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

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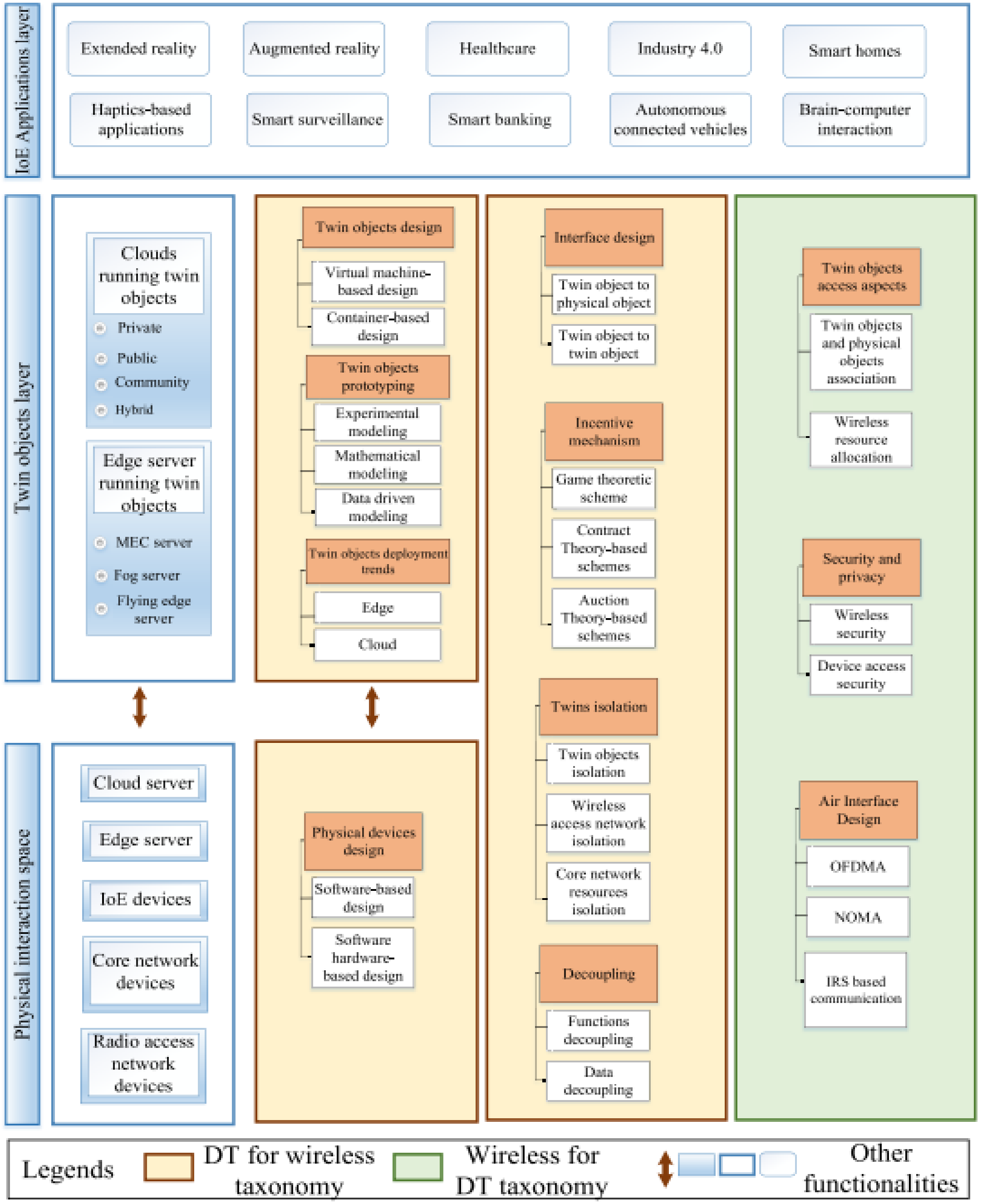

Fig.8 Digital Twin and wireless systems

Taxonomy: Wireless for Twin

- Wireless for twins deals with twin signaling.
- Air interface deals with efficient communication.
- Twin object access allows efficient association of twin and physical devices.

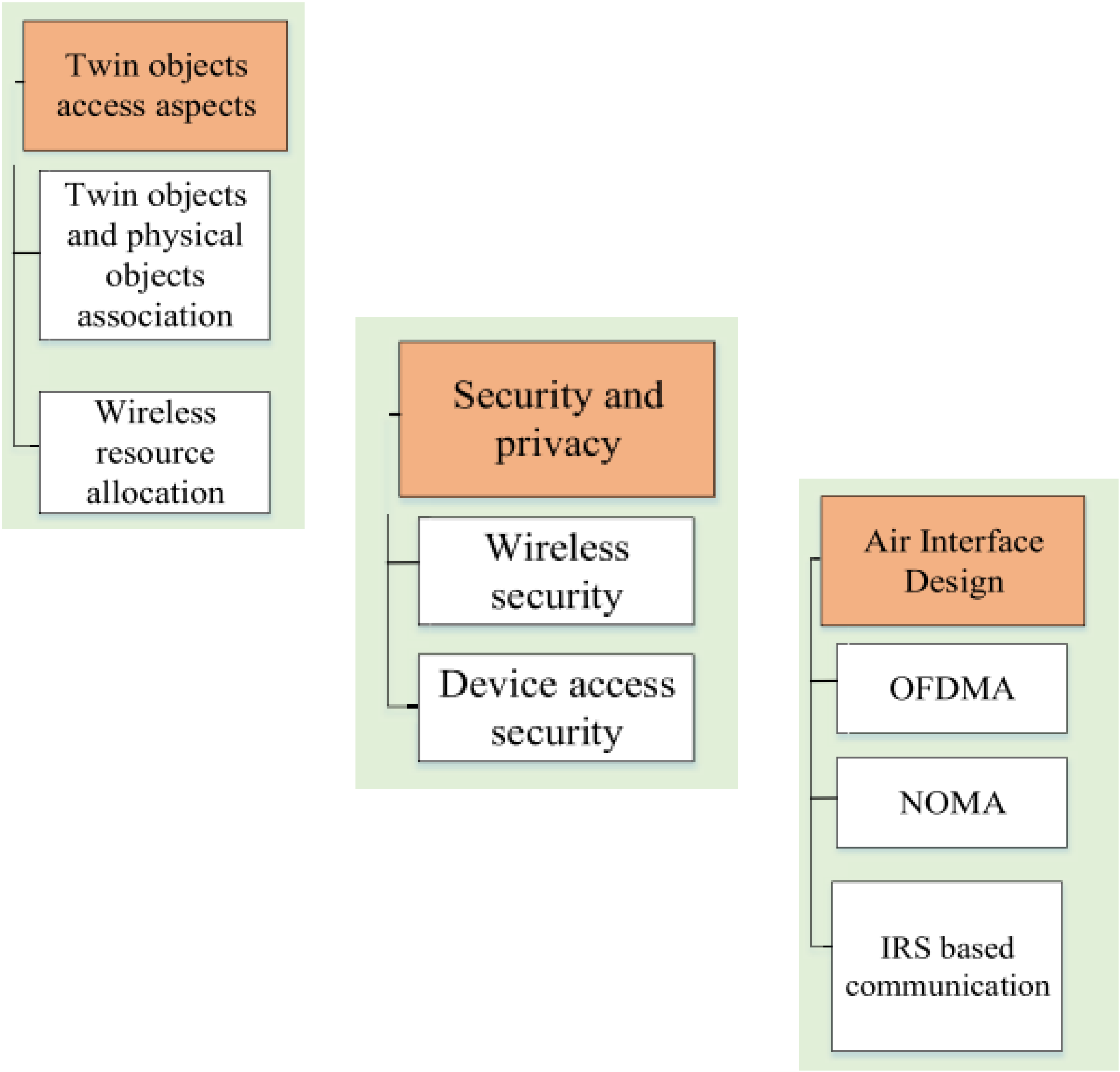

Fig.1 Digital Twin and wireless systems (associated with its imp aspects)

Accessing Twin Object

- Two Key concepts related to accessing the twin objects are :
  - Association between twin objects and physical devices
  - Allocation of computing and communication resources.
- Association occurs due to the presence of binary variables:
  - Represented by the equation:

$$x_{n,m,} = 1$$

  - Relaxation-based solution transforms binary association variable to continuous variable.
  - Heuristic scheme overcomes approximation error.
  - Matching was found to be solving approximation problems with reasonable complexity.
  - Wireless resources are required for transfer of control signal to/from the software-defined network.
- Computing resources are required for twin processing tasks.
  - For machine learning models at edge/cloud.
  - Running blockchain consensus algorithm.
  - Analysis of virtual twin.

Security and Privacy

- Security attacks are of two types physical device security and interface security.

- Authentication schemes are required for unauthorized access to the device and edge cloud server and Blockchain.

- In SDN-based architectures include the vulnerability of network controller, forged control packets injection misconfigured policy enforcement, and weak network policy enforcement, weak network device authentication.

- Misconfigured interface twin to twin interface and protocol twin packet routing protocols results in various security vulnerabilities.

- Weak or improper authentication schemes and plain text channels lead to security attacks.

Security and Privacy

- Training the twin model in centralized learning scenario leads to loss of privacy. On device training models mitigates this problem.

- Differential privacy and homomorphic encryption schemes helps end devices overcome malicious aggregation server attacks.

- Dispersed federated learning computes sub-global model repetitively and are shared and global model is computed.

- Collaborative federated learning model depends on local aggregation at end devices. helps in condition where communication resources are limited.

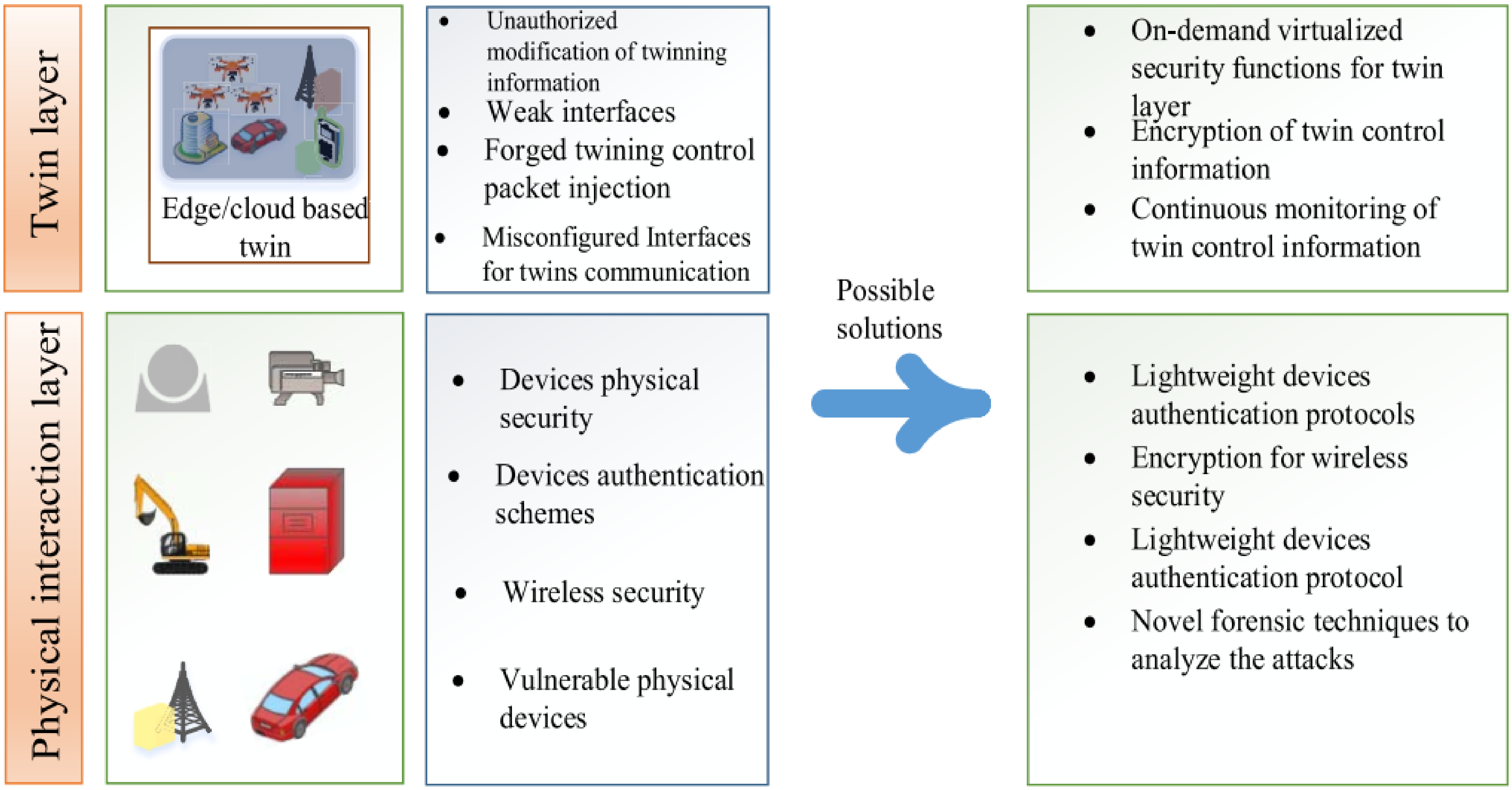

Fig. 2 Security attacks in digital twin-based wireless systems

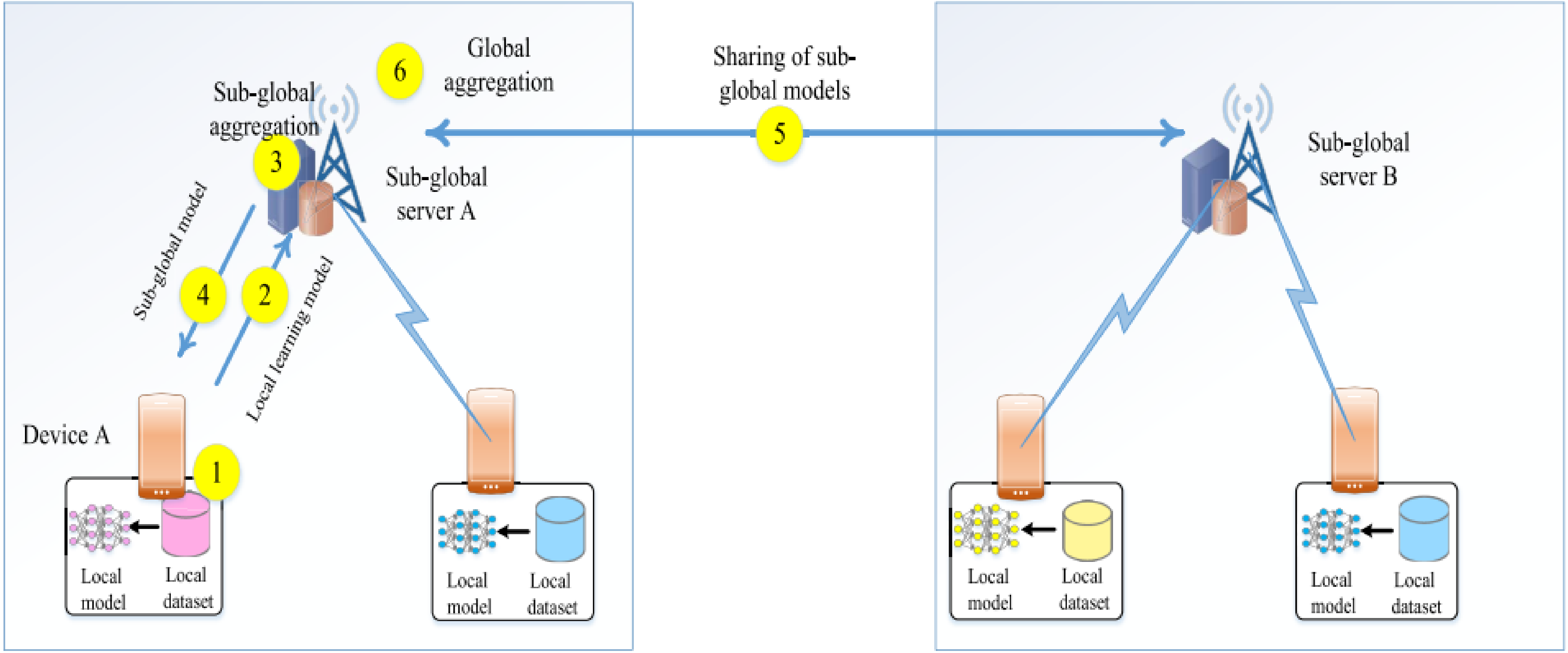

Fig. 3 Dispersed federated learning

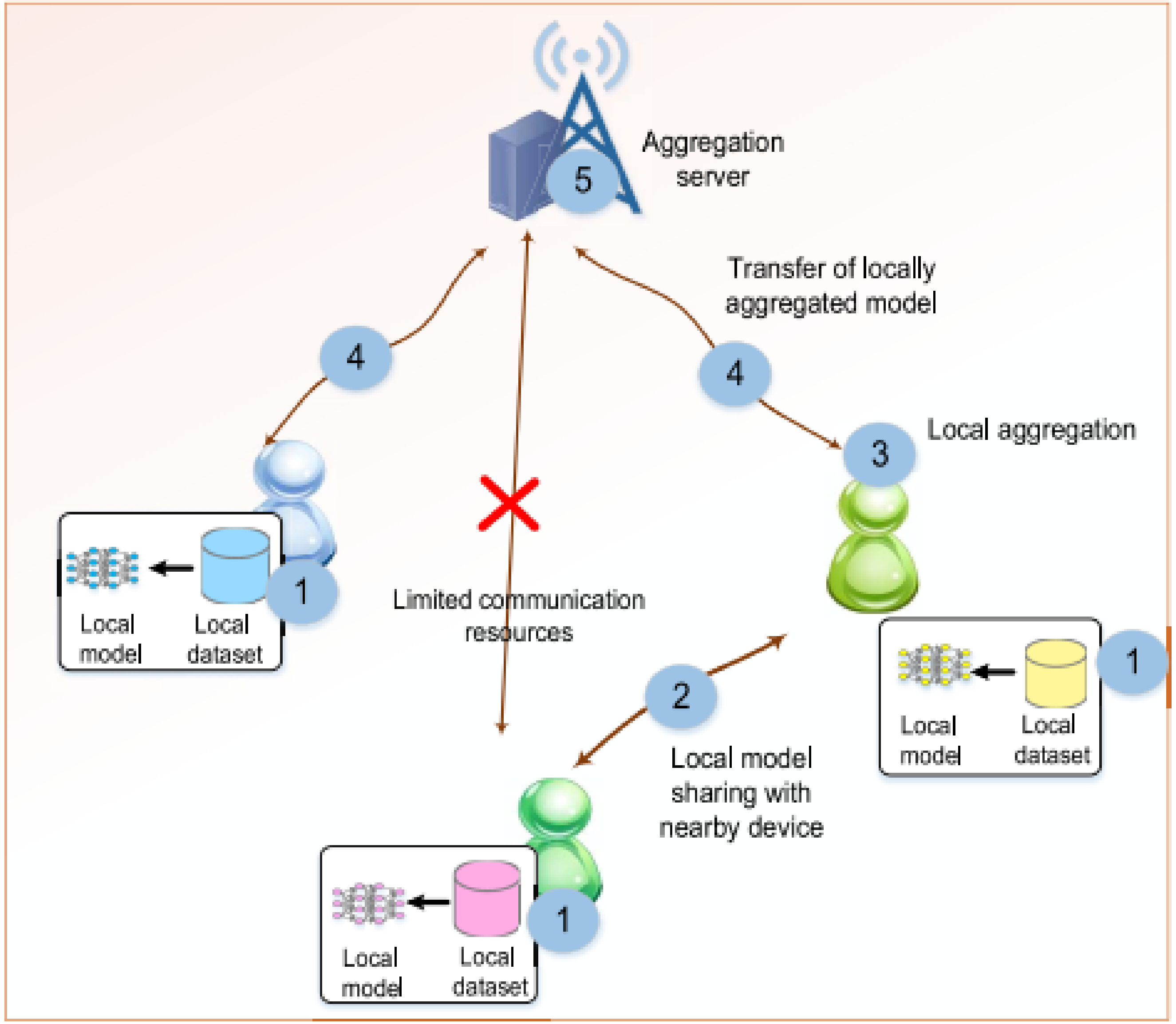

Fig. 4 Collaborative federated learning

Air interface Design

- Air interface interacts with sensors and wireless users for communication.
- Two aspects of digital twinning frequency band for wireless access and access scheme.
- Main wireless access discussed are :
  - Orthogonal frequency division multiple access(OFDMA) propagation of signal are independent of each other, at 90 degrees.
  - Time-division multiple access(TDMA)
  - Non-orthogonal multiple access(NOMA) (whole bandwidth for all users)
  - Code division multiple access
- A large transmission bandwidth or higher frequency band suffers attenuation. Configurable intelligent surface are used for (RIS).this can change polarization, frequency, amplitude allows communication with no line of sight .

Lessons learned and Recommendations

- Forensic schemes are required to investigate before the security scheme.
- Lightweight and effective authentication schemes are required.
- Effective encryption schemes are required for the transfer of data and control signal.
- Forged twinning control instruction will significantly degrade the performance of digital twins.
- Careful selection of design is needed. Heterogeneous requirements of designs of twins have different computing resources.
- Energy efficient algorithm is required for the twinning of wireless network.
- Association of physical end devices with edge servers running twin objects should be considered for energy efficiency.

Open challenges

Table 1 Summary of open research challenges in Existing Survey and Tutorials

Reference	Challenges
Minerva *et al.*, [13]	Standardization, scalability, composability, and business model
Wu *et al.*, [14]	Security vulnerability, privacy leakage, cost-effective solutions, and two-way real-time interaction
Barricelli *et al.*, [15]	Ethical issues, security and privacy, cost of development, equally distributed wealth, government regulations for medical twins, and technical limitations
Yaqoob *et al.*, [16]	Accurately representing an object and affordability of digital twins, ethical, legal, and societal issues, cybersecurity, and barriers to Blockchain Adoption in digital twins
Suhail *et al.*, [17]	Digital twin representation, data related issues, expenditure on infrastructure.
Khan *et al.*, [5]	Isolation between digital twin-based services, mobility management for edge-based twins, digital twin forensics.
Our Tutorial	Dynamic twins, interoperability for twins migration, twins prototyping of physical objects, incentive mechanism for twinning, and efficient twin objects chaining.

Dynamic Twin

- Due to wide benefits of reusability of Digital twin model it is highly desirable for various services.
- Twin machine learning model can train using more general data sets to provide more applicability in different services and applications.
  - Ex: using Image data sets in applications for classification task for mini-imageNet data set.
- Training a twin machine learning model for general data might not perform well because it being domain specific ,being data complex and model complexity.

Interoperability for migration of twin objects

- Mobile devices in wireless systems with edge servers running twin objects move to a coverage area of another base station.

- Connection to the oriented base station can be maintained by the core network through the newly associated base station.

- Some Internet of things devices suffer strict latency.

- Migration to the new small base station is suggested. Ex. twin objects based in virtual machines can be migrated dynamically.

- Easy migration of twin objects can be done with a Unified cloud interface/cloud broker, enterprise cloud orchestration platform/orchestration layer, and open cloud computing interface.

Prototyping of physical object

- For twin modeling, it is necessary to know measurable aspects of a physical object.
- To reduce complexity we can focus on the limited set of parameters.
- Various modeling schemes are experimental modeling, three-dimensional modeling, and data–driven modeling.
- Experimental modeling involves full-scale experimentation of a physical phenomenon.
- 3-D modeling develops a mathematical model of physical objects. The exact representation of the exact model is challenging.
- Data-driven modeling uses data for delivering the functional form of the physical object. Proper selection of a machine learning model can be challenging.

Incentive Mechanisms for Twinning

- In Digital twinning, a variety of players such as edge/cloud servers, miners, end-devices, and network operators interact with each other to enable wireless services.

- perform tasks of training twin models, twin operation and mining for management of twin pre-trained models.

- End devices and edge/cloud servers Participate in the Distributed machine learning model. Expect incentives and Contributes to their local model to update to the central server that aggregates them into a global model.

- To model and design incentives Stackelberg game model is used.

Twinning forensics and security

- Edge/cloud computing server, end-devices, twin-to-device interface and twin-twin interface, twin objects.

- Twin object attack and twin interface attack.

- Blockchain-based defence and video-based evidence system.

- Mobility of nodes causes challenges in implementing defence against attacks. Mobility-aware forensics schemes can be used.

- Security schemes for digital objects and edge cloud servers are different that of twin signaling.

Hardware-Software Co-design of Devices

- Focus is to design a physical interaction space for hardware and software co-design.

- Virtual prototyping using automated computer design, co-verification-based embedded systems, and high-level synthesis.

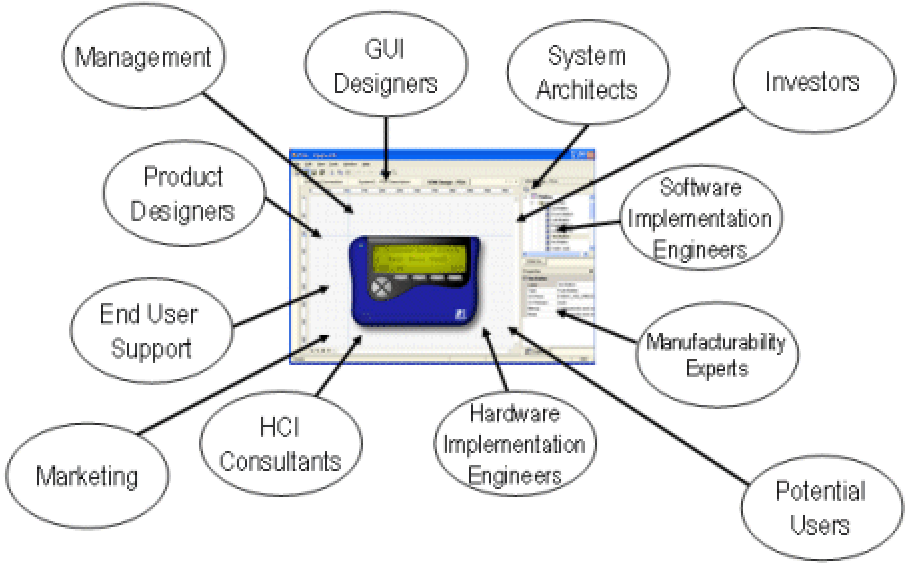

Fig. 5 stakeholder in virtual prototyping(site reference)

Efficient Chaining of twin objects

- Wireless systems are memory constraints and chaining of twin objects allows efficient memory allocation.

- Twin-based AR service may require multiple twin objects deployed at the network edge.

- For AR service combining multiple twins for services may incur communication and computing costs.

- Twin objects running at the edge and cloud are affected by latency: location of objects, network infrastructure, processing power, data volume, and computing power.

Energy-efficient Twining

- Twinning for wireless network involves computational task at the end devices ex: edge/cloud.
- Depends on operating frequency.
- Energy consumption is directly proportional to the operating frequency.
- Computing time is inversely proportional to the operating frequency.
- Depending on twin and wireless propagation characteristics and resources allocation and object association depends on matching theory.
- Energy resources act depending on block successive upper bond minimization(BSUM) and deep reinforcement learning.

Table 2. Summary of open Research Challenges And Solution Guidelines

Challenges	Taxonomy relevancy	Causes	Guidelines
Dynamic twins	Twin object prototyping	• Physical objects'/system dynamic states • Long design time of new twin objects	• Centralized machine learning-based twins • Distributed machine learning-based twins
Interoperability for twin object migration	Twin object deployment trends	• End-devices mobility • Strict latency constraints of the various services	• Open cloud/edge computing interface based design • Similar architecture for edge servers running the twin objects.
True prototyping of physical objects	Twin object prototyping	• Accurate estimation of twin objects measure • Dynamic nature of the physical systems	• Experimental modeling • 3D modeling • Data driven modeling
Incentive mechanisms for twinning	Incentive design	• End-devices consume their resources for training a distributed twin model. • Miners also perform mining for managing twin object pretrained models.	• Game theory-based incentive mechanism • Contract theory-based incentive mechanism • Auction-based incentive mechanism
Twinning forensics and security	Security and privacy	• Wide variety of players are susceptible to security attacks • Different players (e.g., edge server, routers) have different architecture	• Video-based forensics schemes • Blockchain-based forensics schemes • Mobility-aware forensics schemes

Table 3. Summary of open Research Challenges And Solution Guidelines

Challenges	Taxonomy relevancy	Causes	Guidelines
Efficient chaining of twin objects	Accessing twin objects	• Design a new twin is computationally expensive • Long design time for training, testing, and validation for newly designed twins • High cost associated with new twins design	• Optimization-based schemes • Game theoretic schemes • Machine learning-enabled schemes
Energy-efficient twinning	Twin objects access aspects	• Massive number of devices in twin-based wireless system will consume significant energy. • Transmission of data between devices and edge/cloud server consumes transmit power.	• Convex optimization-based scheme for devices computing resource optimization • Matching-based energy efficient resource allocation and association • Energy efficient power allocation using deep reinforcement learning and BSUM
Hardware-software co-design of devices	Design of physical devices	• Massive number of devices in digital twin-based wireless system will result in high cost (e.g., energy consumption, high processing delay)	• Virtual prototyping • High-level synthesis • Co-verification-based embedded systems

Conclusion

- Presents key design aspects and high-level framework.
  - Outlined currently available digital twin framework.
- Digital twin for wireless need proactive analysis and machine learning schemes.
  - Enables the wireless system to make on-demand decisions.
- Most promising technology for :
  - 6G and its diverse requirement for novel applications.

Referred site

- https://www.design-reuse.com/articles/11104/a-systemc-based-virtual-prototyping-methodology-for-embedded-systems.html

Thank you

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