DTN reference architecture proposed by ITU [12] and illustrated in Figure 2 contains three layers, namely the physical layer, the digital twin layer, and the network applications layer, as well as two bidirectional communication layers, named southbound and northbound interfaces. The physical, digital

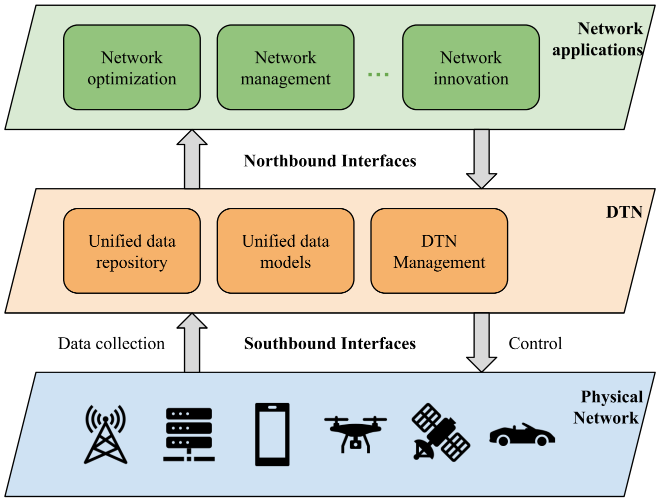


Figure 2. DTN architecture proposed by ITU [12].

twin, and network applications layers in the DTN architecture correspond to the physical, virtual, and service spaces in the DT architecture proposed by Tao and Zhang [3] (shown in Figure 1). The southbound interfaces handle the information stream between the physical and digital twin layers, while the northbound interfaces are responsible for the communication between the network applications and digital twin layers. Apart from this initial architecture, and to the best of our knowledge, the literature lacks a common vision of the specific concepts associated with the DTN layer. The latter introduces various types of models and closed-loop mechanisms that would benefit from further specification and implementation in the future.

### A. DTN for 5G and 6G

Several recent works describe the DTN architectural trends, key enabling technologies, and technical challenges for 5G and 6G networks [11], [15], [20]–[26]. For example, Wu et al. [20] present one of the first comprehensive surveys of DTNs. Among the key enabling technologies, the authors highlight the role of communications, data processing, DT modeling, as well as cloud and edge computing. They also discuss the major technical challenges for each of these technologies. Vaezi et al. [26] discuss DT implementation challenges and deployment architectures from a networking perspective. The authors identify and define several DT features and properties in order to provide a formal methodology to evaluate the quality of DTs in different scenarios.

Nguyen et al. [11] propose a cloud DTN concept for 5G networks. They emphasize the role of AI in the 5G DTN architecture and its benefits in terms of accelerating the validation time of new 5G services and use cases, reducing deployment and management costs, and supporting network automation and optimization. The authors also describe how DTN can be used as a highly interactive emulator, enabling realistic testing of novel 5G deployment scenarios in a controlled environment.

Almasan et al. [21] analyze the benefits of using ML to build core components of the DTN and to optimize the network performance. Hui et al. [24] review different approaches to data-driven performance modeling from three different perspectives: data, models, and applications. Wang et al. [14] design a DTN based on graph neural networks to find the relationship between resource utilization, network slicing, and physical infrastructure. The proposed solution is able to monitor the end-to-end performance of network slices by accurately predicting slice latencies.

The relationship between DTN and 6G is explored by Ahmadi et al. [22], who argue that 6G will be an enabler for the massive adoption of DTs. This will happen as a result of two main drivers: (i) on the one hand, 6G will facilitate the adoption of other domain-specific DTs by supporting their stringent communication requirements, and (ii) on the other hand, DTN combined with AI will facilitate the design, deployment, and operation of the 6G network itself. Future architectures will incorporate AI-based network functions as a core mechanism for automating and optimizing network operations. The DT concept can be used to train and fine-tune these functions before applying them to the physical network, either in real time or predictively. Lin et al. [15] analyze the deployment issues of DTN in 6G networks, focusing on three basic building blocks: data, models, and interfaces. They present a real-world example of building DTNs using Omniverse[1].

Khan et al. [23] present the key design requirements to realize DTN-enabled 6G systems: decoupling, scalable intelligent analytics, blockchain-based data management, scalability, and reliability. They describe three different DTN deployment options, namely edge-based DTN, cloud-based DTN, and collaborative edge-cloud-based DTN. Combining Multi-Access Edge Computing (MEC) and DT is also discussed by Tang et al. [25], who present a new paradigm named Digital Twin Edge Network (DITEN). In this survey, the authors describe the design, enabling technologies, and deployment aspects of DITEN, concluding with existing challenges and open issues.

### B. DTN for Use Cases in Other Domains

Several recent surveys focus on the benefits of DTN for specific use cases and applications [20], [25], [27]. In particular, these surveys provide brief descriptions of the role and potential benefits of using DTN in application scenarios such as manufacturing, Internet of Things (IoT), space-air-ground integrated networks, healthcare, intelligent transportation systems, and urban intelligence. However, they do not consider any specific DTN components for these applications.

Other studies instead propose DT concepts for other domain-specific use cases in which connectivity aspects play a crucial role. For example, an early investigation of communication requirements for remote surgery was undertaken by Laaki et al. [28]. Their approach involves the development of a DT prototype, which includes a robotic arm and a virtual reality system that are interconnected via a 4G mobile network. Although no actual DTN has been proposed, this paper provides some insight into the major communication challenges that a DTN will face in order to support such a use case.

The role of DTN in the transportation domain is indirectly studied by Wang et al. [10], who propose a Mobility Digital Twin (MDT) framework for mobility services. The proposed framework includes connected vehicles, IoT technologies, and a cloud-edge architecture as part of its communication plane. However, the authors identify the management of heterogeneous wireless communication environments as one of the key challenges to be solved, which could be addressed by integrating the proposed MDT framework with the DTN.

Liao et al. [29] design a cooperative ramp merging application based on vehicle-to-cloud communication over the 4G network. Based on the DTs of vehicles and drivers, their proposed solution is able to send real-time ramp merging advisory information to the drivers. A similar use case is tackled by Fan et al. [30], who leverage DT and MEC technologies to improve the lane-changing operation of connected and automated vehicles. Zhang et al. [31] focus on the use case of social-aware vehicular networks and, in particular, on the problem of content caching at the network edge. To solve this problem, the authors propose to use the DT technology to take advantage of the social characteristics of smart vehicles to improve the performance of the caching strategy.

Note that all these works assume the network as a commodity that is being used to update the DT models of physical objects (e.g., vehicles, drivers, edge servers) in the virtual world and send back feedback and recommendations. However, to the best of our knowledge, none of these works integrate the DTN architecture into their solutions.

## III. City Digital Twins

In the evolving landscape of sustainable smart cities, and with the increasing use of IoT technologies to collect data from citywide infrastructure, CDTs have emerged as a central tool for urban planning, infrastructure management, mobility management, and energy efficiency optimization, among others [16], [17]. In terms of their use, CDTs can be divided into operational, which usually implies a short-term horizon (e.g., monitoring assets, responding to alerts), and planning, which explores long-term trends and supports decision making by city stakeholders. Depending on the concrete uses and services of CDTs, and the topics covered, their implementation complexity can increase significantly [32]. In this sense, Local Digital Twins (LDTs)[2] appear as smaller scale CDTs, modeling physical assets and processes of small cities, districts and communities, with a reduced complexity compared to CDTs, both in terms of assets to twin and topics to cover.

There are several works in the scientific literature that define specific use cases for CDTs. For example, Fan et al. [33] define a set of components for a CDT to cover disaster response and emergency management. In [34], a DT is proposed for assessing the energy performance of buildings on a citywide scale. A

[1]https://www.nvidia.com/en-us/omniverse/solutions/digital-twins/

[2]https://digital-strategy.ec.europa.eu/en/library/local-digital-twins-forging-cities-tomorrow

recent study by Xia et al. [35] proposes a state-of-the-art research on existing data-driven models available for CDT and LDT using Geographic Information System (GIS) and Building Information Modeling (BIM) systems, covering many topics of interest for urban scenarios. White et al. [36] propose a CDT design composed of six layers: terrain, buildings, infrastructure, mobility, smart city, and digital twin. The proposed CDT facilitates urban planning of skylines and green space and allows citizens to provide feedback on these plannings and policy decisions.

Recent years have also seen a growing number of CDT development initiatives. The Digital Urban European Twins (DUET) for smarter decision making project [37] appears to be a key milestone in the development of CDT initiatives, providing an open technical approach, including a common DT architecture and data ontology for cities. The LEAD project[3] addresses the issues related to urban logistics using DTs in six European cities. The goal of this project is to develop a framework that will allow stakeholders to predict future developments in order to create informed policies. In parallel, data space initiatives related to smart cities and communities are also being created, such as DS4SSCC[4], which aims to create an inclusive data space for cities. These data spaces aim to ensure a common definition of the key data entities for CDT, while creating a marketplace where data providers and demanders can securely exchange data to feed the CDT.

Concrete use cases of CDT can be found in the literature, including individual CDT models, such as the case of Singapore [38] with a focus on green space development. Other use cases, such as those of Zurich [39] and Amsterdam [40], propose multi-model approaches, where the proposed framework covers interrelated issues such as urban planning, climate, transport and mobility. However, to the best of our knowledge, the different CDT proposals and development initiatives do not integrate the physical assets of the communication networks to be twinned, i.e., we have not identified any integration efforts of CDT with DTN. In this sense, the different CDTs focus on the specific problems to be solved, using communication networks only as a tool to connect the DT components (physical twin, data, and models) [41], but without being able to assess the impact of network issues on the concrete services of the CDT.

## IV. Integration of DTN with CDT

There are several possible approaches to integrating DTN with CDT, depending on the specific requirements and desired applications and services. Our high-level proposal, illustrated in Figure 3, is to design a CDT by stacking several layers, all interconnected by a database and offering a common set of services, as suggested in the literature [36]. This multi-layered and dynamic representation of a CDT starts with the modeling of the urban terrain (e.g., land elevation and typology). Next come the buildings, followed by the infrastructure, which includes road traffic elements. This is followed by a layer of

[3]https://www.leadproject.eu/
[4]https://www.ds4sscc.eu/

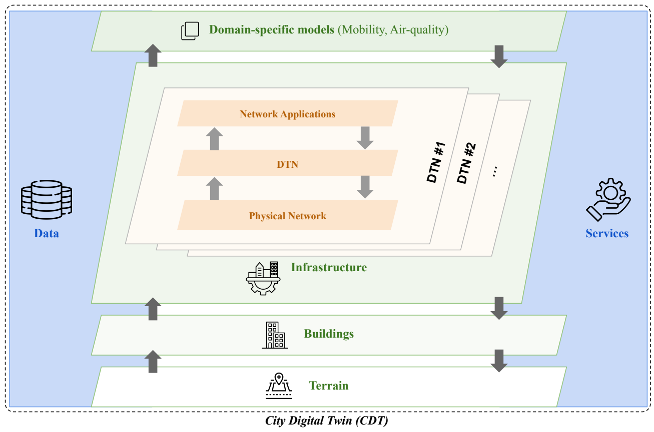


Figure 3. High-level representation of an integrated DTN-CDT architecture.

domain-specific models focused on individual applications (e.g., power grids, public transportation information). The integration of a DTN, or more precisely a set of DTNs to dynamically cover different parts of the communication network and its subnetworks, would enrich the CDT infrastructure layer.

### A. Advantages

There are certainly advantages to combining DTNs into CDTs as a key urban infrastructure. Even if communication networks are typically managed by specific stakeholders (i.e., network operators), there is an interdependence between the deployment strategies and the quality of connectivity with the different components of smart cities and the services that a CDT can offer. As an analogy, we can consider the case of energy grids and their use in CDTs. For example, the trend towards more sustainable cities has highlighted the importance for CDT to integrate the multi-energy grids (e.g., electricity, gas, heat, hydrogen) as a physical asset to be twinned and modeled in order to explore new ways to become cleaner and more energy efficient as a city or community. In this sense, Positive Energy Districts (PEDs) [42] have emerged as a key use of CDT to help city stakeholders to find energy transition strategies to move towards a net-zero energy balance. In this context, cities and communities can take a more proactive role in the energy transition and make recommendations to energy grid operators and regulators by having a more holistic and integrated view of the city's needs and constraints.

Similarly, the integration of DTN into CDT can provide city administrators and planners with a powerful tool to better understand, manage, and optimize the communications infrastructure of the cities and districts. As urban areas become more digitized and interconnected, such tools will play a central role in ensuring their smooth operation and growth. In addition, integrated DTN-CDT architectures will enable new combined use cases and services that otherwise would not be possible, as illustrated in Figure 4.

There are several advantages to such an integration. First, because CDT stands as a decision support tool, integrating DTN can certainly improve the decision-making process. City

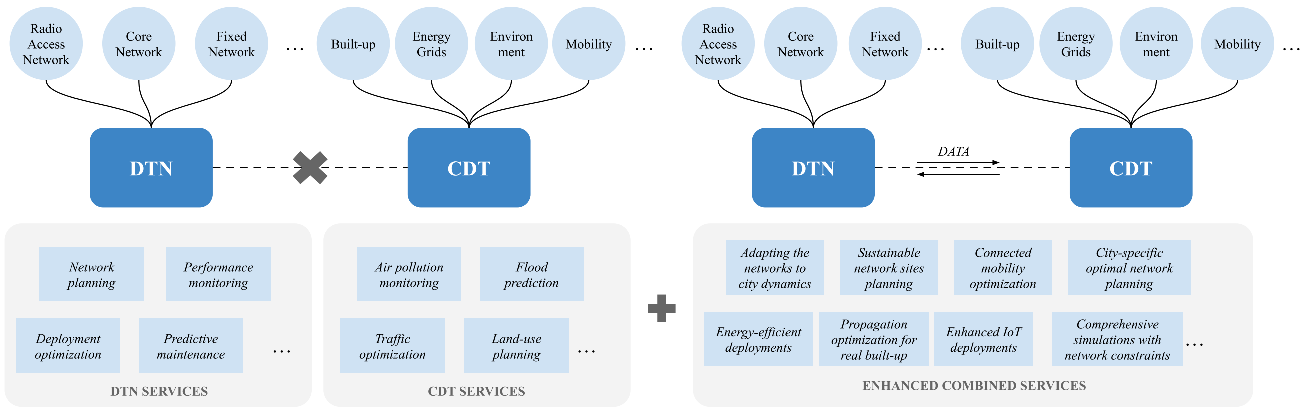


Figure 4. Benefits of integrating DTN into CDT: new enhanced combined services can be created.

planners and administrators can use the DTN to simulate different scenarios, allowing them to make informed decisions about network upgrades, expansions, or potential threats, especially in terms of land use of network sites [43] and radiation exposure [44]. Second, real-time monitoring of the network status can help identify bottlenecks, inefficiencies, or points of failure. This information can then be used to optimize the network performance, especially where city-critical infrastructure is concerned. For city-critical services (e.g., emergency, rescue, traffic incidents) that are increasingly dependent on connectivity, an integrated DTN in the CDT can help ensure that all of these services function cohesively.

In addition to mobile networks, the fixed network infrastructure, such as fiber optics, is also the focus of investment by local authorities in several countries. This is done to ensure a high level of fairness of access to high-speed networks for citizens throughout the territory. Deploying a DTN of the fiber network infrastructure [45] and integrating it into a CDT can certainly help to better identify network capacity needs, while reducing fiber deployment delays and cost overruns. In this sense, city administrators can determine where the network may be underutilized or overburdened and reallocate public resources accordingly.

New urban infrastructures are increasingly interconnected [46]. As cities develop new infrastructure, and integrate it into the CDT, coupling with the DTN can help ensure that these new additions are seamlessly integrated into the existing network, providing maximum efficiency and utility. Different departments or entities within a city, such as transportation, public safety, or utilities, can collaborate more efficiently by accessing and understanding the current state and future projections of the network within the CDT.

It is worth noting that the topology of a communication network, and therefore the physical location of its nodes (e.g., access points, user equipment), has a direct impact on its performance. The combination of DTN and CDT allows network operators to consider the specific topology of cities and their buildings, thus optimizing the use of their networks. In addition, this integration could benefit mobility, travel time, air pollution, and other services by facilitating the connectivity of the transportation infrastructure and sensors deployed throughout the city.

### B. Challenges

The above benefits of integrating DTN with CDT come with a number of challenges, which are discussed below.

*1) Complexity:* A DT of the communication network infrastructure on a citywide scale would require modeling a relevant number of physical entities inherent to network operations, which can be highly complex. Therefore, when integrating them into the CDT, an appropriate level of abstraction must be determined in order to reduce the modeling effort to the minimum required for the use case that the city stakeholders want to derive from the DTN. For example, if the focus is on land use and network capacity, the integration should be limited to modeling key physical entities such as network sites (e.g., base stations, distribution nodes) and focus only on attributes related to the relevant topics, without going into detailed parameters of lower layers that would not add value to the integration.

*2) Privacy:* Privacy concerns should also be considered. Depending on the specific entities to be modeled from the network, once integrated into a CDT, it may be the case that relevant data from the network (e.g., occupancy of a base station, level of usage at a given time) reveals certain behavior of an entity of the CDT in which links to individual activities can be made. To prevent this, it is preferable to assess the potential privacy implications when defining the integrated DT data model in order to avoid potential conflicts with regulations.

*3) Security:* Integrating multiple DTs will inevitably increase the number of entry points and overall security risks. One possible approach would be to implement all of this in the form of independent, modular microservices (i.e., independent API calls). This would isolate potential security issues, while avoiding exposing the entire DTN to third parties.

*4) Interoperability:* One key issue is the diversity of data formats and standards across different systems and industries. This variety makes it difficult to seamlessly integrate data from multiple sources into a cohesive DT model. Moreover, the models used in DTN and CDT often originate from different domains, each with unique modeling techniques and assumptions, leading to compatibility issues. These challenges are compounded by the need for real-time data synchronization between the physical system and its digital counterpart, requiring robust and flexible data exchange mechanisms. Addressing these interoperability challenges is critical to the effective implementation and scalability of digital twin technology across various sectors, including DTN and CDT.

*5) Standardization:* As a relatively new concept and being applied in highly heterogeneous domains, there may be different understandings of the DT concept, modeling, architecture, and implementation aspects. Nevertheless, domain-specific DTs are expected to interoperate within larger CDT frameworks to achieve common goals. In this context, standardization becomes crucial for the future development and efficient operation of CDTs. While some domain-specific standardization efforts have recently started [47], such as the ISO 23247 series of standards [48], which defines the DT framework for manufacturing, or the ITU-T Y.3090 standard [12], which defines the high-level architecture and requirements of a DTN, the standardization work is still in its early stages and considerable effort is still required.

*6) Added value for operators:* From another perspective, communications networks managed by network operators responsible for their monetization may be reluctant to contribute with key data from their operations to a CDT integration initiative. This is because they will certainly not see the value for them as operators to invest in such an integration effort and, more importantly, to actively and continuously contribute with data to feed the digital twin. In this sense, public stakeholders should involve network operators in these initiatives by developing new services on the CDT that may be of interest to them, in order to obtain mutual and quantifiable benefits from such integration.

### C. Use Case: Connected and Autonomous Electric Vehicles

This section describes an example that could take full advantage of the integrated DTN-CDT concept. Consider the use case of a connected, fully autonomous (i.e., SAE Level 5) electric vehicle that needs to anticipate and plan its journey from one point to another before it actually makes it. In this context, accurately predicting a route and minimizing uncertainties (e.g., accidents, traffic jams) requires taking into account a number of factors:

- The energy the vehicle will use;
- The presence and availability of charging stations;
- The presence of connectivity infrastructure and communication resources (i.e., network slices) that provide adequate Quality of Service (QoS) and Quality of Experience (QoE), taking into account other potential users and the overall capacity of the network;
- The uncertain nature of the road network, starting with its topology, users, traffic lights, etc.;
- Many other factors that can make route planning as accurate as possible.

Combining these factors and proposing a route to this vehicle could be addressed by simple simulations, but these would probably not be sufficient given the dynamic and complex nature of the scenario being considered. Real-time data representing the area to be covered (CDT), the associated network (DTN), and the real-time interaction with the physical elements (e.g., vehicle, network) must be considered.

In particular, the DT of the vehicle itself, which could be provided by the car manufacturer, is required to obtain data related to the status of the vehicle (e.g., battery level, consumption). The mobility DT of the city would certainly be useful to have an overview of traffic lights, potential accidents, and traffic parameters that could affect the vehicle's journey. The energy DT could be relevant, for example, to analyze the load on the electrical grid and suggest an available charging station accordingly.

All of these DTs could be represented in a multi-layer CDT, which could interface with a DTN to connect the various elements and ensure that they are all connected and accessible at all times, guaranteeing adequate QoS and QoE for the entire journey. In addition, the integrated DTN-CDT architecture allows multiple objectives to be optimized when planning the trip, i.e., optimizing battery consumption, minimizing travel time, and preallocating network resources (i.e., network slices).

## V. Conclusion

In this paper, we discussed the benefits of merging the Digital Twin Network (DTN) and City Digital Twin (CDT) concepts to provide more comprehensive and accurate twinning of citywide systems, enabling more realistic use cases in urban environments. In particular, we reviewed the ongoing efforts to define DTN and CDT architectures and potential applications for each of these concepts. We presented a potential integrated DTN-CDT architecture, highlighting the benefits for key stakeholders, and discussed some of the key challenges and bottlenecks that such integration would entail.

In the future, we plan to further explore the potential benefits of such a conceptual architecture by performing a quantitative analysis of key performance indicators of the enhanced combined services enabled by the proposed architecture. To this end, we intend to build a proof-of-concept prototype to evaluate the performance of such an integrated architecture in a controlled environment.

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