Digital twins: applications and prospects in wireless communications

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Outline

Introduction to digital twins

Applications of digital twins in wireless communications

Prospects and challenges

Conclusions

Introduction

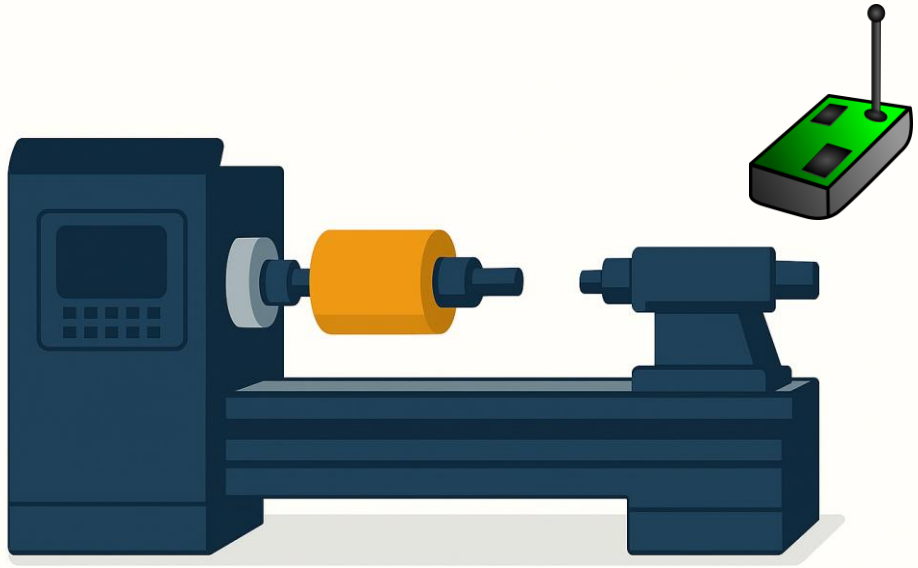
Era	Development	Highlights
1960s–1970s	Conceptual Origins	NASA used mirrored systems to simulate spacecraft behavior during Apollo missions
2002	Formal Definition	Dr. Michael Grieves introduced the term “Digital Twin” in product lifecycle management
2010s	Industrial Adoption	Widely adopted in manufacturing, aerospace, and automotive sectors for predictive maintenance
2020s	Cross-Industry Expansion	DTs integrated into healthcare, smart cities, energy, and transportation with real-time wireless data
Future (2030s+)	Human-Centric DTs	AI-powered, personalized DTs for individuals, digital societies, and sustainable ecosystems

Introduction

- **What are digital twins (DTs)?**
- Real-time virtual replica of a physical system
- Continuously updated with live sensor data
- Enable monitoring, prediction, and optimization
- Bidirectional communication with the physical asset
- Used across the entire lifecycle

Digital Twins:

- Virtual replicas of physical systems
- ‘Synchronize’ replicas using data from physical systems



Sensor Data →

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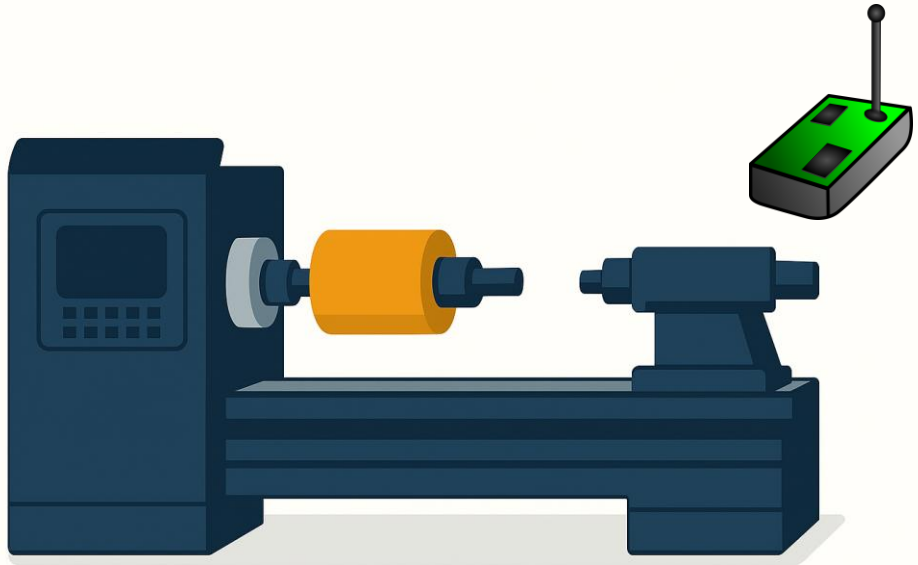
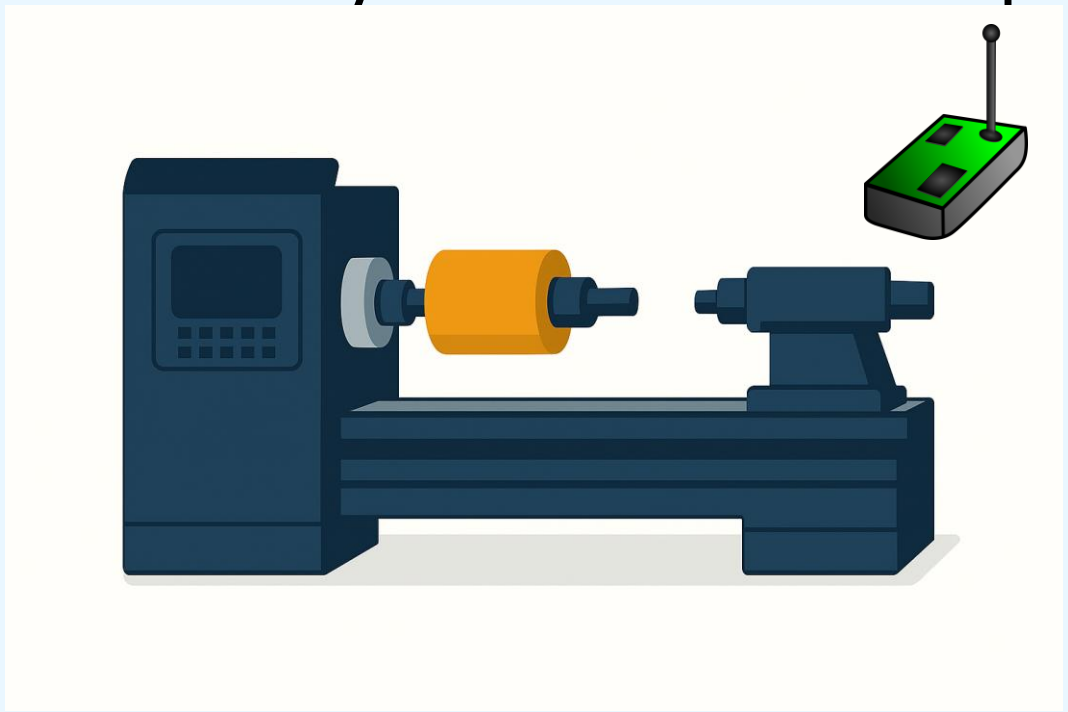


Sensor Data →

Digital Twins:

- Virtual replicas of physical systems
- Lower synchronization frequency



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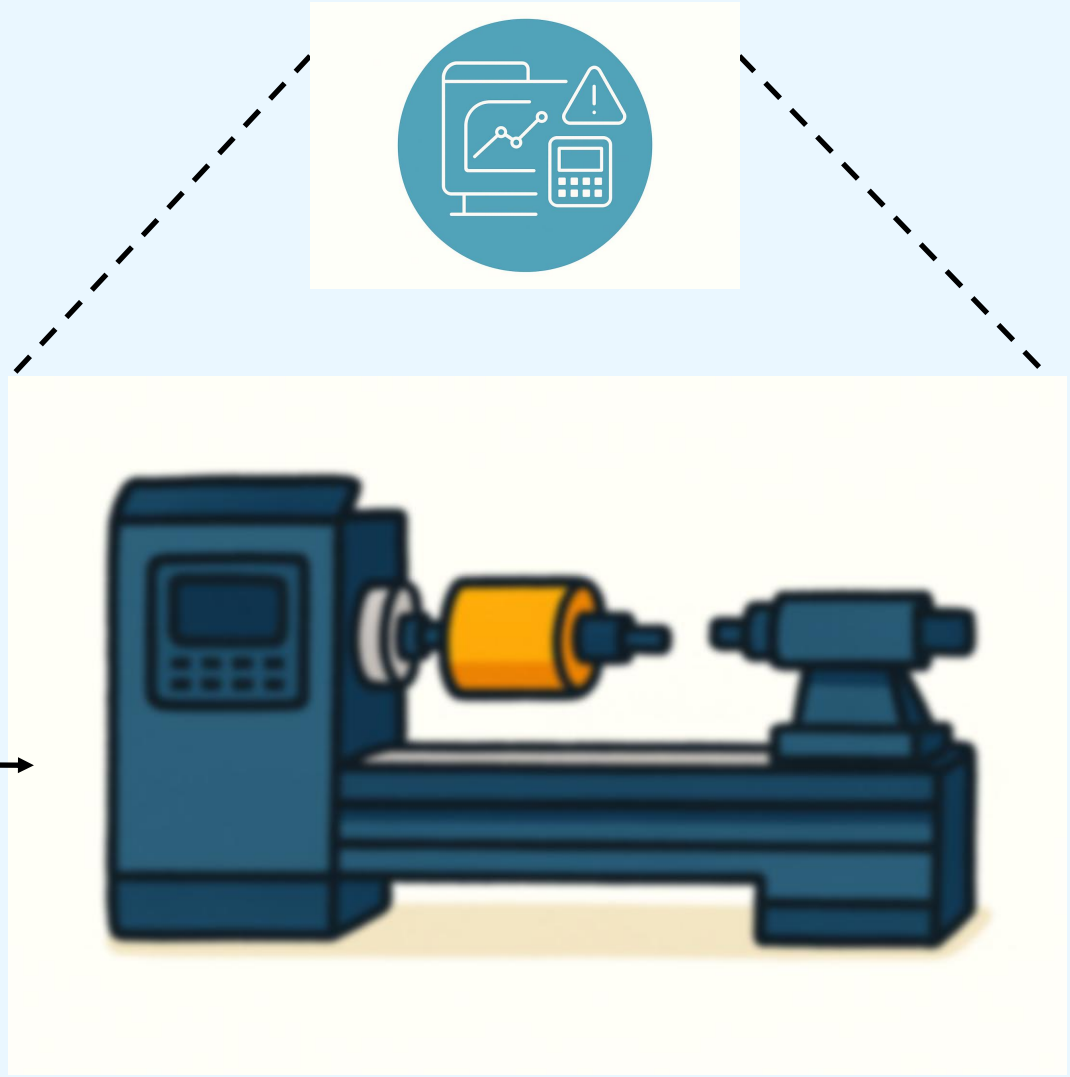

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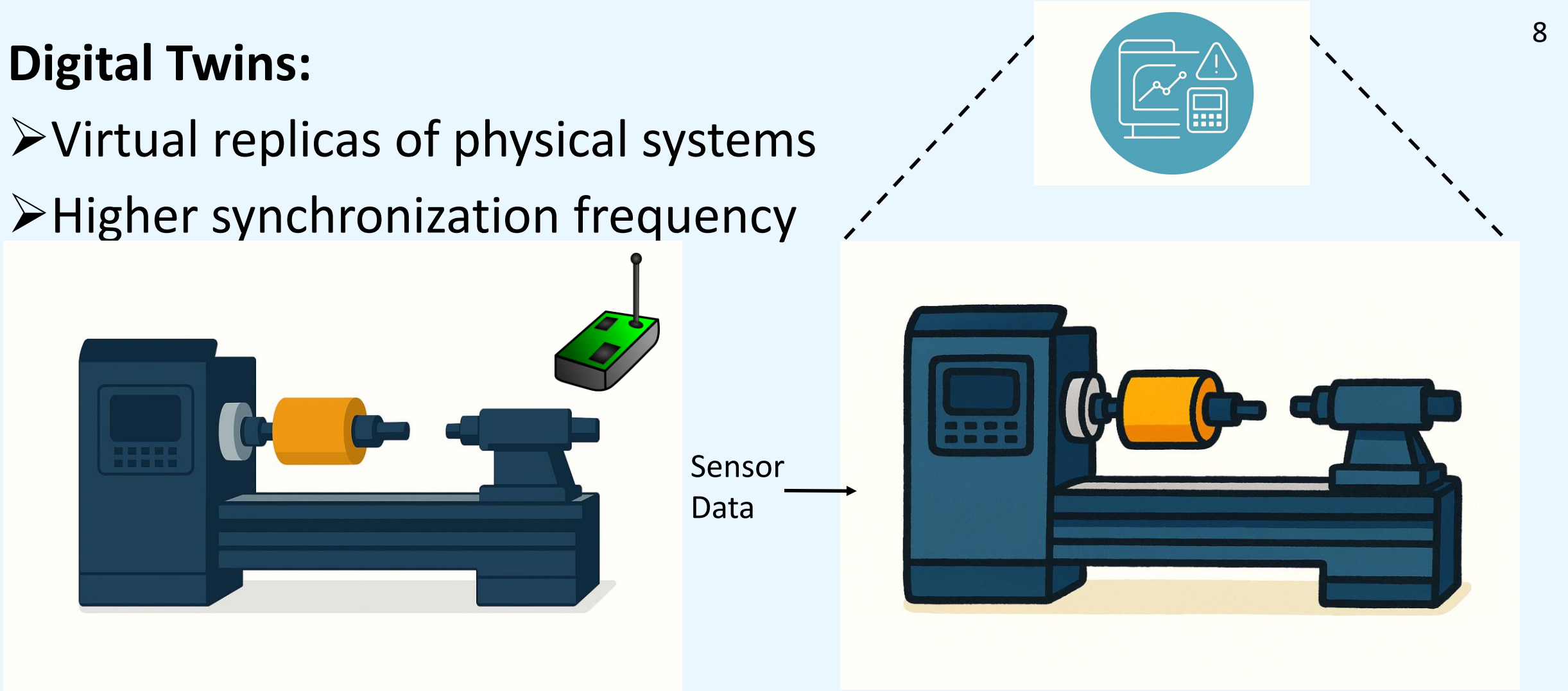

Digital Twins:

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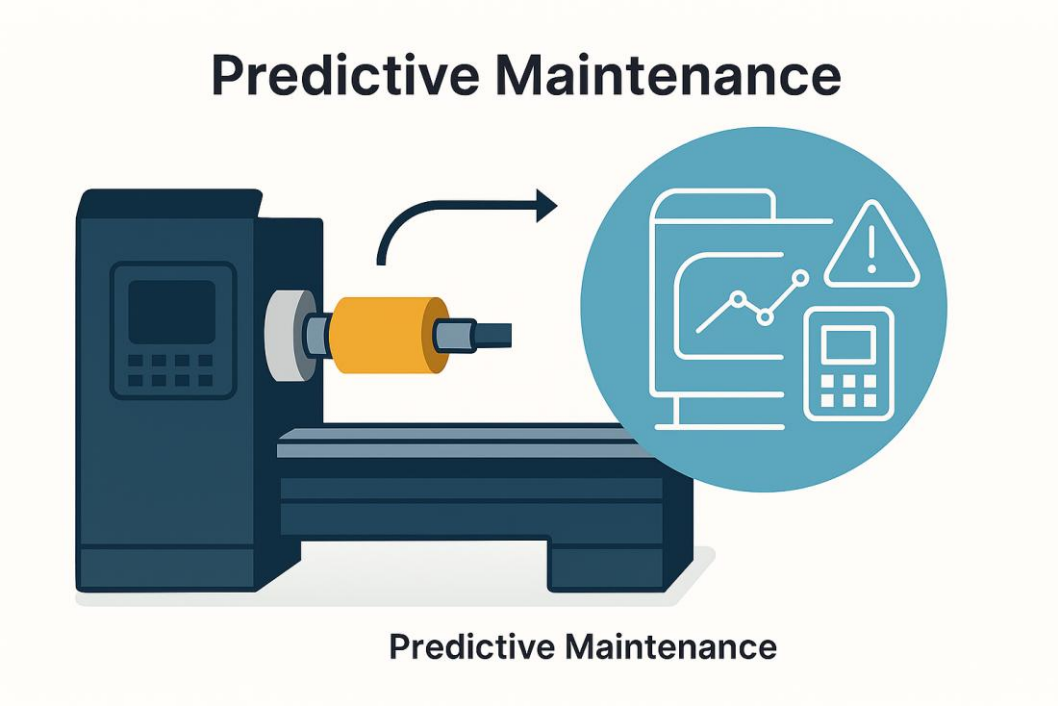

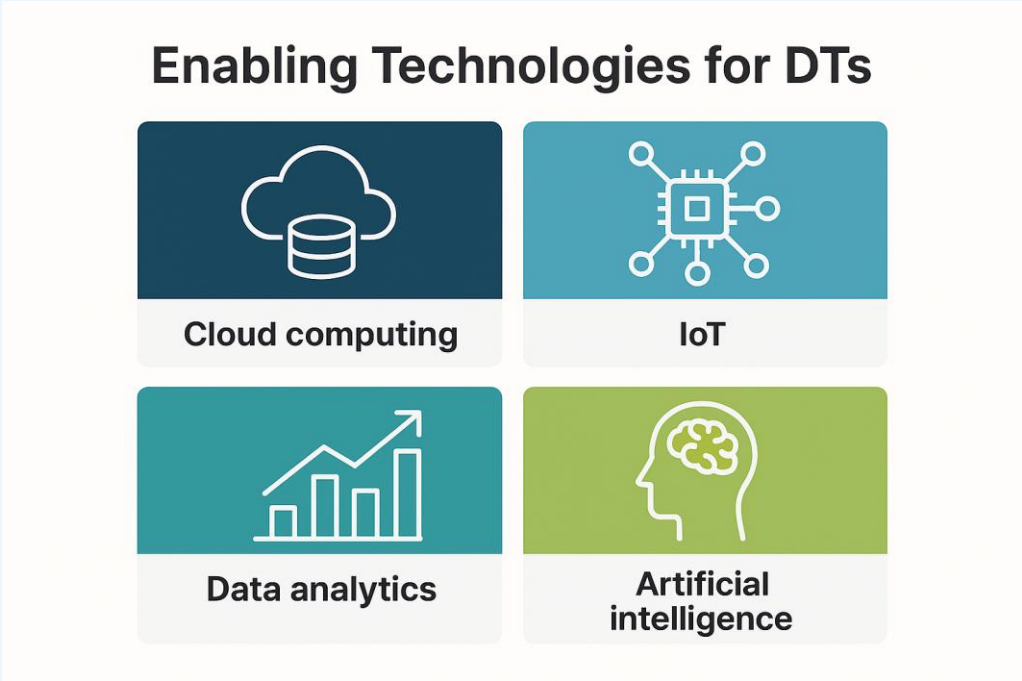

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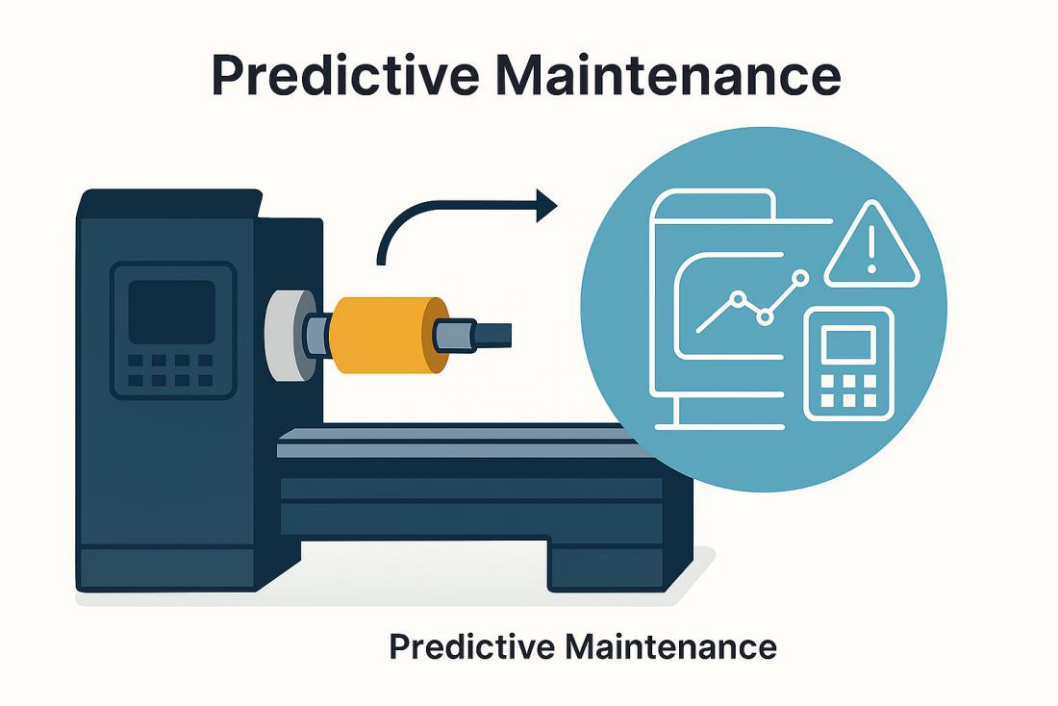
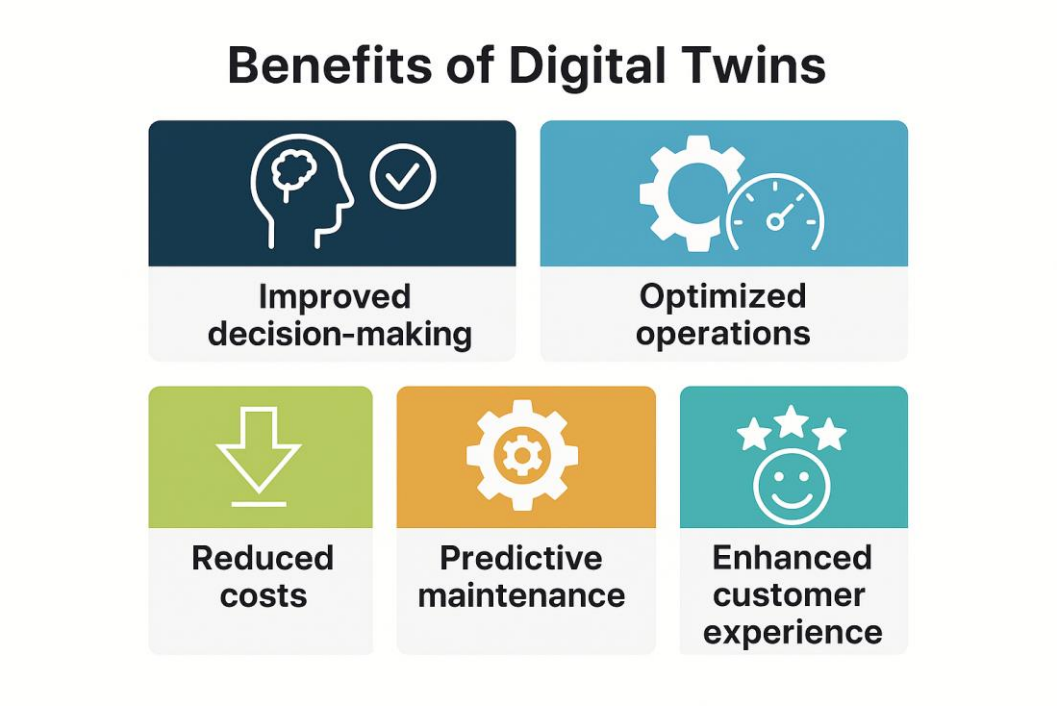
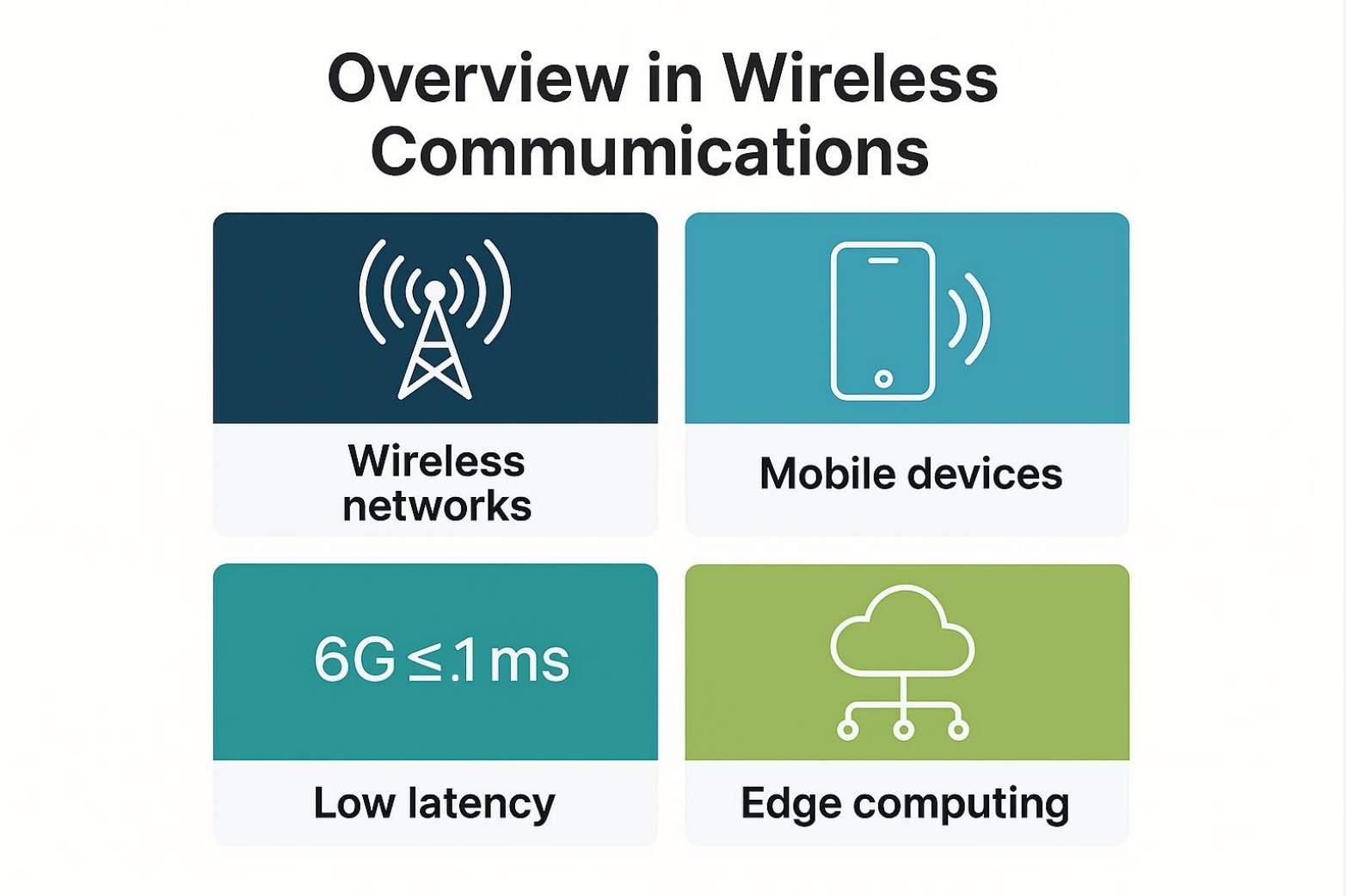




Differences between DTs, simulators and emulators

Feature	Digital Twins	Simulators	Emulators
Live Data Integration	✅ Yes	❌ No	❌ No
Real-time Sync	✅ Yes	❌ No	❌ No
Lifecycle Coverage	✅ Full lifecycle	⚠️ Design phase only	⚠️ Testing phase only
Bidirectional Feedback	✅ Yes	❌ No	❌ No
Use Case	Monitoring, prediction	Hypothetical modeling	Compatibility testing

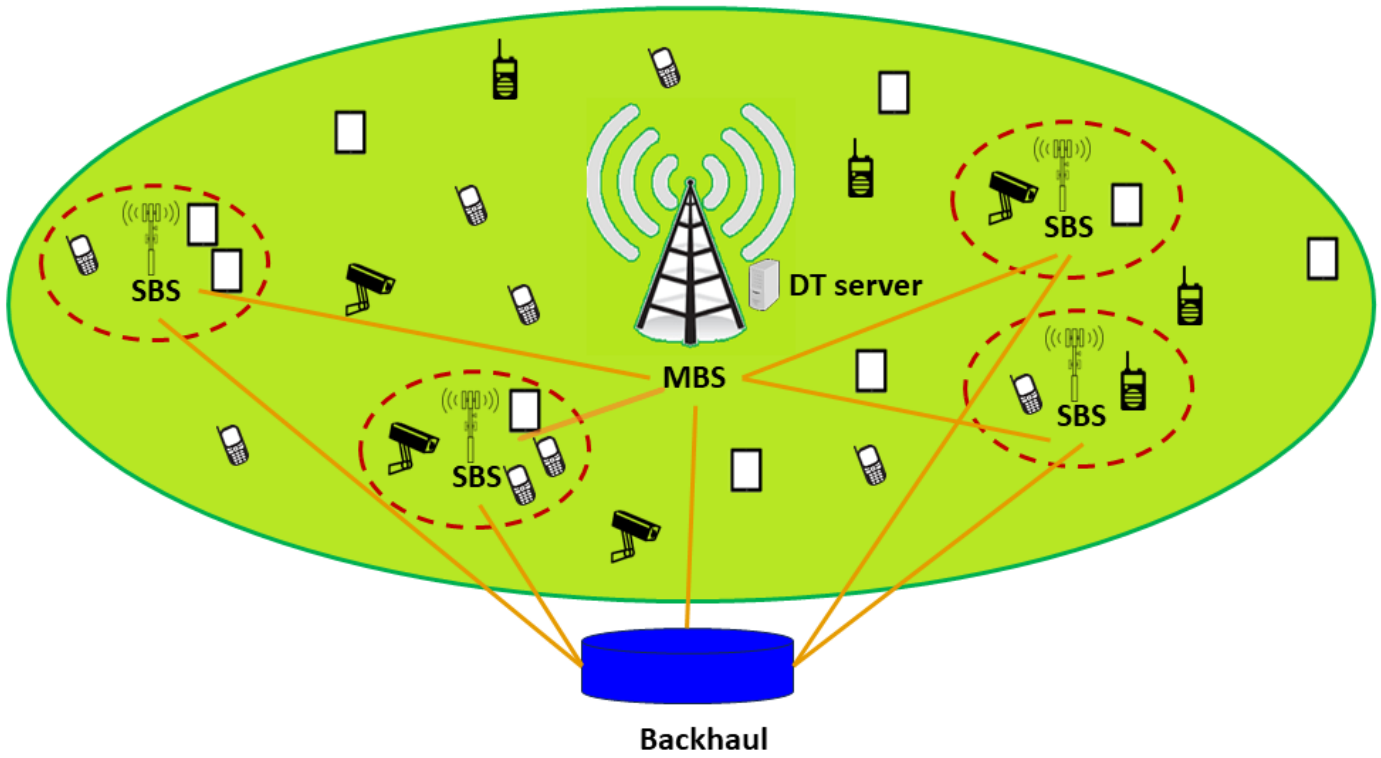
Applications of DTs in wireless communications



Applications of DTs in wireless communications

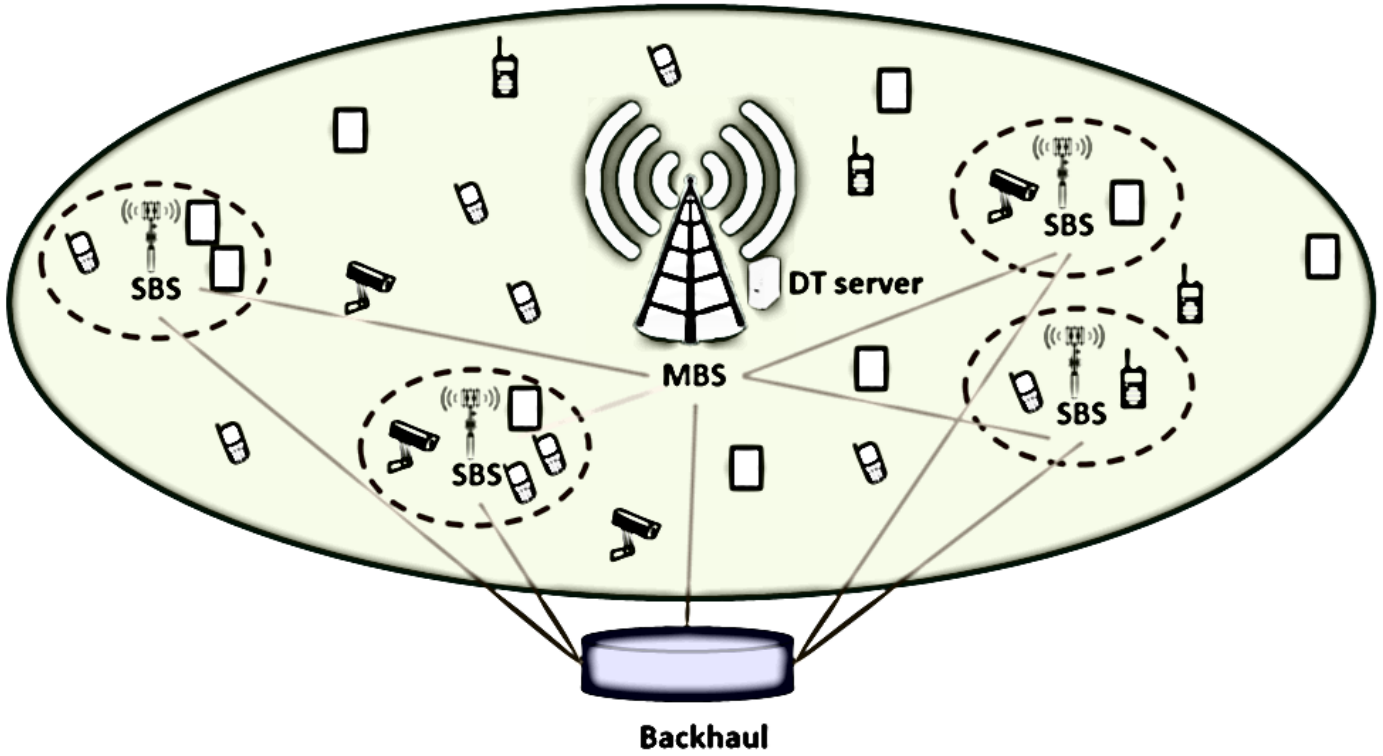
- Digital twins create virtual models of wireless networks, including components like base stations, user equipment, and radio environments
- They support 5G evolution and 6G development by simulating complex architectures, predicting behaviors, and enhancing security/communication technology
- Key benefits: Real-time monitoring, optimization, and innovation in heterogeneous, large-scale networks

Heterogenous Wireless Network



A. S. Khwaja, N. T. Vo, W. -P. Nwadiugwu, I. Woungang and A. Anpalagan, "Digital Twin-Assisted Load-Balanced User Association and AoI-Aware Scheduling in IoT Networks," *IEEE Access*, vol. 13, pp. 95888-95910, 2025.

Digital Twin



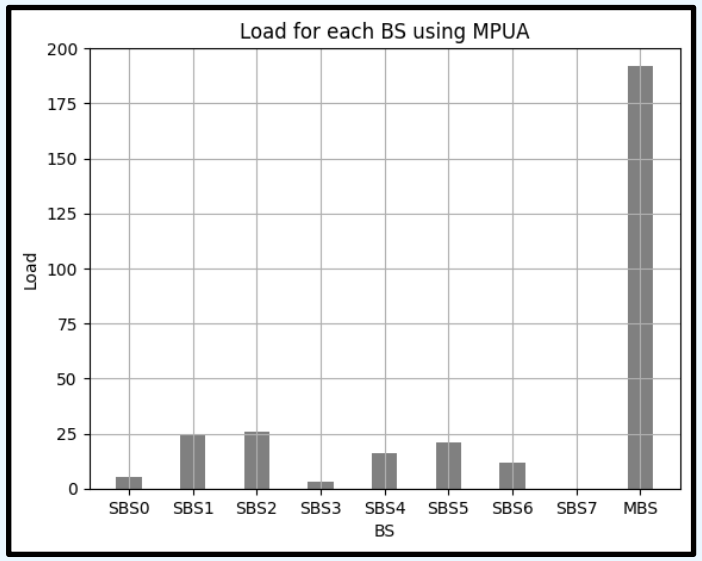
DTs for Intelligent Decision-Making

- Maintain global view of network resources and constraints
- Enable joint optimization of association and scheduling
- Reduce radio access network disruptions

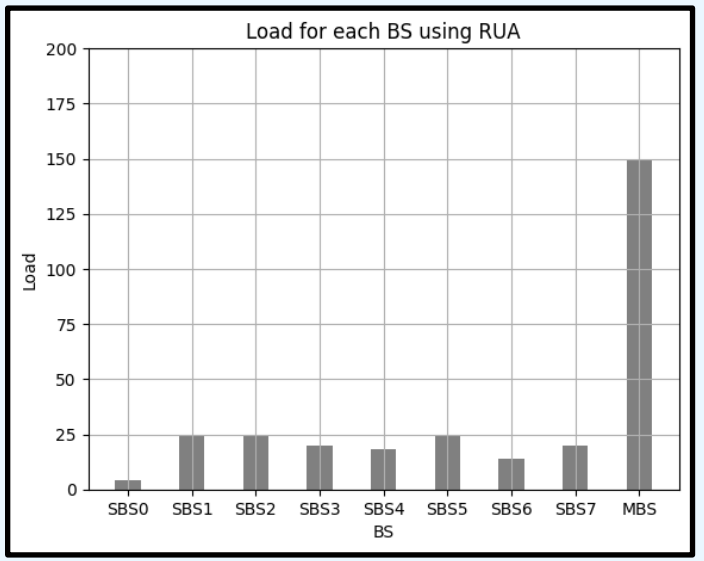
Applications of DTs in wireless communications

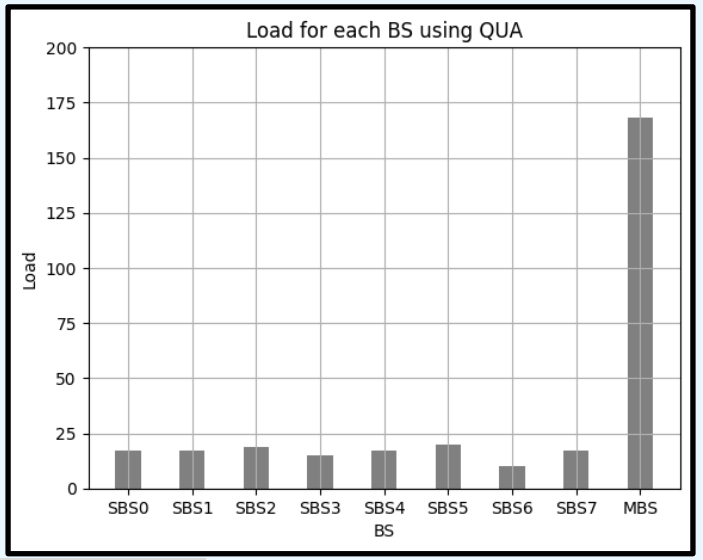
- Digital twins can provide load-balanced user-base station association services
- Modeling of the propagation environment
- Model network topology and user distribution
- Balance loads across MBS and SBSs
- Improve QoS by reducing congestion

Applications of DTs in wireless communications

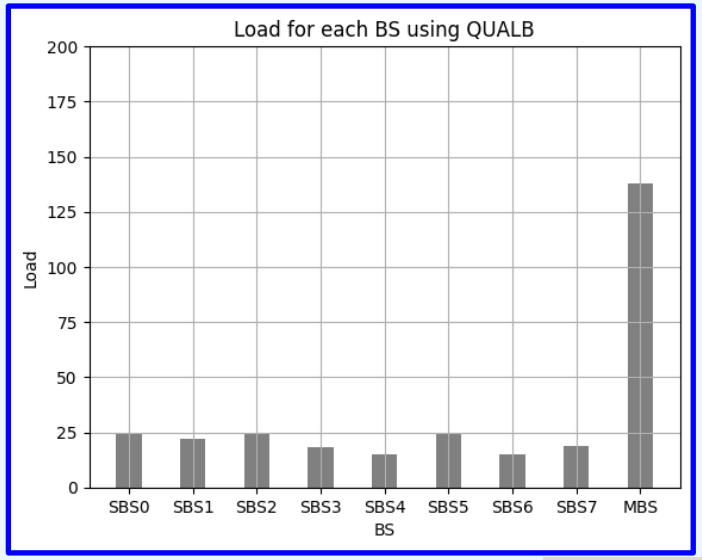


Reducing load at MBS
&
balancing load at SBSs





Traditional
vs.
DT-assisted



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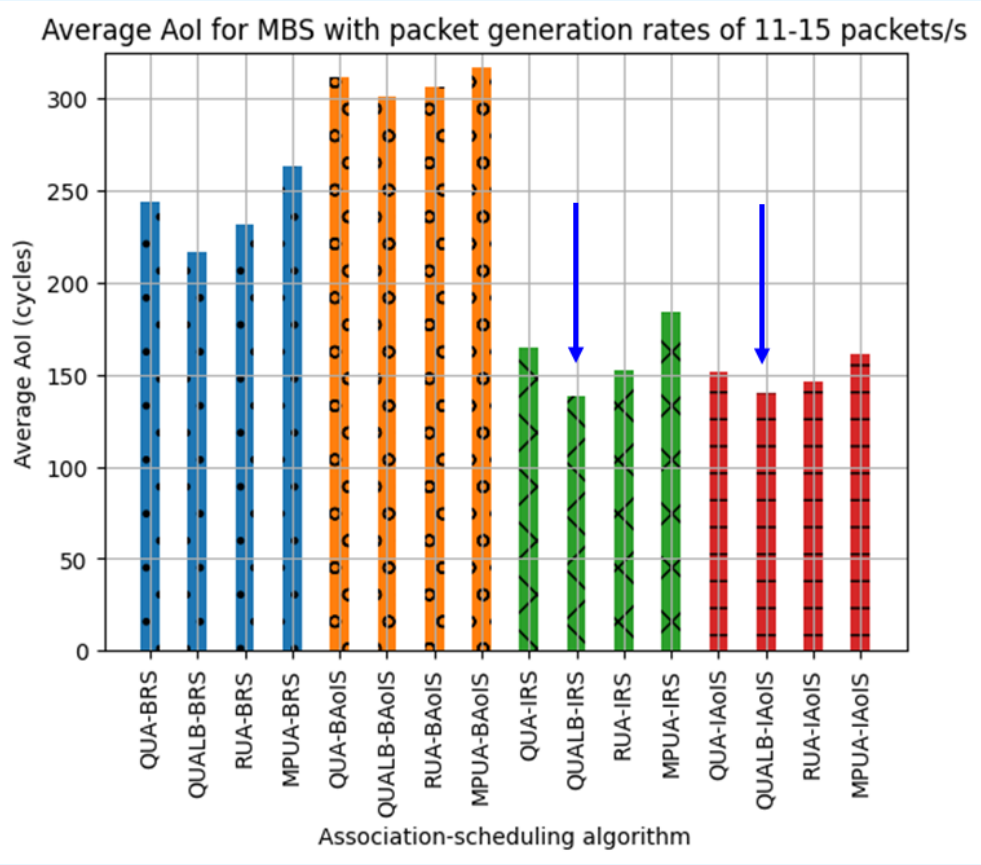
Applications of DTs in wireless communications

- DTs can provide age of information (AoI)-aware scheduling
  - Prioritize timely data transmission
  - Minimize AoI across network nodes
  - Enhance responsiveness in time-critical applications

Traditional vs. DT-assisted



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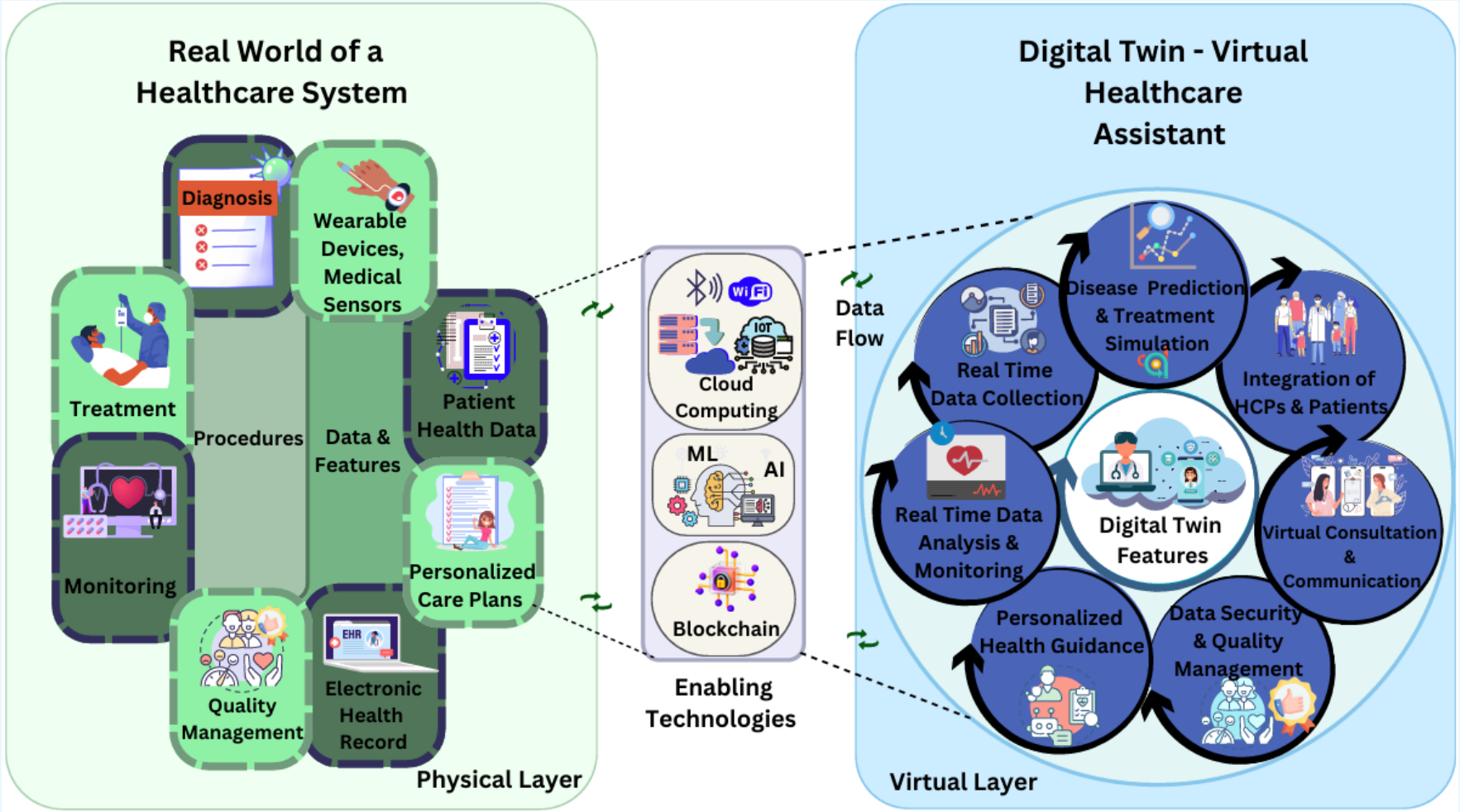
Applications of DTs in wireless communications



A. Huzzat, A. Anpalagan, A. S. Khwaja, I. Woungang, A. A. Alnoman, A. S. Pillai, A comprehensive review of Digital Twin technologies in smart cities, Digital Engineering, Volume 4, 2025.

Applications of DTs in wireless communications

- DTs in medical body-area networks
- Simulate patient conditions and monitor health metrics
- Enhance reliability and safety in wireless medical systems
- Support real-time diagnostics and emergency response

H. B. Eldeeb, S. Naser, L. Bariah, S. Muhaidat and M. Uysal, "Digital Twin-Assisted OWC: Toward Smart and Autonomous 6G Networks," *IEEE Network*, vol . 38 no. 6,pp . 153-162, Nov. 2024.
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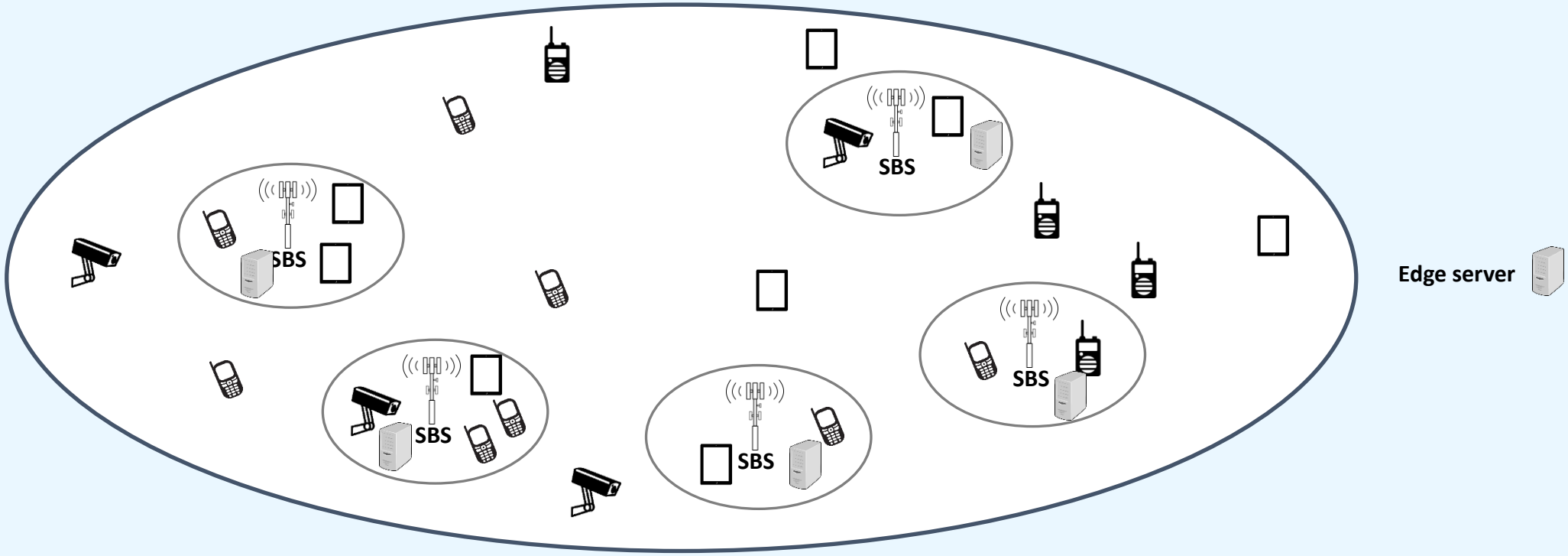
Applications of DTs in wireless communications

- DTs in autonomous aerial vehicles (AAVs)
  - Predict flight paths and optimize task allocation
  - Improve communication efficiency in AAV-assisted networks
  - Enable AoI-aware scheduling for real-time updates

Applications of DTs in wireless communications

- DTs in vehicular networks
  - Model vehicle behavior and traffic flow
  - Support low-latency communication for autonomous driving
  - Enhance safety through predictive analytics

Applications of DTs in wireless communications



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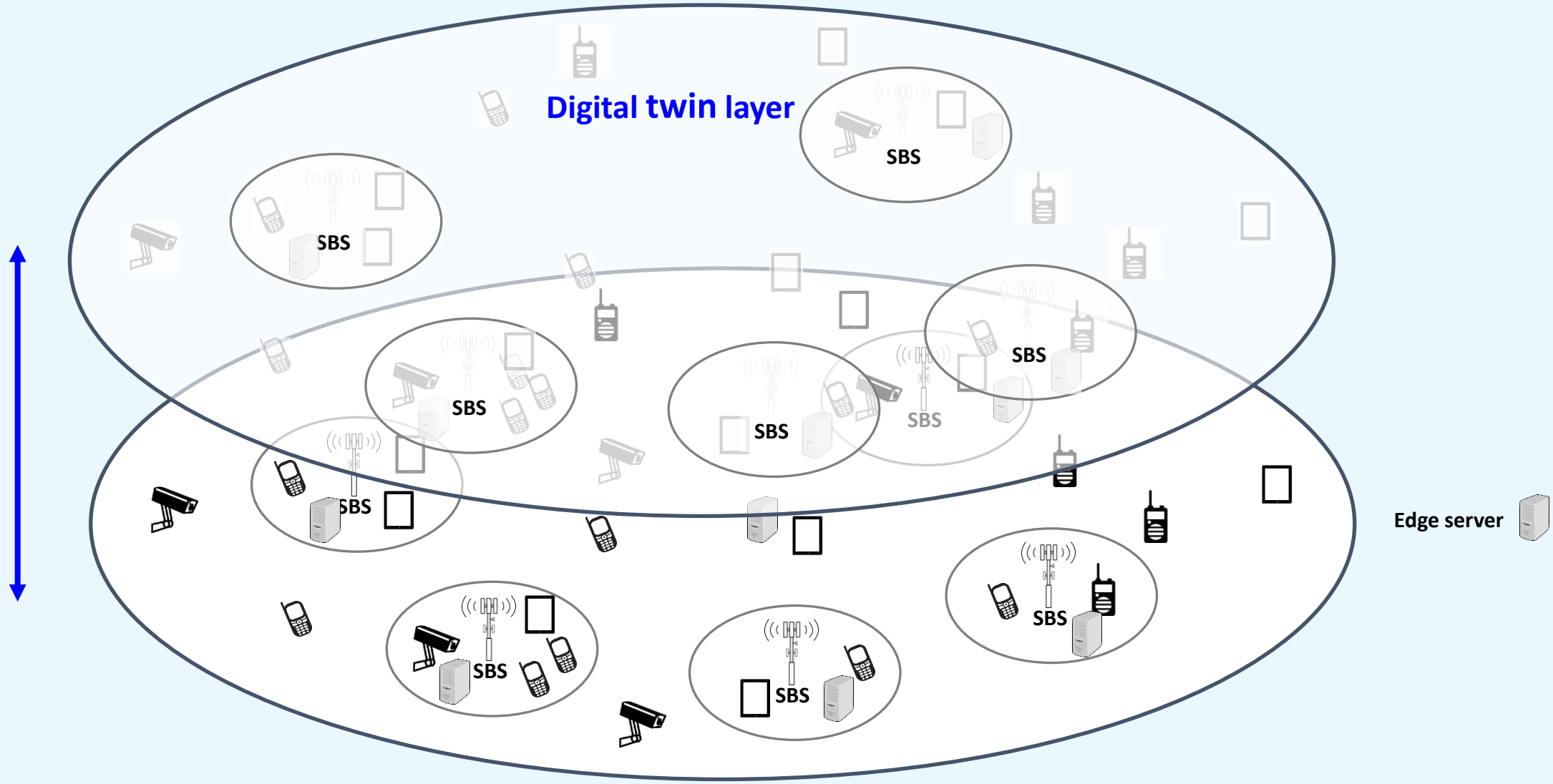
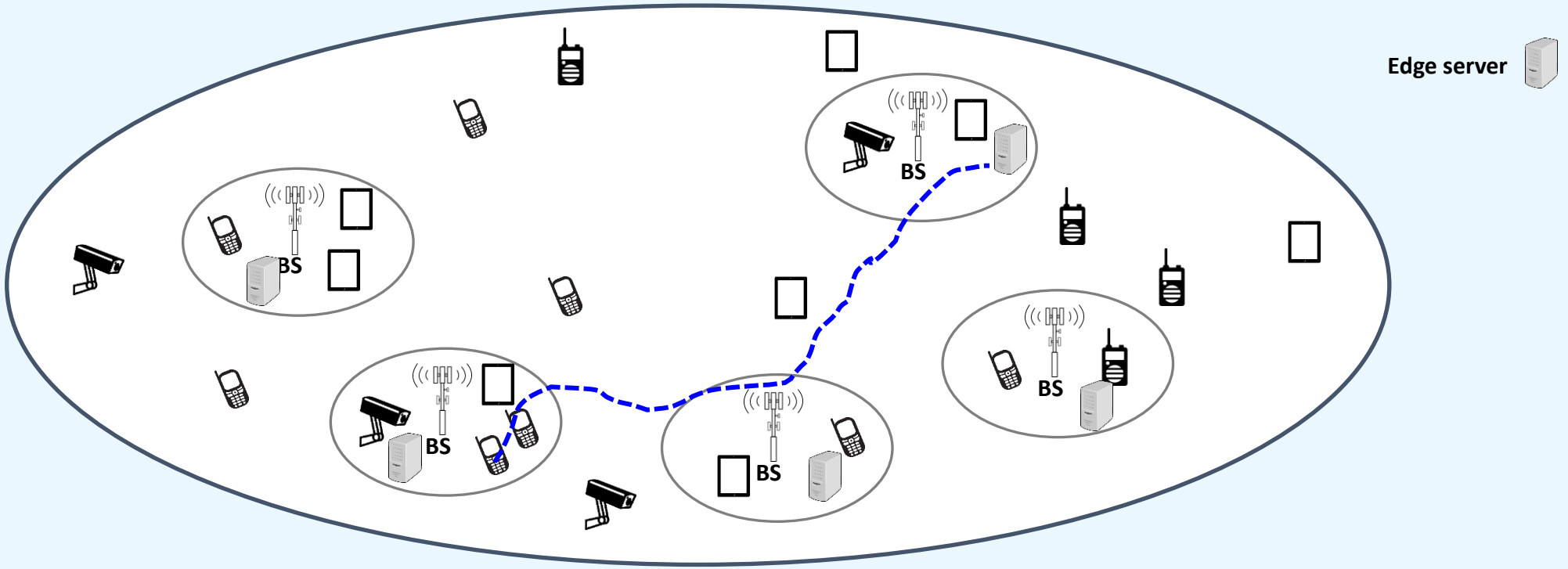


Applications of DTs in wireless communications

- DTs at the edge in 6G networks
  - Offload tasks to edge servers using DT replicas
  - Reduce latency and improve resource allocation
  - Enable decentralized decision-making

W. Sun, H. Zhang, R. Wang and Y. Zhang, "Reducing Offloading Latency for Digital Twin Edge Networks in 6G," *IEEE Transactions on Vehicular Technology*, vol. 69, no. 10, pp. 12240-12251, Oct. 2020.

Applications of DTs in wireless communications



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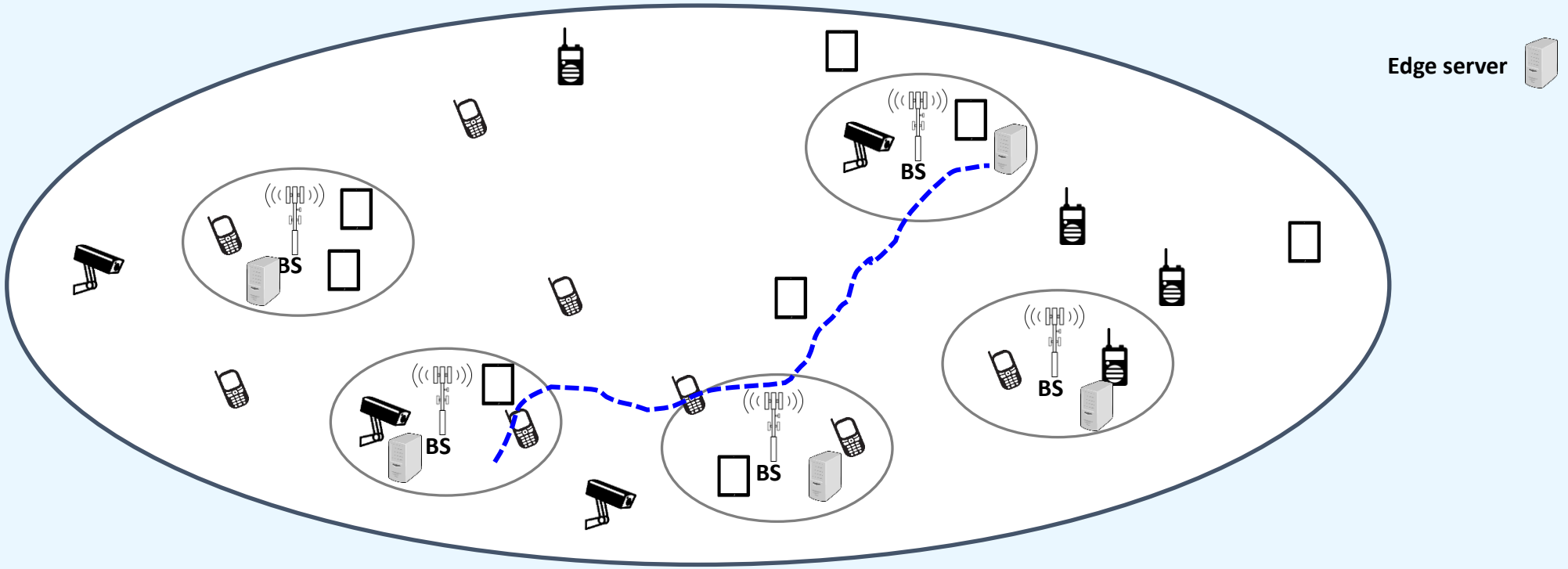

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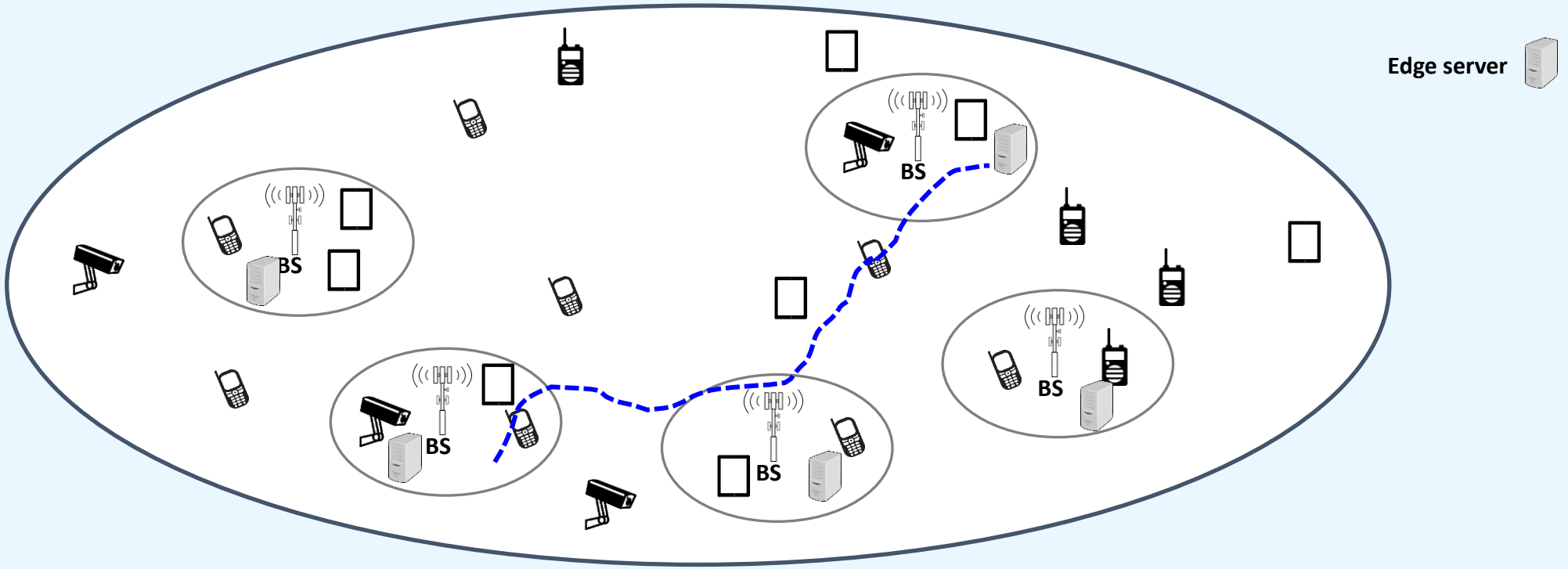
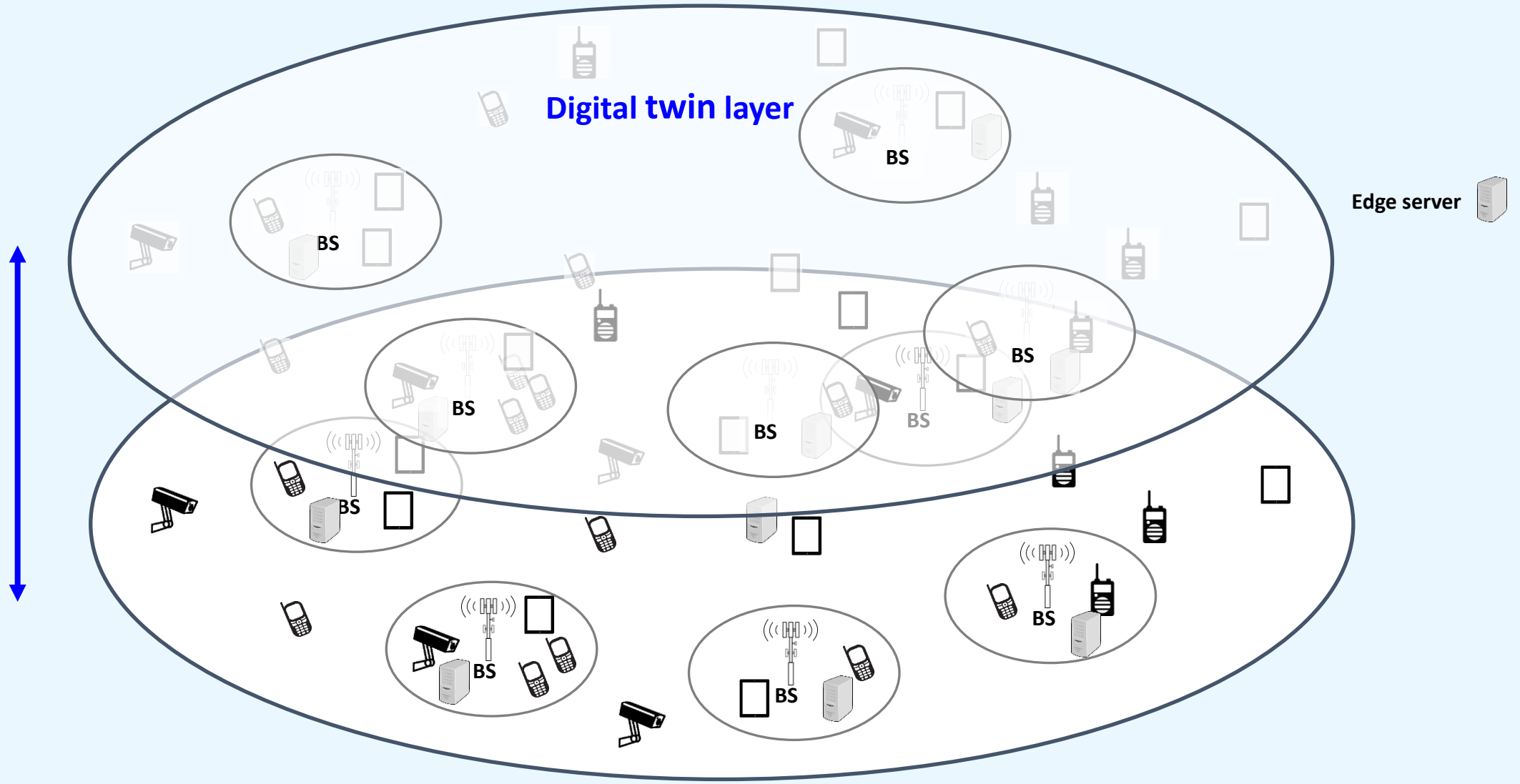


Applications of DTs in wireless communications

- DTs for base station sleep management
- Predict delay risks in base station sleep cycles
- Optimize energy efficiency without compromising performance
- Support dynamic network adaptation

M. Masoudi, E. Soroush, J. Zander and C. Cavdar, "Digital Twin Assisted Risk-Aware Sleep Mode Management Using Deep Q-Networks," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 1, pp. 1224-1239, Jan. 2023.

Prospects and Challenges



Prospects and Challenges

- Implementations*:
  - RAN DT 2.0: A DT allows experiments to optimize power levels while maintaining coverage and QoS
  - Site DTs: Quick and efficient maintenance and expansion of networks
  - Subscriber DTs: Modeling complex scenes using 3D gaming model and propagation models

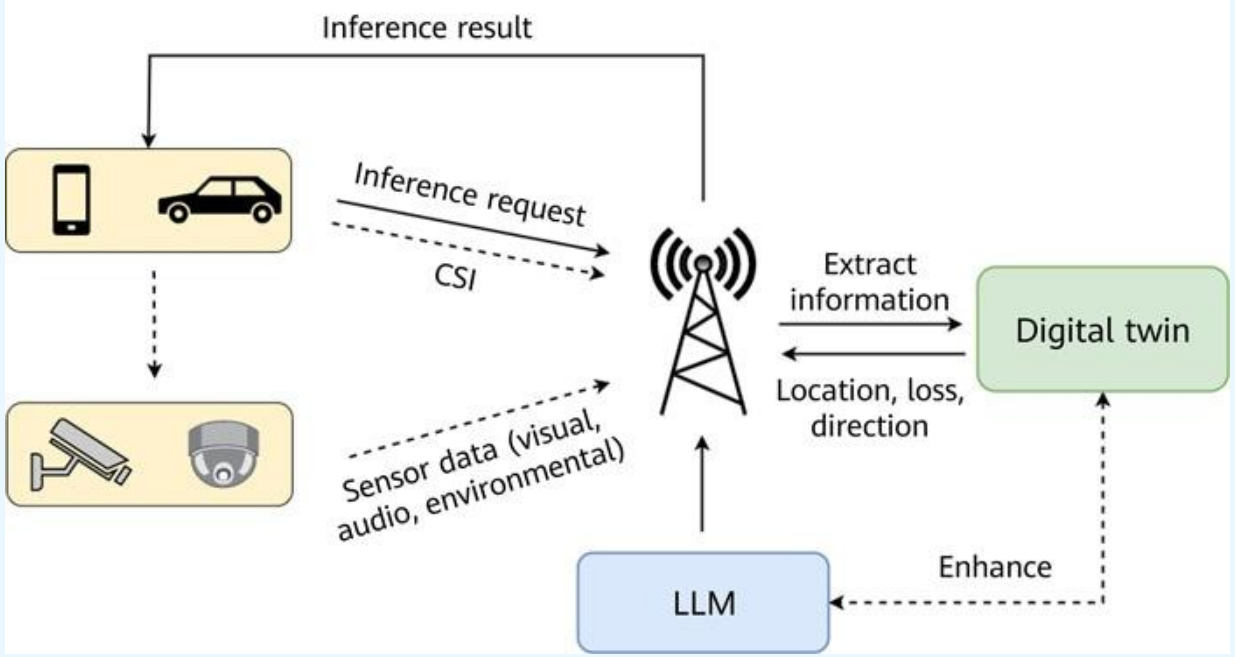
*https://www.ericsson.com/en/blog/2022/3/what-are-digital-twins-three-real-world-examples

Prospects and Challenges

- Implementations*:
  - New service introduction, such as XR user experience within live commercial networks
  - Network quality and efficiency improvement, such as high-speed railways and ports
  - Nvidia aerial omniverse DTs, research and development of 5G and 6G wireless system

*https://www.zte.com.cn/ → Wireless network digital twin as a service technology white paper
*https://developer.nvidia.com/blog/nvidia-aerial-omniverse-digital-twin-boosts-development-of-ai-native-wireless-and-deployment-flexibility/

Semantic Digital Twins*



ISAC and LLMs can be integrated to establish a semantic DT, enhancing wireless communications and AI inference efficiency

*https://www.huawei.com/en/huaweitech/future-technologies/semantic-digital-twins-wireless-communication-llm-inference

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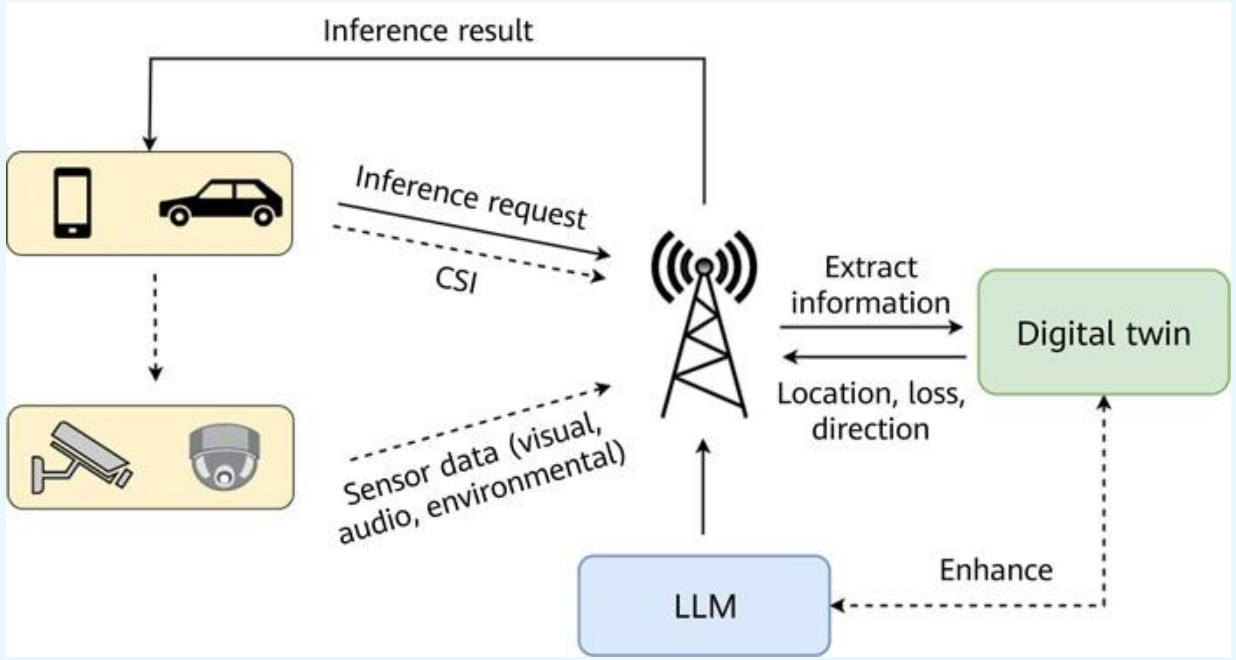
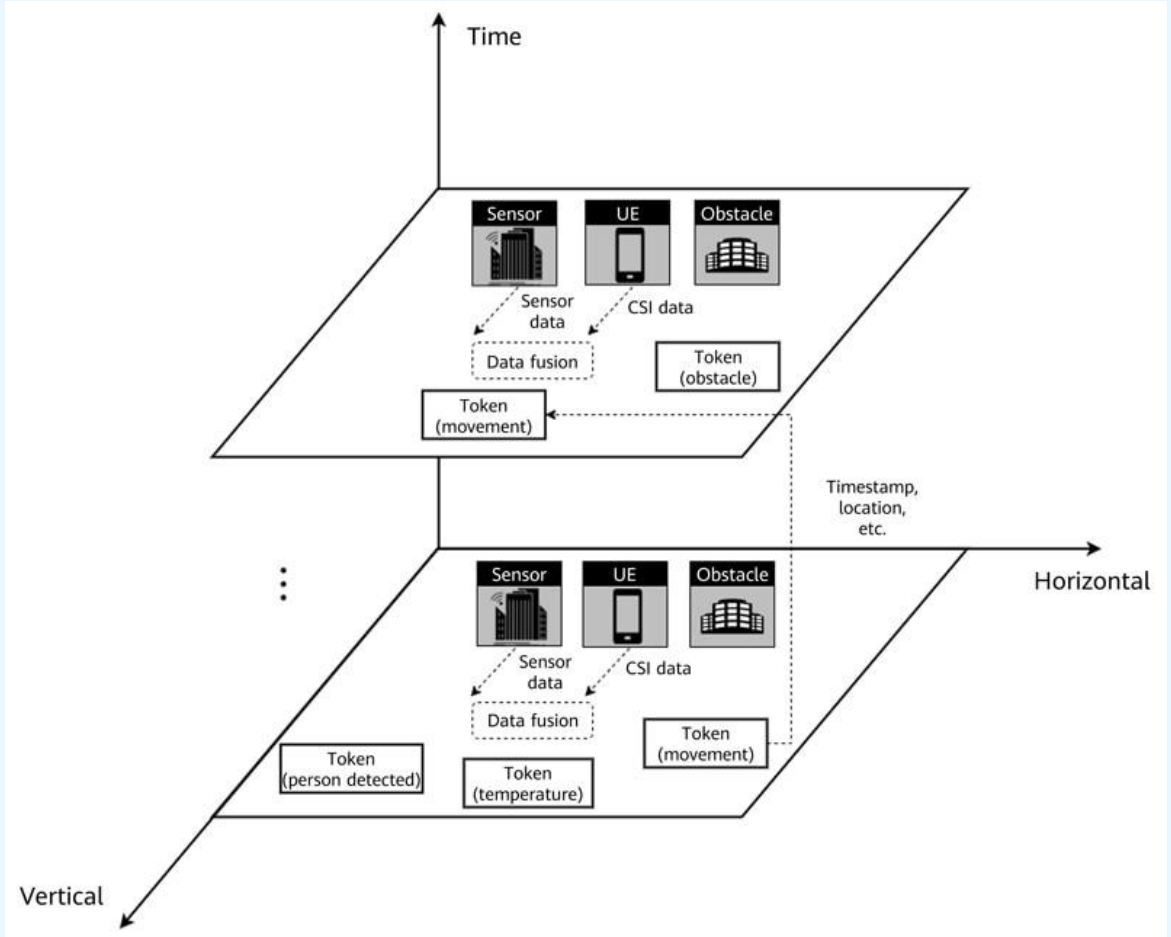
Semantic Digital Twins*





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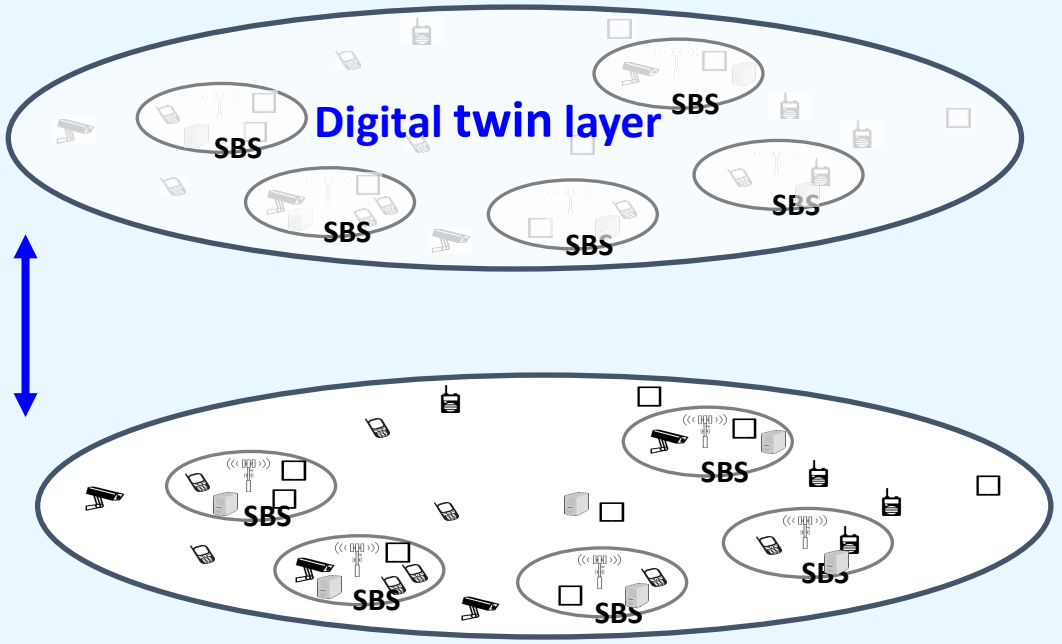
*https://www.huawei.com/en/huaweitech/future-technologies/semantic-digital-twins-wireless-communication-llm-inference

Prospects and Challenges

- Data privacy and security concerns
- Interoperability issues
- Complexity and scalability
- High implementation costs
- Synchronization and DT accuracy
- Use in real-time applications



Conclusions

- Digital twins are transforming wireless communications by enabling simulation, optimization and predictive capabilities.
- Key impacts: Faster innovation, reduced costs, improved reliability, and preparation for new wireless networks.
- As technology evolves, their role in AI-driven networks will expand.