Digital Twin Network and Network Digital Twin

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Abstract:

Digital twin (DT) as a connection between virtual instances and physical instances, acting a more important role in present industry fields. To improve the performance of DT instances, and also to simulate large systems, Digital Twin Network (DTN) is proposed to merge and synchronize multiple DT instances together for a better management and feedback. Networking is the key for DTN to be built and new standards and techniques are added to support the complex networking system. On the other hand, not only networking is providing efficiency to DT systems, but DT systems are also helping the industry experimenting with the new architecture of the current network framework. By using virtual DT instances of the network, which is called Network Digital Twin (NDT), companies could easily implement and test new ideas using real data flow. This paper talks about current DTN and NDT development and their application in the current networking area, involving Data Center Networks, Data Flood Prevention, Networking Standards for DT, and IOT.

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Keywords

DT, NDT, DTN, IOT, Network, Data Center

1. Introduction

Digital Twin is a concept that has been gaining more and more attention from both academic and industrial fields. The concept was first been mentioned by Michael Grieves in 2002, and later been defined as "an agent-based architecture where each product item has a corresponding virtual counterpart or agent associated with it" [Shafto12] [Wu21]. The formal definition of DT was given in Grieves and Vickers white paper in 2017 [Grieves17], stating that the three major entities in DT would be a physical space object, a virtual space object and the data link in between. The development of DT helps people test, adjust and verify new designs in the virtual field and hence reducing the cost and potential risks of deploying new systems in physical scenario. And this largely benefits the networking companies and researchers. However, there still exists problems such as the lack of standards which slow down the advancing in this realm.

In this paper, we would focus on Digital Twin Network (DTN), Network Digital Twin (NDT), and the correlated application of DT in the networking field, and try to give a clear explanation on their advantages and disadvantages.

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2. Digital Twin Network (DTN)

This section will focus on DT's definition, networking requirements, standards, and some techniques applied to help building a better DTN.

2.1 Definition of DTN

From the introduction we had defined DT as a physical-virtual system which monitors the physical status and reflects in the virtual world. But DT mainly focuses on one major object, thus, to implement DTs for complex systems, DTN is introduced. DTN is defined as a many-many network system formed by multiple one-one DT instances. By using network data communication, it realizes the real-time data sharing and communication between multiple physical objects to multiple virtual objects, providing a possibility for individual DTs to work together and form a greater system [Wu21][Zhou23].

To conclude, DTN is extended from multiple DTs. The network enables the composition of multiple components of a complex system and thus provides a more precise status monitoring, and faster real-time analysis. However, the scale of the network means a high requirement on networking and data communication.

2.2 DTN requirements in network communication

Current DTN usually holds a large scale of DT instances. This results in a huge and complex network between DTs. Therefore, the process of data collection, storage and transmission requires high efficiency [Zhou23]. Another key aspect for DTN is the latency. According to Vaezi et al.[Vaezi22], the delay of synchronization between physical system(PS) and DT is the major reason causing great latency.

To improve the aspects mentioned above from a networking perspective, we focus mainly on the communication and calculation. In DTN data communication, it's divided into P2P, P2V, and V2V communications where P stands for physical and V stands for virtual [Wu21]. Figure 1 shows a graph of the 3 different kinds of communication.

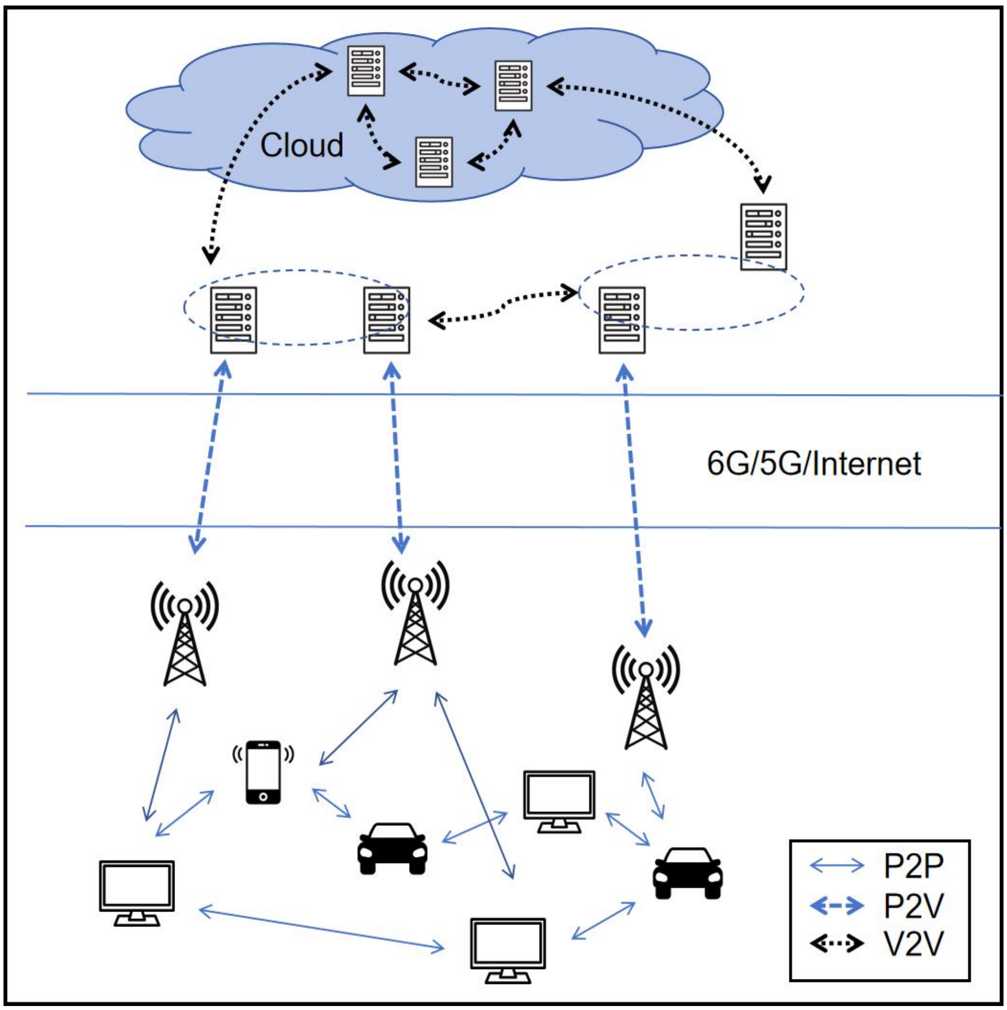

Figure 1: P2P,P2V and V2V Communications [Wu21]

P2P is the communications between physical objects. Current P2P connectivity and communications are using Bluetooth (IEEE 802.16), Wi-Fi (IEEE 802.11ax) and LoRa protocol [Mashaly21]. P2P needs new protocols and hardware improvements to give a better performance.

P2V refers to the connection between PS and DT instances. This communication requires low latency to keep virtual and physical objects synchronized. Two main ways to improve this part are deploying high speed network and compressing data [Mashaly21]. 5G and incoming 6G techniques might be a key to improve P2V performance greatly [Nguyen21].

V2V is the communication between virtual servers that hold DT instances. Virtual communication could use a rather low cost to simulate activities that may take long time in physical scenario, thus it is also the most calculation-related module in DTN. Because of the dependency on calculation, V2V's optimization mainly relies on the optimization of the calculation process.

2.3 DTN calculation and data processing

The calculation refers to the data processing and DT status management in the servers. However, this part requires huge resources including but not limited to computational units, data storage, and function modules [Almasan22a] [Vaezi22].

The requirements for an efficient DTN system exceeds normal servers' capability. Thus, cloud computing/storage and edge computing (EC) are introduced to improve the performance. Specifically, Lu et al. [Lu20] provided a Digital Twin Wireless Network (DTWN) model to separate calculation requests to edges rather than main servers and in the meanwhile use federated learning to reduce the actual data flow that is transferred.

2.4 Application of DTN

DTN shows its potential benefits in many fields. Aside from NDT which we are going to talk about in the next section, DTNs are also used in Health Caring, Intelligent City, and even hardware optimization [Wu21]. One example is The Smart DC proposed by Zhang et al.[Zhang22] which uses DTN to simulate the cooling system and apply AI control to implement real time adjustment. Their Simulation result basing on a sample China Telecom's data center show that by applying Smart DC, the PUE of the data center reaches 1.0891, and RESR reaches 41.07%.[Zhang22]

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3. Network Digital Twin (NDT)

In section 2 we have discussed about definitions and some applications of DTN. It's natural to find out that the structure of DTN is similar to the networking structure. By using DTNs to simulate physical networking systems, it's easier to adjust and test new protocols or structures in the virtual realm than actually implementing them in the reality.

Also, while DTN requires a more efficient networking system, researchers found that the features of DTN could be beneficial to the improvement of the current networking systems, which will eventually form a positive loop. Thus the concept of NDT was introduced. In this section, we will talk about why and how NDT helps in improving networks, AI usage in NDT and some real application of NDT [Almasan22b] [Guemes-Palau22].

3.1 NDT's capability in optimizing networks

NDT is a specific case of DTN which is specialized in simulating networking systems in reality. DTN, as mentioned above, could provide a complex network of individual DTs and simulates complex system, which is quite similar to the huge modern networking system currently used. DTN enables an online simulation for huge network, and its virtualization as well as the use of edge and cloud computing makes it possible for Internet service providers (ISP) to test different modifications and protocols in the virtual realm [Almasan22b].

The key that people trust NDT to be a proper simulator is that, DTs do not only simulate software processes, but it create a complete physical-virtual simulation process which its data is always basing on real equipment and real scenarios [Guemes-Palau22]. This eventually allows ISPs to either validate new functionalities or do detailed analysis to certain circumstances [Mozo22].

3.2 AI in NDT

We have discussed how NDT might help in optimizing physical networks. But in realistic situations we might want some other techniques to help reducing the cost of building the whole NDT system. According to Guemes-Palau et al. [Guemes-Palau22], Mozo et al. [Mozo22] and many other researchers, applying ML methods to the building and adjusting process of NDT system could improve the judging and data processing performance as well as decreasing the time cost.

3.3 Application of NDT

Mozo et al. [Mozo22] provided a model called B5GEMINI which applies ML methods in the DTN system simulating complex 5G system. Its goal is to help maintaining and analyzing the physical network. In B5GEMINI, the DTN provides a virtual simulation of networks' physical reactions. Using RL and ML model to optimize the current DTN network and do the analysis. B5GEMINI provides a new way of optimizing network path and the reconfiguration when the topology of the network is changed.

Hong et al.[Hong21] provided an intelligent operated DT platform for DCN called NetGraph and has already been deployed in HUAWEI's DCN, helping the company in redefining network operation and network maintenance. Janz et al. [Janz22] used NDT in automating the configuration process of optical transmitting networks. Using DT instances to simulate optical devices and use AI in monitoring and optimizing the network structure, they believe that NDT could help in aspects such as optical margin reduction, risk mapping, etc.

3.4 Problems and future directions of NDT

Though researchers consider NDT a potentially powerful tool to help in upgrading networks, but current NDT system is still facing many urgent problems. One major problem is the data flood occurrence when large scale CPS-DT data transmission happens. As mentioned above, the physical network is already a complicated system. So when we are trying to synchronize virtual DT with physical CPS, it might cause huge data flow exceeding the network's capacity [Lengerke22].

Lengerke et al. [Lengerke22] proposed a coding-based solution reducing the post-shannon traffic to prevent data flood. The reduced data traffic is within 0.3% of the optimal value. But the solution was tested in specific scenarios. Another problem is, the process of building a perfect DT replicating physical network might be much harder and expensive than building a real physical network. And there is still not a widely accepted standard for NDT. WS4 - 1st International Workshop on Technologies for Network Twins was held in 2022, and proposing the concept of modulating NDT components and tried to discuss about making a standard [IEEE22].

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4. Conclusion

DTN and NDT are correlated to each other. While NDT is built by DTN, NDT helps DTN optimizing it's networking structure. Although Jacoby et al. [Jacoby20] gave a relatively detailed standards for DT, DTN and NDT are more general than single DT so we still need more researches and opinions to build a more formal environment for NDT to develop.

This field is still a new field, which still contains many possibilities. IEEE raised a "Call for Papers" concerning NDT topics in July 2023. The conference indicates some topics concerning NDT. Topics include but not limited to Network simulation or emulation, performance evaluation with DT, and Standardization for NDT [IEEE23]. Hopefully we would soon find a standard or guidance in NDT development.

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5. List of acronym

DT	Digital Twin
DTN	Digital Twin Network
NDT	Network Digital Twin
AI	Artificial Intelligence
PS	Physical System
P2P	Physical to Physical
P2V	Physical to Virtual
V2V	Virtual to Virtual

EC	Edge Computing
DTWN	Digital Twin Wireless Network
PUE	Power Usage Effectiveness
RESR	Refrigeration Energy Saving Rate
ISP	Internet Service Provider
ML	Machine Learning
RL	Reinforcement Learning
DCN	Data Center Network
CPS	Cyber-Physical System

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