# Digital Twins of Computer Networks

Jacqueline Kroyer, Kilian Holzinger*
*Chair of Network Architectures and Services, Department of Informatics
Technical University of Munich, Germany
Email: kroyerjackie@gmail.com, holzinger@net.in.tum.de

*Abstract*—**Digital Twin Technology such as Digital Twins (DTs) and Digital Twin Networks (DTNs) are part of an emerging trend in the operation of computer networks. However, in order to apply the appropriate digital twin technology, their functionality, core goals and technical requirements have to match the field of application. By examining digital twin technology and providing a structured overview of the relevant parameters around terminology, goals and requirements of DTs and DTNs, this seminar paper contributes to existing research in the field of DTs. A widely pursued goal is to leverage all available machine data by applying digital twin technology.**

*Index Terms*—**Digital Twin, Digital Twin Technology, Digital Twin Network, Computer Network, P2V Communication**

## 1. Introduction

The idea of leveraging state of the art computer network technology in the field of machine to human communication is highly relevant as it bears the potential to revolutionize many industries as well as our every day lives. Digitization of the industry is continuously progressing and its demands are increasing. The process is referred to as Industry 4.0 and requires a tremendous amount of machine data. The development of digital twin technology can e.g. be harnessed for more efficient and sustainable cities. Applying digital twin technology goes beyond smart cities: manufacturing, aviation, healthcare or transportation systems are just a few examples.

This seminar paper researches and examines digital twins of computer networks. It focuses on the question which technical requirements have to be met for respective technological core goals and their implementation in the form of fields of applications.

With the increased amount of personal data and especially the increased amount of available machine data, the statistical relevance increases as well as the reliability of the models used for the virtual twin and all elements related to the digital representation of the physical object.

Within this seminar paper, after outlining the theoretical background of digital twin technology by defining the most relevant terms the functionality of digital twins and digital twin networks will be examined. Building on technical requirements of DTs and DTNs, core goals will be derived and illustrated in which fields of application DTs and DTNs are most relevant. In the following theoretical foundations such as relevant definitions around digital twins, their functionality as well as technical requirements and core goals will be illustrated.

## 2. Theoretical Background of Digital Twins of Computer Networks

In order to provide the reader with the relevant, theoretical underlying concepts, the following section defines DTs and DTNs, their functionality as well as the different types of DTs.

### 2.1. Digital Twins and Digital Twin Networks

" [. . . ] DT is an intelligent and constantly evolving system, which monitors, controls, and optimizes the physical object through its life-cycle." [1]. This system consists of one or more physical and virtual interconnected objects. Figure 1 shows the typical concept of a DT. The arrows connecting the physical with the virtual twin represents the transmission of information and decision-making assistance. It also indicates the direction of the data flow.

Three aspects related to DTs are especially relevant. Firstly, the type of connection between the physical object and the physical object is a one-to-one connection. Secondly, the concept is comprehensive as it contains and relies mostly on these two objects. Thirdly, the static form of a DT is a perfect virtual representation of the physical object and therefore can be a mere simulation of the status-quo.

The formal definition of DT by Michael Grieves emphasizes the three elements of a physical object in the physical space, a virtual object in the virtual space and the data link between the two objects and spaces [2]. From an industry perspective, this definition is tightly knit to concepts in product engineering [2]. Examples for physical objects are machines, humans or human-related things like in a smart city. Types of physical objects are complex physical systems, machines, robots or industrial processes [1]. The concept of a virtual twin in general can also be described as a virtual representation of the physical object. It is a virtual 3D model [3]. Consequently, it is arranged and conceptualized as similarly as possible to the corresponding physical object. A physical object and its virtual twin can be developed together and are connected via a bi-directional data flow which also marks a shift from a static to a dynamic scenario.


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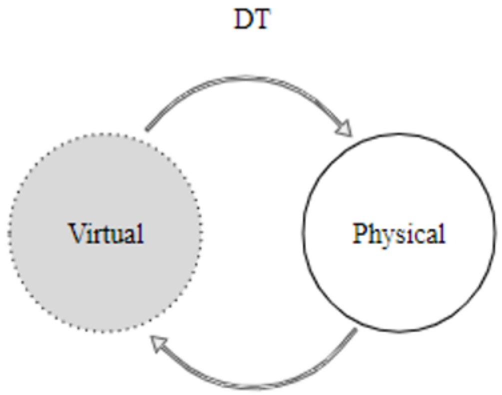


Figure 1: Concept of a DT; information transmission and decision-making assistance; own illustration based on [1];

DTs can be categorized in three types, depending on perspective, focus and type of connection.

- 1st DT type: The first type covers the exact virtual representation of a physical object. It has no automatic connection to the physical twin and is characterized by no data exchange between physical object and virtual object.
- 2nd DT type: The second type possesses a unidirectional connection to the virtual twin and is therefore able to illustrate an evolution of the physical object.
- 3rd DT type: The third and last type is the most enhanced category of DTs and includes services and the respective connection among the objects. Thus, it enables mirroring the current state of the physical object because it continually adapts and predicts future states.

As a second crucial term within the field of DT technology, DTNs will be explained. Within the course of this paper, DTNs can be defined as multiple one-to-one DTs, building a many-to-many mapping network [1].

This means the physical object is connected to other physical twins as well as to the virtual twin and its virtual twins which enables real-time information interaction. By applying key technologies such as communications, accurate DT modeling, physical data processing, cloud and edge computing, a DTN can capture dynamic interactions and evolutions of multiple physical as well as virtual objects [1].

Figure 2 illustrates the typical concept of a DTN. The ways of communication are a physical-object-to-physical-object connection (P2P), a virtual-twin-to-virtual-twin connection (V2V) as well as the typical physical-object-to-virtual-object connection (P2V). For P2V connections shared intelligence and cooperation is applied. For a P2V connection, information is transmitted. It also serves decision-making assistance. Three aspects about DTNs are important to emphasize. Firstly, the type of connection between the physical objects and the virtual twins is a many-to-many connection. Secondly, the physical objects and virtual twins aren't isolated. Consequently, it is a cooperation approach. Thirdly, when creating and conceptualizing a DTN, the physical objects and the virtual twins are put in relation and co-developed. Therefore, the physical objects and the virtual twins evolve together. This concept is called co-evolution.

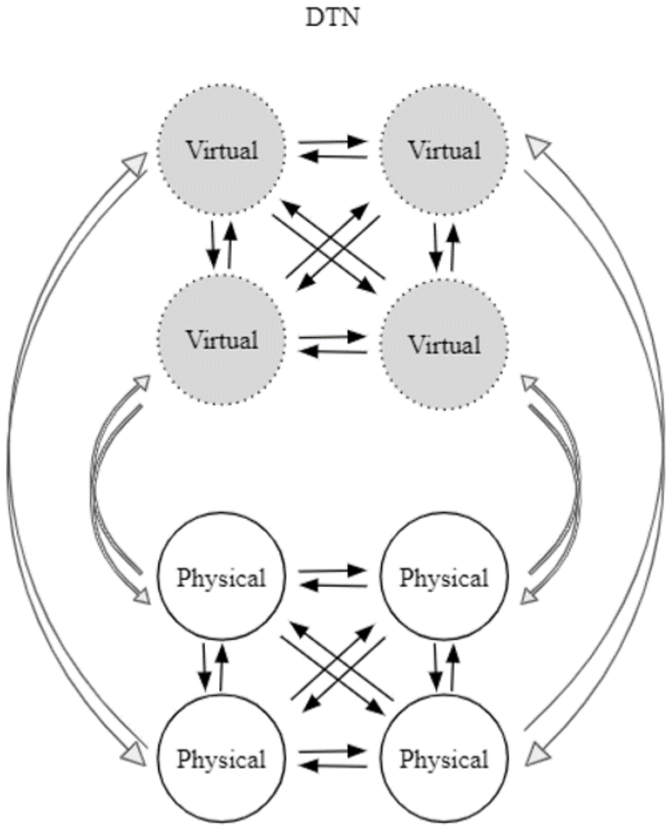


Figure 2: Concept of a Digital Twin Network: information transmission and decision-making assistance (P2V); shared Intelligence and Cooperation (P2P, V2V); own illustration based on [1];

When comparing DTs and DTNs one quickly notices a shift from a static to a dynamic scenario [4]. This means, time independent, three dimensional objects turn into actionable CAD objects. Thereby changes can be simulated and behavior can be predicted more accurately and precisely over time.

So called cyber-physical systems (CPS) are often mentioned in the context of DT technologies. It is important to terminologically differentiate a DT and a DTN from a CPS. A CPS is defined to be a "physical and engineered system whose operations are monitored, coordinated, controlled and integrated by a computing and communication core" [5]. A DT, DTN or CPS differ in application scenarios. DTs and DTNs are often used in an industrial context whereas a CPS is more often applied in embedded systems due to physical properties like sensors or actuators. Furthermore, it is important to highlight that


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DTs and DTNs are model-based systems that are either applicable for a single object (DT) or a group of objects (DTN).

### 2.2. Functionality

When looking at the functionality of DTs and DTNs one has to understand the underlying key technologies. As briefly mentioned previously, these are namely communications, physical data processing, DT modelling, cloud computing as well as edge computing [1]. In the following they will be explianed in more depth.

Communications are focused on the type, direction and content of exchange of information. This can be P2P, P2V or V2V communications:

- Physical object to virtual twin: P2V communications describe the exchange of data of a physical object with a virtual twin through the means of wireless communication technologies. This exchange and transmission of data can be conducted in real-time. In addition to that the virtual twin is able to receive and apply feedback provided by the physical object. Suitable networks are LoRa or 5G/6G cellular communication networks. Accurate mapping and real-time feedback are desired goals.
- Physical object to physical object: P2P communications refer to exchange of information between two physical objects. By connecting with IoT gateways or Wi-fi access points, RFIDs, actuators or controllers of the respective physical devices the connection between two physical objects can be established. The network connection itself is supported by several communication protocols such as Wireless Personal Area Network or Low Power Wide Area Networks.
- Virtual twin to virtual twin: V2V communications reflect ongoing communications between two physical objects. As virtual twins can be seen as virtual replicas they mirror the exchange of data between physical objects. Hence, V2V transmission of data occurs between DT model entities. The virtual level of communication relies on computing capabilities in order to mirror the data transmission behavior in the respective DT model.

Besides communications, it is important that the raw data that derives from multiple sources is appropriately handled as it is typically still full of noise. This is specifically relevant in order to make effective use of the data as the amount of raw data is likely to increase with the increasing number of sensors and data sources.

Furthermore, it is important to clarify the applied DT model and framework early in the process. Although there are several options, the state-of-the-art framework would be Tao et al. 's who suggest a DT five-dimensional model taking the physical part, virtual part, data connection and service modeling into consideration [6].

Cloud Computing is a key technology in the context of DTs as it enables large-scale computing. Thereby, it is a crucial element to allow sharing processes on demand and also facilitating the option to use the services anytime and anywhere.

As a last key technology, edge computing uses new computing models for several operations such as analysing or storing data. It is a solution for privacy protection, reduced latency and also reduces power and costs as well as makes the system more reliable.

It takes all the mentioned technologies to efficiently handle processing data and ensure well-functioning DT or DTN communication.

## 3. Digital Twins of Computer Networks

In the context of DTs and DTNs the respective core goals as well as the technical requirements to meet these goals are important building blocks to properly apply DT technology. Examples for fields of applications will be derived from technical requirements and core goals.

### 3.1. Core Goals and Technical Requirements

All of the addressed key technologies of DTs and DTNs, including the three types of communications (P2P, P2V, V2V), physical data processing, digital twin modeling, cloud computing as well as edge computing possess certain technical requirements that have to be met. This specifically applies to the types of communications of DTNs.

In the context of this seminar paper the most important technical requirements are addressed. Namely they are:

- Low latency for real-time feedback: In most situations and scenarios real-time feedback and interactions are necessary. The P2V connection determines the required latency needed for the specific scenario. The higher the time sensitivity for the physical object as well the data connection is the lower the latency has to be. Medical use cases require ultra-low latency.
- High transmission reliability for accurate modeling: Accurate data needs to be exchanged in a reliable and immediate way in order to implement and make use of dynamic high-fidelity modeling approaches. Depending on the use case either medium transmission reliability is sufficient. In certain use cases like medical scenarios, it has to be especially high.
- Secure data transmission for higher data privacy and security: At the level of data exchange, mostly between the physical object and the virtual twin, the security of data and its privacy are of high priority. Typical protocols and encryption methods

of the field of IT security need to be applied in order to guarantee safe and private data exchange.

- Higher network bandwidth and capacity increase than rise of demand of interconnected elements in the network for reliability and availability: As sensors deliver a much greater amount of data the total amount available increases which is helpful in terms of prediction accuracy of the relevant models. Due to the sheer amount of data, it remains challenging to process the data. Therefore the bandwidth as well as the capacity of the network has to increase faster than the demand of the risen number of interconnected objects.

In total, all of these requirements, namely, low latency, high transmission reliability, secure and private data exchange as well as a fast enough increase of network demand and bandwidth are crucial but also strongly dependent on the use case and therefore the industry in which the DT or DTN is applied.

The corresponding core goals are the provision of real-time feedback, accurate modeling, privacy and security as well as reliability or respectively availability.

### 3.2. Comparison of DT and DTNs

When comparing DTs and DTNs, several parameters are relevant and decisive to consider: The modelling approach, interaction, collaboration with other models, efficiency, accuracy, components and mapping relationship. Table 1 shows how DTs and DTNs differ or resemble.

Both categories still aim at accurate modeling, real-time feedback as well as the higher level goals of security, privacy and availability.

| | **Comparing DTs and DTNs** | |
|---|---|---|
| | ***DT*** | ***DTN*** |
| Modeling Approach | Single, independent object | Group of objects with complex internal interactions |
| Interaction w. other models | Not applicable; no interaction with other models | Cooperation approach; processing results shared among collaborative DTs |
| Accuracy | Mirroring approach; Virtual twin as accurate digital replica | Higher; Physical and virtual twin evolve together |
| Components | Physical object and virtual twin; P2V data exchange | Physical objects and virtual twins; P2V, P2P and V2V data exchange |
| Mapping Relationship | One-to-one method | Many-to-many method |

*Table 1: Comparison between the concept of DTs and the concept of DTNs; own illustration slightly based on [1]*

The direct comparison of DTs and DTNs emphasizes how the two concepts tend to differ. Depending on the field of application, the specific industry or even just the use case, one of the two concepts might fit better than the other. Furthermore, certain aspects like the exact definition of the technical requirements will have to be adjusted.

### 3.3. Fields of Application

The use cases for DT technology are broad and have strong advocates in the industry. Microsoft's HoloLens for example can be applied to view the three dimensional, virtual model of a physical smart factory. Moreover it can then be used to control some of the production's functions remotely. Batty also names industries, cities and communities as some of the most relevant application fields [2].

The most relevant industries and use cases are manufacturing, aviation, healthcare, 6G networks, intelligent transportation systems as well as urban intelligence [1]. In each of the examples DT technologies bear vast potential to add more efficiency to the related business processes, increase the control over what processes are actually conducted in real-time and enhance monitoring capabilities. This means that certain insights, like the current energy consumption, can be displayed or intelligent control mechanisms of production processes in manufacturing can be leveraged.

In summary, the virtual twins can be generally seen as human-centric user interfaces for data exchange and specifically for the transmission of digital information from the physical object [3].

## 4. Conclusion

DT technology is a field of high relevance for manifold technologies evolving based on DTs or DTNs. It is crucial to understand the differences in the technologies in order to properly apply, implement and efficiently use it.

Core goals like reliability, latency, capacity, connectivity and efficiency require different values depending on the type of communication: P2V, P2P or P2V. It is also decisive to depend on the design of the DT technology on the type of use case it is applied to. The most relevant fields of application are around business and production contexts like manufacturing or key use cases in medicine and health care.

As DTs and DTNs bear tremendous potential for our economy and foster technological progress and innovation, further research has to be conducted to meet the technology's potential.


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