HCIR Lab Seminar

Digital Twin of Wireless Systems: Overview,Taxonomy, Challenges, and Opportunities.

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1. Introduction

A. **Market Statistics and research trends**
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1. Introduction

- Future wireless services will have to play a key role in improving the quality of various applications such as brain-computer interaction, flying vehicles, and extended reality (XR), among others.

- These applications will have diverse performance requirements (e.g., user-defined quality of experience metrics, latency, and reliability) which will be challenging to be fulfilled by existing wireless systems.

- To meet the diverse requirements of the emerging applications, the concept of digital twins has been recently proposed.

- A digital twin uses a virtual representation along with security-related technologies (e.g., blockchain), communication technologies (e.g., 6G), computing technologies (e.g., edge computing), and machine learning, so as to enable the smart applications.

1. Introduction

- These new technologies will enable the wireless systems to meet the diverse requirements via enabling two main trends:
  - Self-configuring wireless systems
  - Proactive-online-learning-enabled systems

- To design a self-configuring and proactive-online-learning enabled wireless system, digital twin can be used to represent the wireless system.

- A digital twin takes inputs from a real world and makes predictions and/or control decisions. For this, in addition to the virtual representation of a wireless system, a digital twin-based wireless system will use tools from optimization theory, game theory, and machine learning.

- Additionally, to enable transparent and immutable handling of data, a digital twin-based system will use blockchain.

1. Introduction

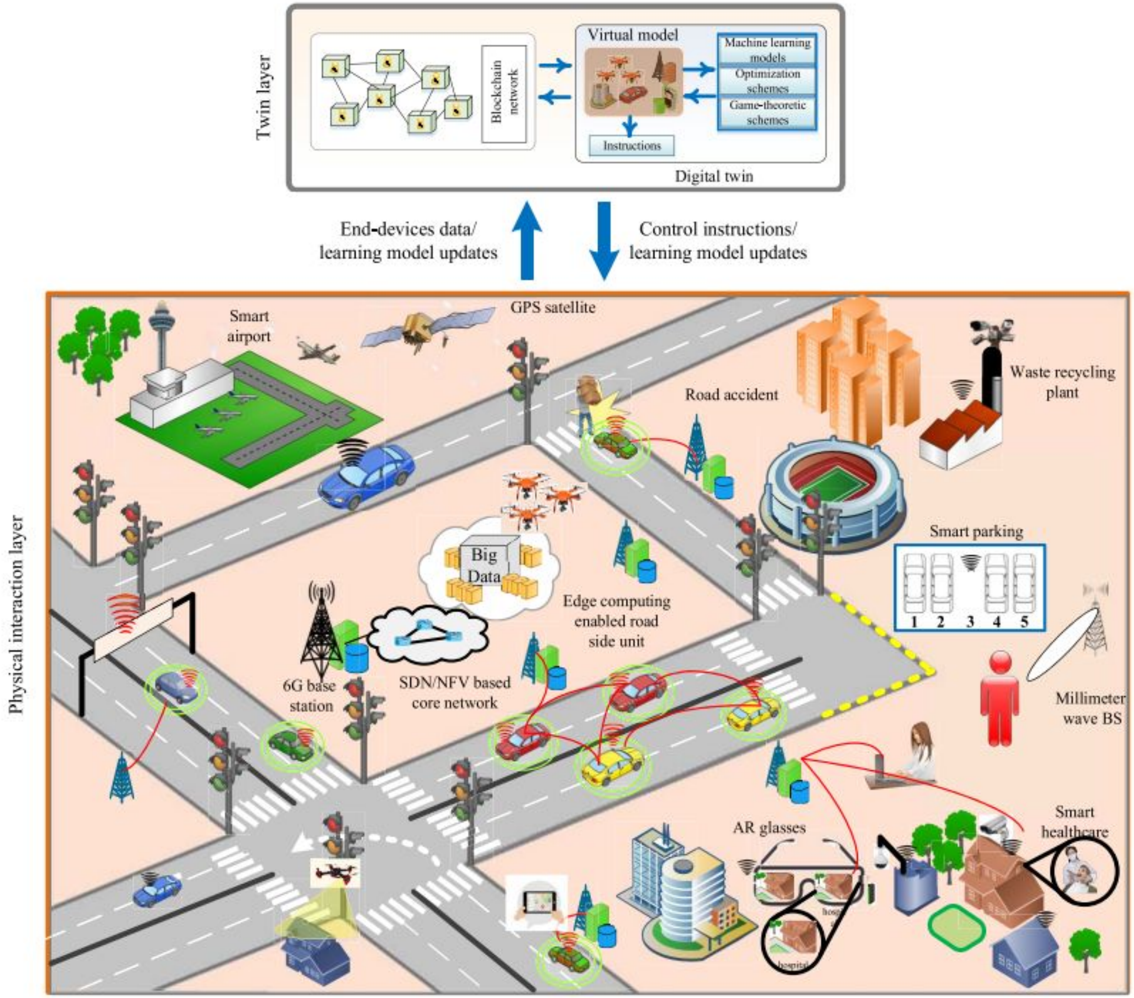
- A digital twin is different from traditional simulation tools, as it can use realtime (i.e., actual) data generated at the sensors attached to the physical objects and run simulations and analysis for online control of wireless systems.

- The two-way flow of information between the twin and the sensors can increase the accuracy of predictive analytical models.

- Hence, digital twin provides a more general platform for simulations and decision making.

1. Introduction

- Conceptual overview of a digital twin for a wireless system.



1. Introduction

A. Market Statistics and Research Trends

- ***The Internet of Things (IoT) market*** will grow at a Compound Annual Growth Rate (CAGR) of 26.9% during the period of 2017-2022. The market share will grow from 170.6 Billion USD in 2017 to 561.0 Billion USD in 2022.

- This is mainly due to an increase in the IoT market for smart buildings, smart grids, smart industries, and intelligent transportation.

- The key market players in the digital twin market are:
    - *General Electric (U.S.), Bosch Software Innovation GmbH (Stuttgart, Germany), Amazon Web Services Inc. (U.S.), Hewlett-Packard Enterprise (U.S.), Google Inc. (U.S.), PTC Inc, International Business Machine (IBM) Corporation (U.S.), Oracle Corporation (U.S.), Microsoft Corporation (U.S.), Cisco Systems, Inc. (U.S.), SAP SE (Walldorf, Germany), and Intel Corporation (U.S.).*

1. Introduction

A. Market Statistics and Research Trends

- According to statistics of Markets and Markets, ***the market of digital twins*** will grow at a CAGR rate of 58% during the period of 2020-2026.

- The market value of digital twin in 2020 was 3.1 Billion USD and it will reach 48.2 Billion USD by 2026.

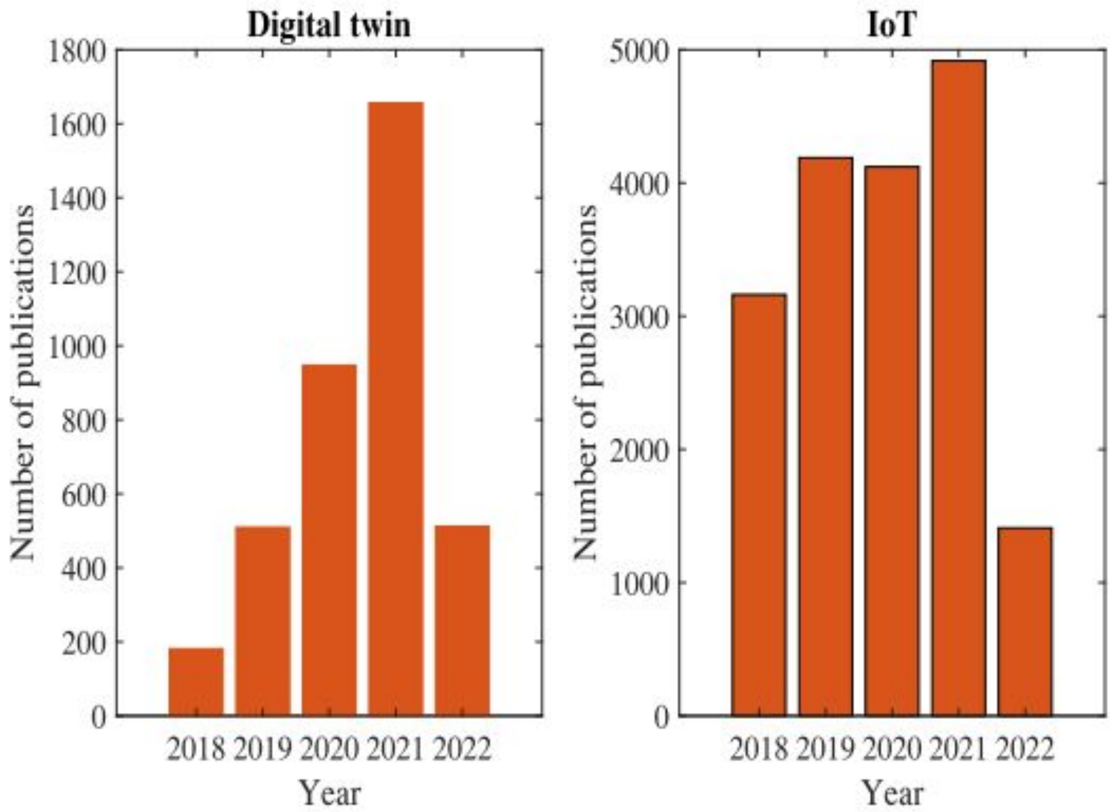
- Due to the increasing importance of digital twins in the development of smart applications, various countries, such as Brazil, Norway, Mexico, China, Japan, South Korea, and Singapore, are trying to implement twin-based systems.

- The key market players in the digital twin market are:
  - *SWIM.AI (USA), Robert Bosch (Germany), ANSYS (USA), Siemens AG (USA), Oracle (USA), SAP (Germany), Microsoft Corporation (USA), PTC (USA), IBM (USA), and General Electric (USA).*

1. Introduction

A. Market Statistics and Research Trends

- On the other hand, the number of publications for digital twin and IoT also shows a significant increase.



B. Existing Surveys and Tutorials

SUMMARY OF EXISTING SURVEYS AND TUTORIALS AND THEIR PRIMARY FOCUS

Reference	Wireless for twins	Twins for wireless	Taxonomy	Remark
Minerva *et al.* [13]	✗	✗	✗	This survey comprehensively presents technical features, scenarios and architectural models for digital twins in the context of IoT.
Wu *et al.* [14]	✓	✗	✗	This survey presents the twin fundamentals, as well as key enabling technologies, and open challenges.
Barricelli *et al.* [15]	✗	✗	✗	This paper presents the fundamentals, implementation details, and applications of digital twins.
Yaqoob *et al.* [16]	✗	✗	✗	The authors discuss the role of blockchain on enabling digital twins. Also, a taxonomy is devised.
Suhail *et al.* [17]	✗	✗	✗	Blockchain-based twins are discussed. Furthermore, research trends and future directions are presented.
Khan *et al.* [5]	✗	✓	✗	This tutorial presents the key design requirements, architectural trends, and future directions for digital-twin-enabled 6G.
Our Tutorial	✓	✓	✓	Comprehensively discusses issues for designing digital twins for wireless systems and also optimizing wireless communications for digital twins.

2. Digital twin: Concepts, key design aspects and frameworks

A. Concept
B. Design aspects
C. High-level architecture
D. Frameworks
E. Example scenario.
F. Summary and lessons learned

2. Digital twin: Concepts, key design aspects and Frameworks

A. Concepts

- A digital twin is a virtual representation of the physical system serving as a digital counterpart.

- The main purpose of a digital twin is to jointly optimize the cost and performance of a system or overall process using various emerging technologies (e.g., virtual modeling, simulation technologies, blockchain, edge computing, cloud computing) and optimization tools.

- Digital twin provides proactive analysis of the physical process using various simulation tools (e.g., AMEsim, SimScale, Simulink), artificial intelligence, mathematical optimization, game theory, and graph theory, among others.

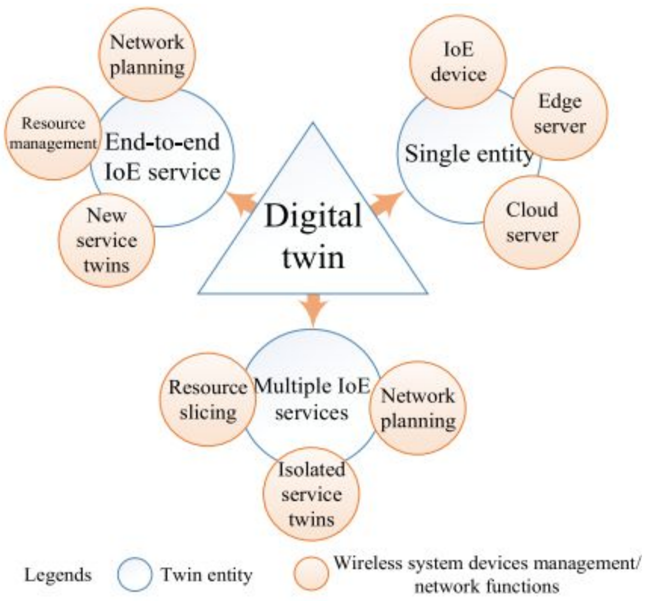
2. Digital twin: Concepts, key design aspects and Frameworks

A. Concepts

- Digital Twin Categories

DIGITAL TWIN CATEGORIES: SOURCE, TYPE, AND EXPLANATION

Reference	Category (defined by source)	Description by the source	Key objective
Siemens [23]	Product digital twin	To use a digital for enabling a new product. This twin offers the ability to make various experiments by varying different system parameters to analyze the cost, efficiency, and performance for a new product before it is actually manufactured.	New product design
	Production digital twin	To use a digital twin in the process of manufacturing. Digital twins of various components are tested for performance and cost. This will lead to efficient selection/placement of manufacturing process component in real-time deployment.	Efficient deployment of system components
	Performance digital twin	To use a digital twin for capturing and acting on operational data. This twin will enable smart plants (e.g., smart grid, smart industry) to operate in an efficient way to optimize the cost and performance by using the generated data. This data can be further used by machine learning models and other techniques to enhance the twin performance.	Data analysis for performance enhancement
Vercator [25]	Standalone digital twin	This twin refers to the virtual models of individual entities (e.g., heating, ventilation, and air conditioning system in a smart home) of a system.	Modeling of a single entity.
	Duplicated digital twin	This refers to a twin for optimized use of multiple stand-alone twins (e.g., car twins and smart industry twins).	Performance optimization of a component that is made of many twins in a complex system.
	Enhanced digital twin	This twin deals with modeling of complex systems that have a broad scale than those of a duplicate twin and will consist of multiple duplicate twins.	To enhance the performance of a complete system (e.g., 6G-based smart surveillance in a city).
Tributech [26]	Component twin	Such a twin represents a single component in an entire system.	Single specific component in a system.
	Asset twin	This refers to a twin that can manage the system that is made up of multiple component twins (e.g., autonomous car engine).	System multiple components.
	System twin	This twin scales by covering a large system (e.g., entire autonomous car).	Single system
	Process twin	This twin models the entire process facility (e.g., autonomous car plant).	Entire plant
XMPRO [24]	Status twin	This twin is used to monitor the system (e.g., dashboards and simple alerting systems).	To monitor the phenomenon.
	Simulation twin	It enables us analyze the system performance via simulation and provide insights into future states.	To analyze the system performance.
	Operational twin	It enables us to interact with the system and control the system for efficient and cost performance.	To efficiently control the system.



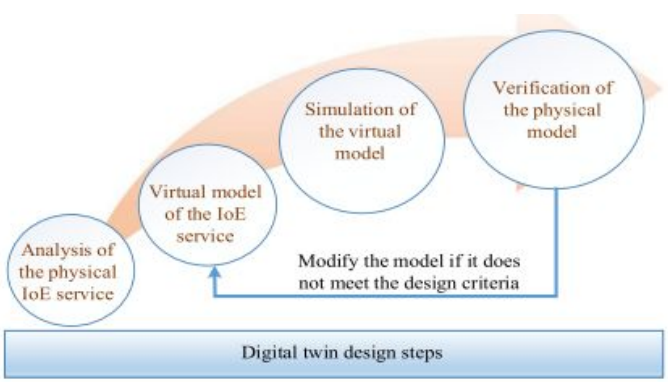
2. Digital twin: Concepts, key design aspects and Frameworks

A. Concepts

- The implementation process of a digital twin starts with the analysis of a physical system. Next to physical system analysis, a virtual system is designed that represents the physical system.

- After virtual modeling, the virtual design needs to be verified by simulating the virtual model and comparing the performance with the physical system.

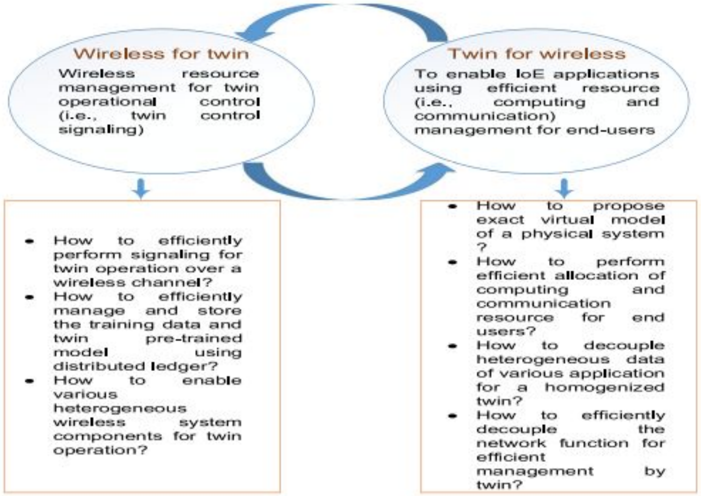
- Modeling a virtual system is challenging. The challenges include designing an accurate representation of a system using mathematical equations.



2. Digital twin: Concepts, key design aspects and Frameworks

B. Design Aspects

- There are two aspects of the design:
  - Wireless for twin:
    - Deals with the design of twins to enable various network functions/ applications.
  - Twin for wireless
    - Deals with efficient communication methods to enable signaling for implementation of twins.
- A twin-enabled wireless network will have blockchain networks, edge/cloud servers, data decoupling interfaces, function decoupling interfaces, and physical devices to enable the successful operation of IoE services.



2. Digital twin: Concepts, key design aspects and Frameworks

B. Design Aspects

- Wireless resources can be used in twinning mainly for two operations:
  - Training of twin objects.
  - Signaling for twin operation.

- Twins training will use wireless resources to transfer data and learning updates.

- For centralized learning, a wireless channel is used to migrate the data from end-devices to the shared storage (i.e., servers installed at the edge/cloud).

- In case the data is enormous (autonomous driving cars), distributed learning (e.g., federated learning [FL]) can be used. FL is based on sending only learning model updates rather than the whole data, and thus consumes fewer communication resources compared to centralized learning.

2. Digital twin: Concepts, key design aspects and Frameworks

B. Design Aspects

- To train digital twin models using distributed learning over wireless networks, a significant amount of resources will be required.

- Variable latencies will be induced for transferring learning model updates between devices and twin model servers.

- For a twin model update of size u and channel throughput Γ, the transmission latency can be given by $d = u/\Gamma$.

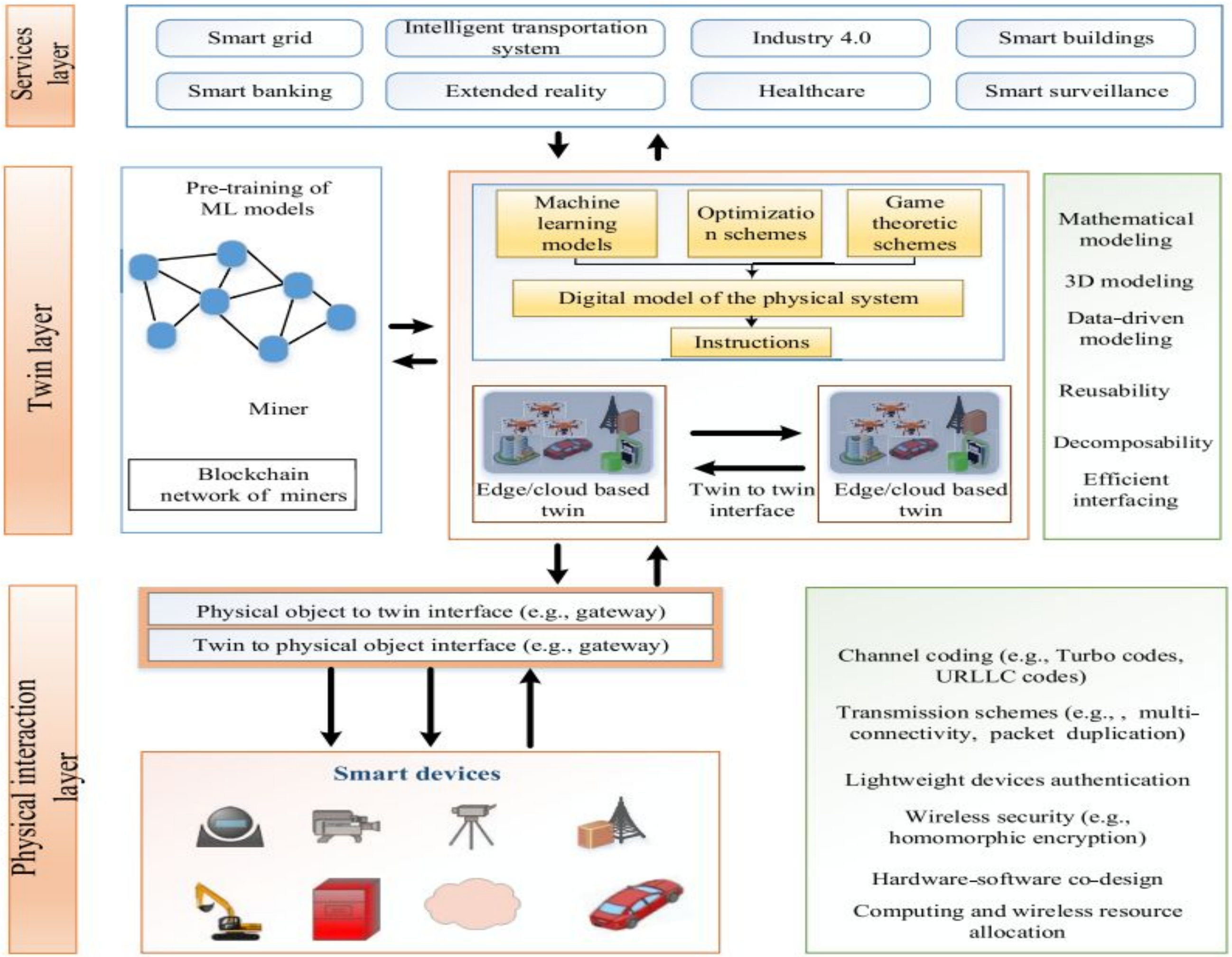
- The transmission latency can be minimized, for example, by reducing the size of twin model updates, and improving the throughput, e.g., by performing efficient association of devices with edge/cloud server and efficient wireless resource allocation.

s a machine learning technique that trains an algorithm across multiple decentralized edge devices or servers holding local data samples, without exchanging them

Wrapping up, we can say that distributed learning is about having centralized data but distributing the model training to different nodes, while federated learning is about having decentralized data and training and in effect having a central model.

C. High-Level Architecture

- High-level architecture of a digital twin for wireless systems based on logical twin objects.

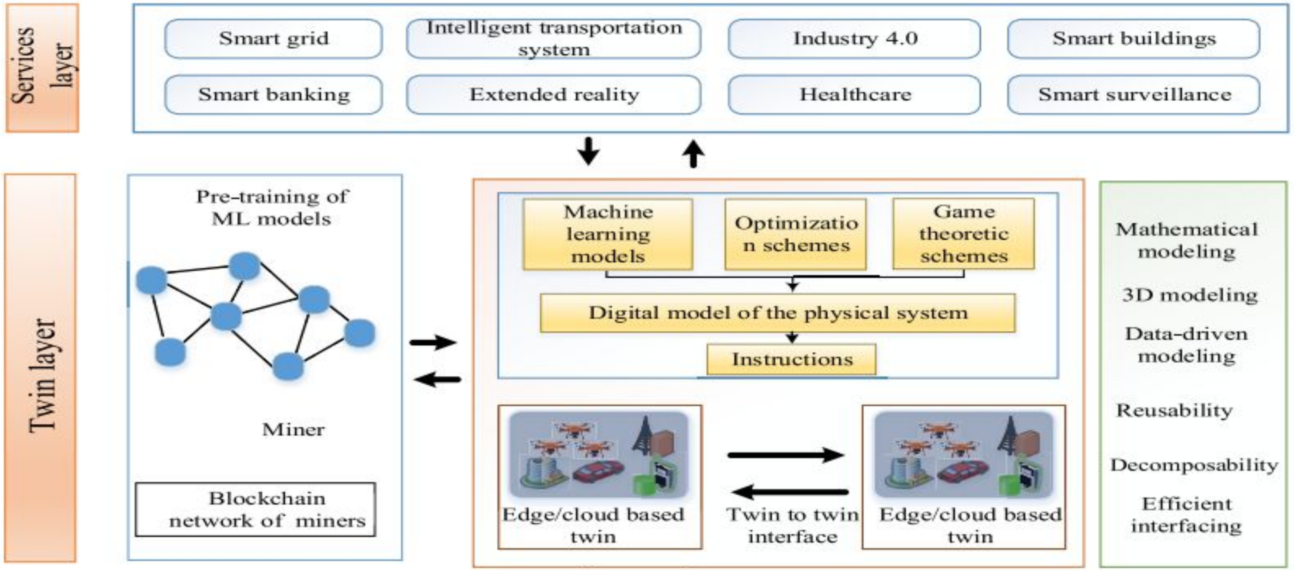


2. Digital twin: Concepts, key design aspects and Frameworks

C. High-Level Architecture

- The services layer contains interfaces for applications. One can request a service from a twin-based wireless system.

- In response to the user request, semantic reasoning schemes are used to translate the request, which is then passed to the twin layer.



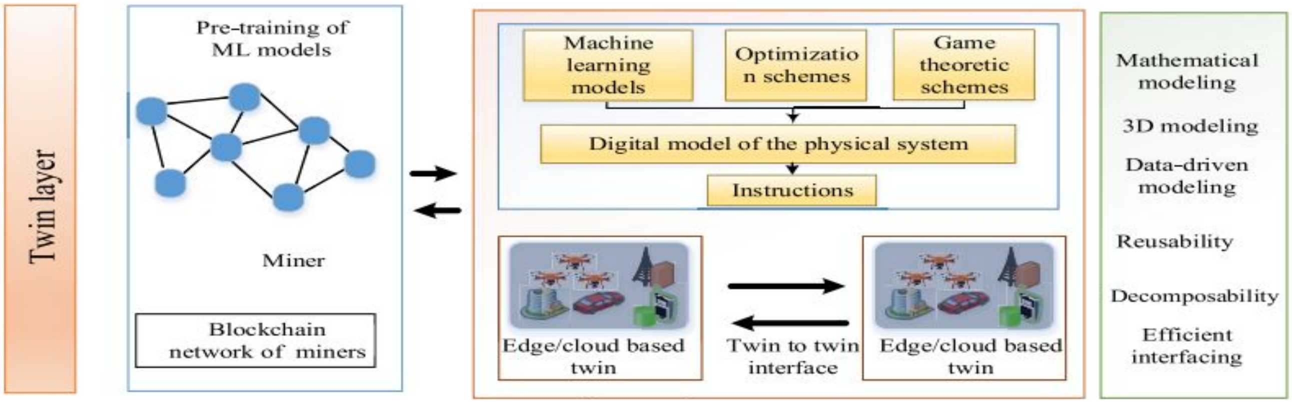
2. Digital twin: Concepts, key design aspects and Frameworks

C. High-Level Architecture

- The twin layer contains logical twin objects which use a virtual representation of the physical object/ phenomenon.

- For a digital twin, there can be different models for the physical objects/ phenomenon, such as mathematical model, 3D model, and data-driven model.

- Twin layer objects can be implemented using container/s or virtual machine/s. Also, twin objects can be deployed either at the network edge or at the remote cloud.

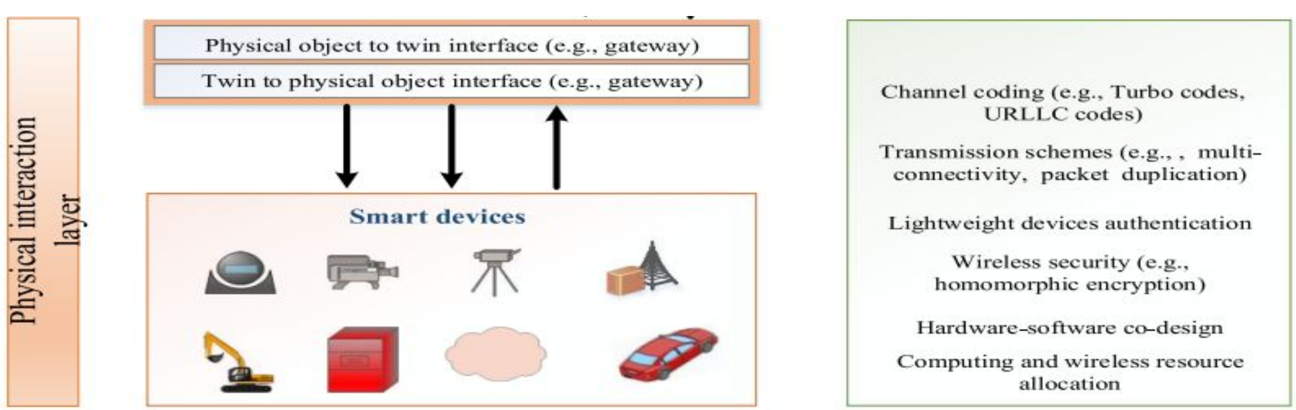


2. Digital twin: Concepts, key design aspects and Frameworks

C. High-Level Architecture

- The last layer is the devices' physical interaction layer, which contains all the physical devices, such as end-devices, edge/cloud servers, base stations, miners, and core network switches, among others.

- Effective interfaces are required between different layers of in a twin-based wireless system. These interfaces can be twin-to-physical object interface, twin-to-twin interface, and twin-to-service interface.



2 Digital twin: Concepts, key design aspects and Frameworks

C. High-Level Architecture

- For a digital-twin-enabled wireless system, there are two aspects of reliability:
  - Twin reliability
  - Twin-based service reliability.

- ***Twin reliability*** refers to the operation of a twin with minimum possible interruption due to the failure of the edge/cloud server running the twin object.
  - An IoT service based on a single twin deployed at the cloud has lower reliability than an IoT service based on multiple twin objects deployed at edge servers. However, the management of multiple twins for a certain service will incur more complexity.

- ***Twin service reliability*** mainly depends on wireless channel reliability and reliability of edge/cloud computing. Similar to twin signaling, channel coding schemes can be used for this.
  - A digital twin can be used for predictive maintenance of 6G systems to avoid system malfunctions and cyber-attacks through artificial intelligence analytics and simulation.

2. Digital twin: Concepts, key design aspects and Frameworks

C. High-Level Architecture

- Steps for a twin-based wireless system operation
  - The end-user will request a service. This request will be translated using semantic reasoning schemes to make it compatible with the twin object-based architecture.
  - Next, the twin object will be created to serve the end-user.
  - Finally, the twin object uses mathematical optimization and machine learning schemes in addition to virtual representation to enable efficient resource optimization for various services.
  - The twin objects will use pre-trained twin model to serve the requesting user. Meanwhile, the newly generated data may be used by twin object to further train the pre-trained model for performance enhancement. After training, the twin model will be stored using a blockchain network. Finally, after serving the requesting user, the twin objects based on virtual machines/containers are released.

2. Digital twin: Concepts, key design aspects and Frameworks

D. Frameworks

- Frameworks designed for implementing digital twins.
  - **Eclipse Ditto**: is a framework for creating digital IoT twins. The framework consists of Ditto services (components), external dependencies (MongoDB and nginx), and application programming interfaces (APIs).
  - **Model Conductor-eXtended Framework** is framework for digital twins experimentation. The framework enables us to co-execute the digital systems and physical systems as well as asynchronous communication. Furthermore, support for machine learning models, customized models, and running FMUs (simulation models packaged according to the FMI specification) is also provided.
  - **Mago3D** is a digital twin platform developed by Gaia3D Inc.The purpose is to model real-world objects, phenomenon, and processes on Web environment.
    - The platform consists of a geospatial data server, data conversion server, platform core server, and Web server, for realizing the digital twin-based architecture. Mago3D has been applied in various sectors, such as Korean national defense, indoor data management, shipbuilding, and urban management, and has shown good results.

2. Digital twin: Concepts, key design aspects and Frameworks

D. Frameworks

- All frameworks (i.e., Eclipse Ditto, Model Conductor-eXtended Framework, and Mago3D) are promising for the realization of digital twinbased systems.
- However, none of them effectively considers the effects of wireless channels on the performance of digital twins.
- In wireless systems, wireless channel uncertainties will significantly affect the performance of IoT applications.
- Therefore, these wireless channel uncertainties need to be modeled effectively for digital twinning of wireless systems.

2. Digital twin: Concepts, key design aspects and Frameworks

E. Example Scenario

- Consider an XR device that requests a service from the access point.
  - First of all, authentication will be performed by the digital twin-based wireless system at the service layer in response to the end-user request.
  - Next to authentication, a translation scheme will translate the user request into the form understandable by the twin-based wireless system.
  - The next step will be instantiation of the twin object/s. The deployment of twin object/s will be either at the network edge or the cloud depending on the latency constraints.
  - These twin objects should be associated with the blockchain so that twin objects can reuse the pretrained models stored in blockchain.
  - Additionally, the blockchain stores the data required for efficient analysis. To serve the requesting user, twin object/s will use pretrained models in addition to mathematical optimization to perform efficient resource management and other functions, twin control signaling must be efficiently performed.

2. Digital twin: Concepts, key design aspects and Frameworks

F. Summary and Lessons learned

- A digital twin should be designed in a generalized way so that it can be easily reusable for future services. Twins based on machine learning should be trained using more data to make them generalized so as to use them for multiple scenarios.

- The current digital twin frameworks are designed without effectively taking into account the wireless channel impairments. Novel frameworks will need to be designed for digital twinning over wireless systems.

- Digital twins for a wireless network can be used for effective use of computing and communication resources and serving users with different requirements (“twin for wireless”). On the other hand, efficient wireless resource management methods will be required for twin signaling (“wireless for twins”).

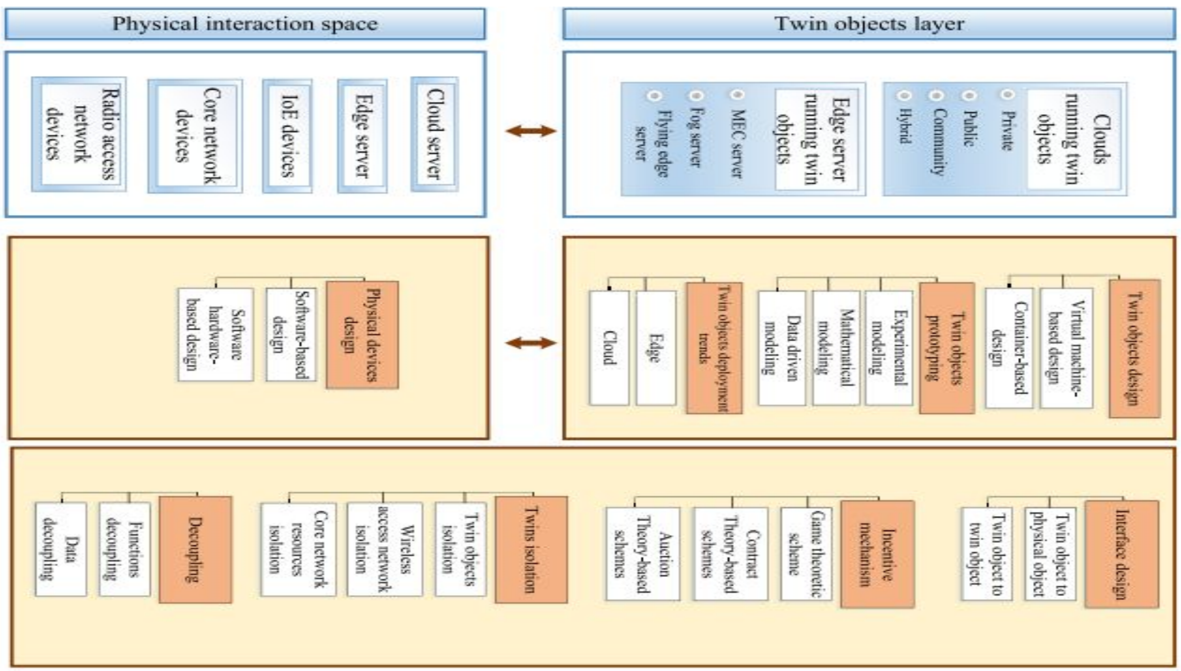
3. Taxonomy: Twins for wireless

A. **Design of Twin objects**
B. **Prototyping of Twin objects**
C. **Deployment approaches for Twins**

3. Taxonomy: Twins for Wireless

- The taxonomy is divided into two layers, namely, the physical interaction layer and the twin layer.

- The main aspects related to designing twins for wireless systems are identified to be: twin isolation, incentive design, twin object design, twin object prototyping, twin object deployment, physical end-device design, decoupling, and interface design.



3. Taxonomy: Twins for Wireless

- Twin isolation enables the seamless operation of twins for various services without interrupting the performance of each other.
- Twin object design helps in the on-demand creation of twins using existing computing hardware for various applications.
- Twin object prototyping helps in the creation of virtual models of the wireless systems.
- Twin object deployment is about the placement (e.g., cloud or edge) of twin objects.
- Decoupling allows the seamless operation of the twin-based services with minimum possible dependency on the underlying hardware.
- Interfaces are used for various types of communications, such as those among twin objects, and those between twin objects and physical devices. To motivate the participation of different devices in twinning, incentive mechanisms will be required.

3. Taxonomy: Twins for Wireless

A. Design of Twin objects

- There are two ways to instantiate the twin objects, such as virtual machine-based twin objects and container-based twin objects.
- A virtual machine can be defined as the architecture that is independent of the underlying hardware.
- Virtual machines can be mainly of two types, such as system virtual machine and process virtual machine.
- In the context of a twin-based wireless system, the system virtual machine can be used to model a complete IoT service (e.g., AR-based healthcare system), whereas the process virtual machine can be used to model the particular portion (e.g., edge caching module for smart infotainment system) of digital twin-based system.
- Modeling a complete system may be easier than modeling a particular part.

3. Taxonomy: Twins for Wireless

A. Design of Twin objects

- The virtual machine is different from the operating system. In an operating system, language-independent extensions of hardware are created, whereas a virtual machine creates a machine-independent instruction set.

- Virtual machine-based virtualization can be seen as an infrastructure as-a-service (IaaS) that can enable the same hardware via virtualization for running multiple operating systems (e.g., twins).

- This operational approach has the main drawback of high management complexity. To address this issue, container based twin objects can be used. Containers can help minimize management complexity by running multiple twins on the same operating system. However, container-based twin objects may be more prone to security attacks than the virtual machine-based design.

3. Taxonomy: Twins for Wireless

B. Prototyping of Twin objects

- Prototyping twin objects involves estimating the parameters of virtual twin models for the physical system counterparts. True prototyping of twin objects is one of the primary challenges in digital twinning over wireless networks.

- Physical objects are characterized by a set of attributes (e.g., shape, mass, energy). These attributes are difficult to model exactly. In experimental modeling, a series of experiments are performed to find out the various parameters of a physical wireless system.

- Various entities of a wireless system can be modeled using experimental data. Alternatively, mathematical modeling can be used that is based on a mathematical representation of a wireless phenomenon. Typical mathematical models are based on various assumptions that need to be valid for a real-life scenario so that a more practical model of the digital twin can be developed.

3. Taxonomy: Twins for Wireless

B. Prototyping of Twin objects

- There are some scenarios which are difficult to model mathematically. In these scenarios, data-driven modeling can be used.

- Wireless system applications (e.g., XR) can generate a significant amount of data that can be used in modeling their behavior. One can use the data to train machine learning models.

- However, training of a machine learning model within a certain period of time for a certain data set may require a significant amount of computing resource (CPU-cycle/sec).

- An increase in computing resources will minimize the training time but at the cost of an increased energy consumption.

3. Taxonomy: Twins for Wireless

B. Prototyping of Twin objects

- There are two types of machine learning models, namely, centralized machine and distributed machine learning models.

- Centralized machine learning relies on centralized training at the remote cloud or edge server. With centralized machine learning, there is an issue of privacy leakage because of transferring end-devices' data to the centralized cloud/edge server.

- To mitigate this problem, distributed machine learning can be used, in which case the end-devices iteratively train the global model using their local data sets. The local model updates are then sent to the edge/cloud server for aggregation to yield a global model.

3. Taxonomy: Twins for Wireless

C. Deployment Approaches for Twins

- Depending on the application requirements, twins can be mainly deployed either at the network edge or cloud.
- Every application has distinct requirements in terms of latency, quality of physical experience, computing resource requirement, and reliability, among others.
- Twins deployed at the network edge can enable services with low latency compared to those deployed at the cloud. Also, the twins at the edge can have more context awareness (e.g., locations of end-devices, mobility-awareness).
- However, the edge-based twins have limitations in terms of low computing resources. When deployed in the cloud, there could be more computing resources.

3. Taxonomy: Twins for Wireless

C. **Deployment Approaches for Twins**

- A hybrid approach can be used in which twins are deployed at both network edge and cloud.
- For instance, consider the digital-twin-enabled infotainment system for autonomous cars.
- One can use caching assisted by a hybrid twin that consists of two twins deployed at both the network edge and the cloud.
- The edge twin will make the caching decisions for infotainment users where latency is stringent. Meanwhile, due to limited storage capacity at the edge, one can use the cloud to cache the information that is needed less frequently compared to cached information at the edge. To control caching in the cloud, cloud twins can be used.

3. Taxonomy: Twins for Wireless

C. Deployment Approaches for Twins

- Comparisons of various twins depending on the deployment trends.
    - The table shows that edge-based twins (i.e., for multiple twin objects) have the highest robustness to failures compared to cloud-based twins and hybrid twins.
    - The elasticity of edge-based twins is higher than a cloud-based twin.
    - Mobility support for users and context awareness could be higher for edge-based twins due to the proximity of the end-devices.

	Description	Edge-based twin object	Cloud-based twin object	Edge-cloud-based twin objects
Twin robustness (reliability)	It refers to seamless operation during failure of one of twin objects.	Highest (for multiple edge-based twins)	Lowest	Medium
Geo-distribution	This metric enable us with the information about the geographical distribution of twin objects.	Distributed	Centralized	Hybrid
Elasticity	This metric shows the ability of a twin-based wireless system to provide highly dynamic requirements of various services via elastic resource allocation.	High	Low	High
Mobility support	It refers to the ability of a twin-based wireless system to serve mobile devices seamlessly.	High	Low	Medium
Latency	It deals with the overall delay in providing the service to end-users.	Low	High	Medium
Context-awareness	It deals with the ability of a twin-based wireless system to obtain network and devices information.	High	Low	Medium
Scalability	It deals with fulfilling the requirements of a massive number of wireless devices. Additionally, the addition of more devices should not degrade the latency performance.	High	Lowest	Low