Towards an Internet of Federated Digital Twins (IoFDT) for Society 5.0: Fundamentals and Experimentation

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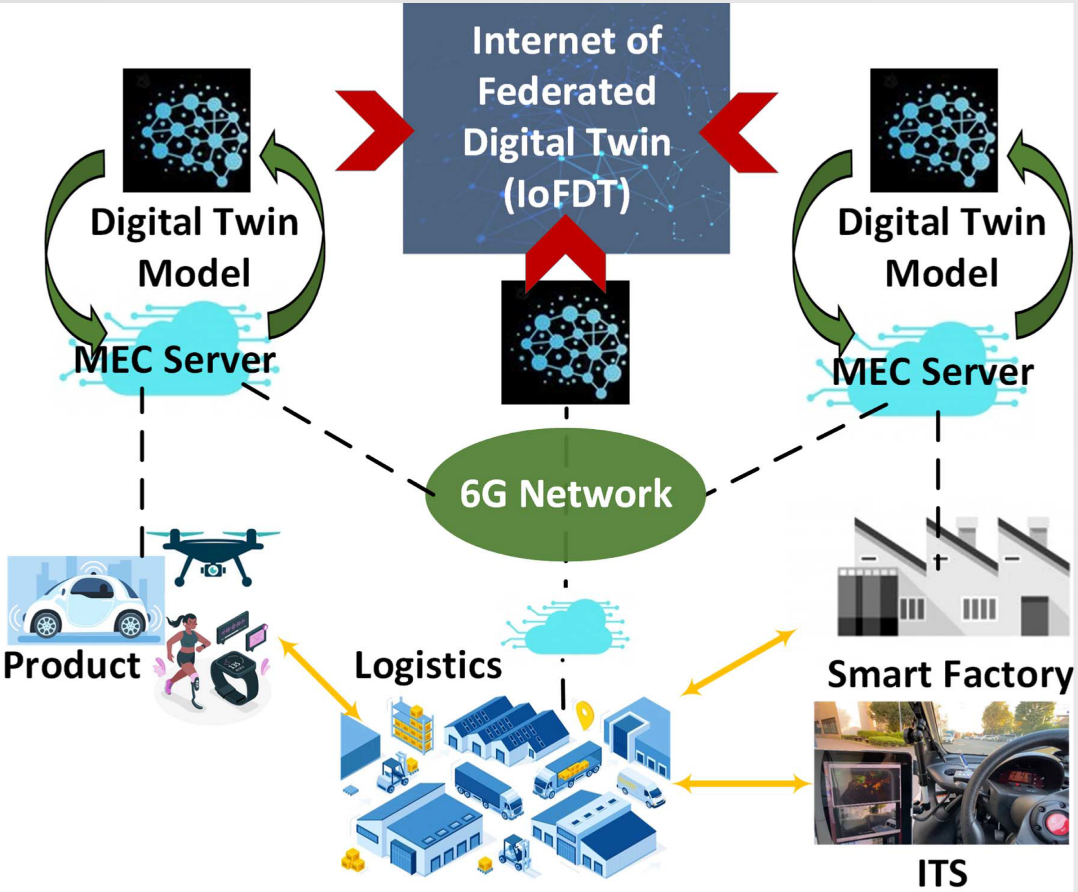
Towards an Internet of Federated Digital Twins (IoFDT)



- Digital Twins **for** 6G vs Digital Twins **over** 6G
- Building an Internet of Federated Digital Twins
  - ➢ Brings in many fundamental questions across communications, computing, and AI
- Synergies with emerging concepts (e.g., metaverse)

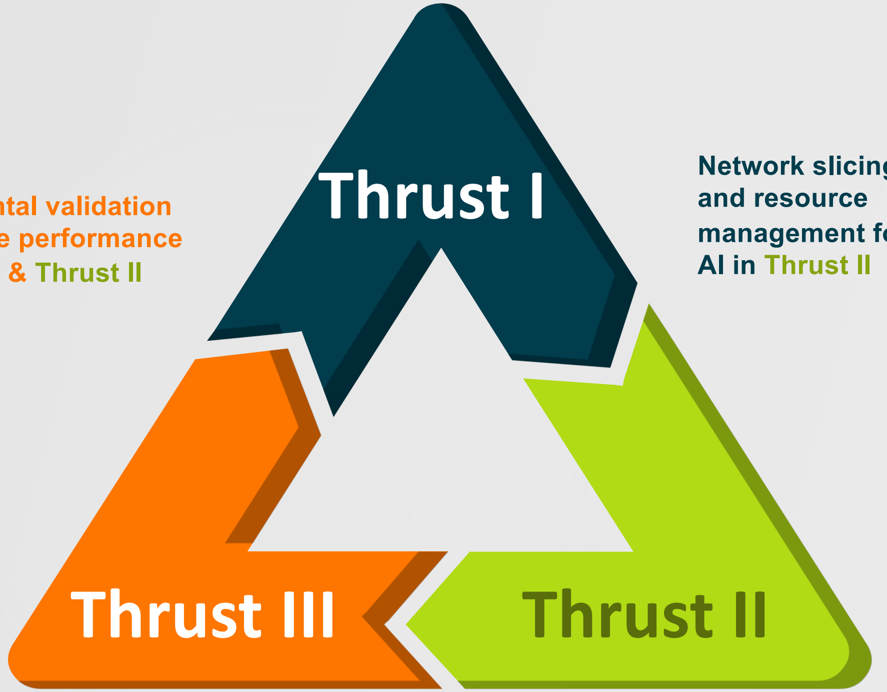
Research Thrusts

END-TO-END WIRELESS NETWORK ORCHESTRATION AND OPTIMIZATION FOR ENABLING IOFDT

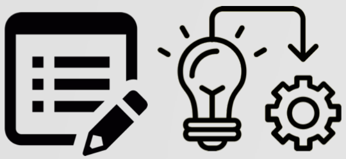
Designing network slicing and resource management protocols to address the challenges of IoFDT

Resource management

Experimental validation to enhance performance of Thrust I & Thrust II



Network slicing and resource management for AI in Thrust II



DEVELOPMENT OF PROGRAMMABLE IOFDT PLATFORM AND DEMONSTRATION OF DTS

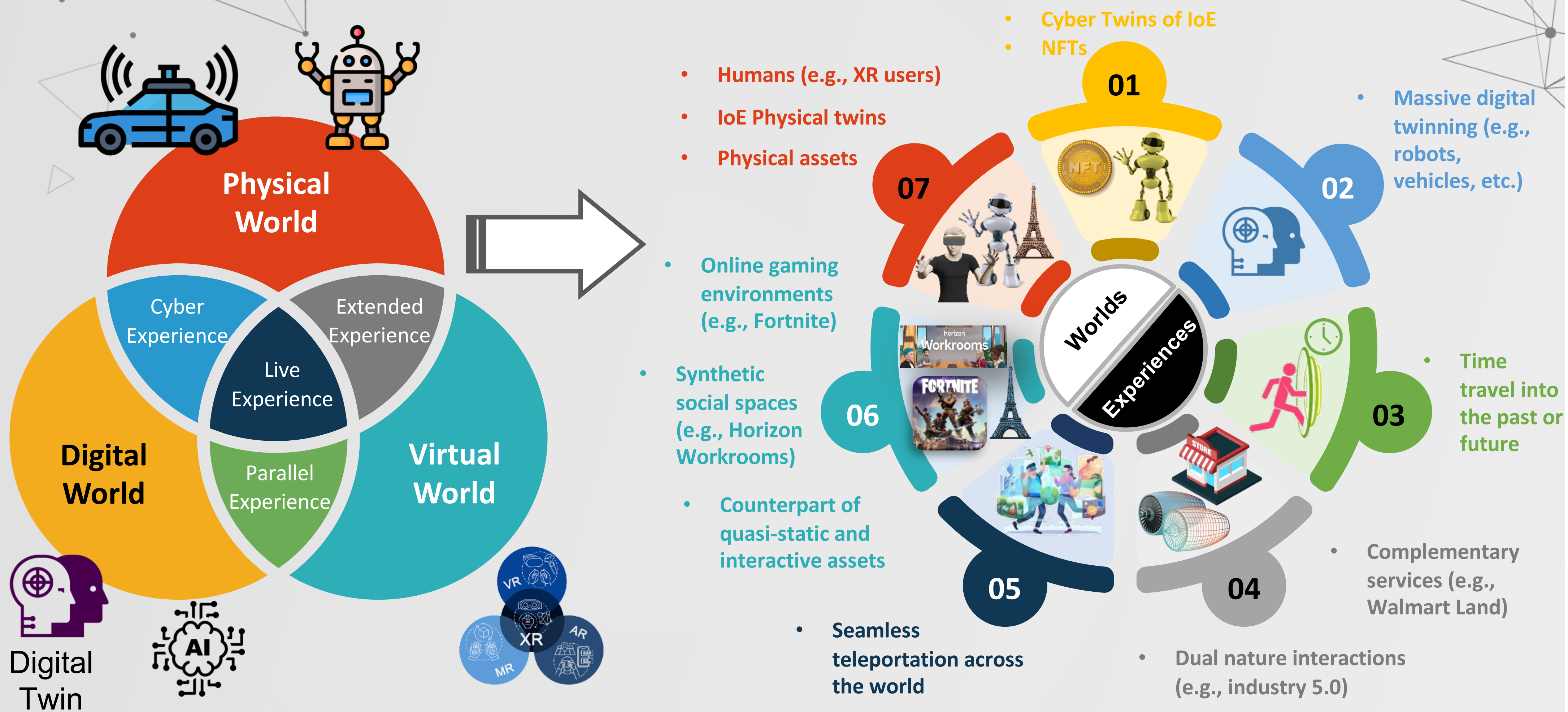
Implementing the designed schemes in Thrusts I and II over an advanced testbed at Tokyo Institute of Technology

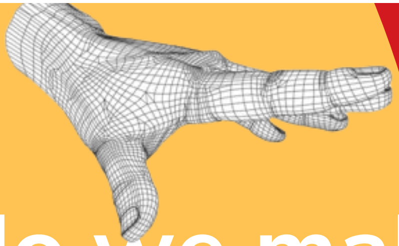
PROGRAMMABLE, CONTINUAL LEARNING FOR EFFICIENT NETWORK-AWARE TWINNING

Designing ML solutions to enable energy-efficient, network-aware twinning across an IoFDT

Continual AI algorithms that tradeoff *communication, computing, energy, and accuracy* for implementation in Thrust III

Seven Digital World Experiences within IoFDT





How do we make the physical and digital world interact?

Decentralize the Limitless Metaverse

Synchronize Sub-metaverses

How do we orchestrate sub-metaverses and digital twins in a limitless metaverse?

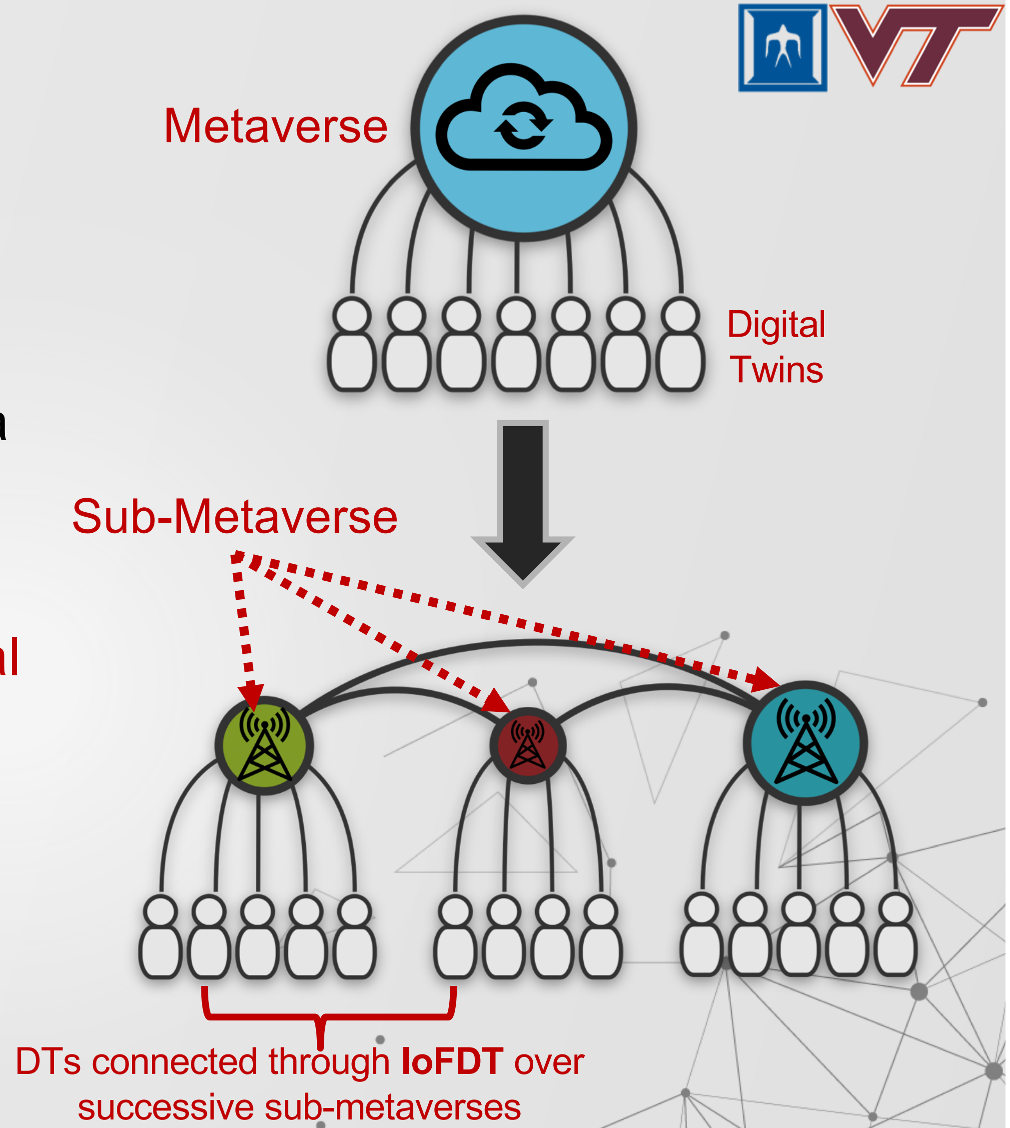
Towards a Decentralized Metaverse: Synchronized Orchestration of Digital Twins and Sub-Metaverses

Omar Hashash, Christina Chaccour, Walid Saad,
Kei Sakagushi, and Tao Yu

Under review and available on:
https://arxiv.org/abs/2211.14343

Introduction

- Digital twins (DTs) are key players in the metaverse
- Shifting DTs to the edge ➔ demand for a decentralized edge-enabled metaverse
- Metaverse decomposed into sub-metaverses, i.e., digital replica of physical spaces, that are rendered at the edge
- **Challenge:** How can we harmonize the interoperability between DTs and sub-metaverses at the edge to enhance the *physical-digital duality* ?



Distributed Metaverse Framework

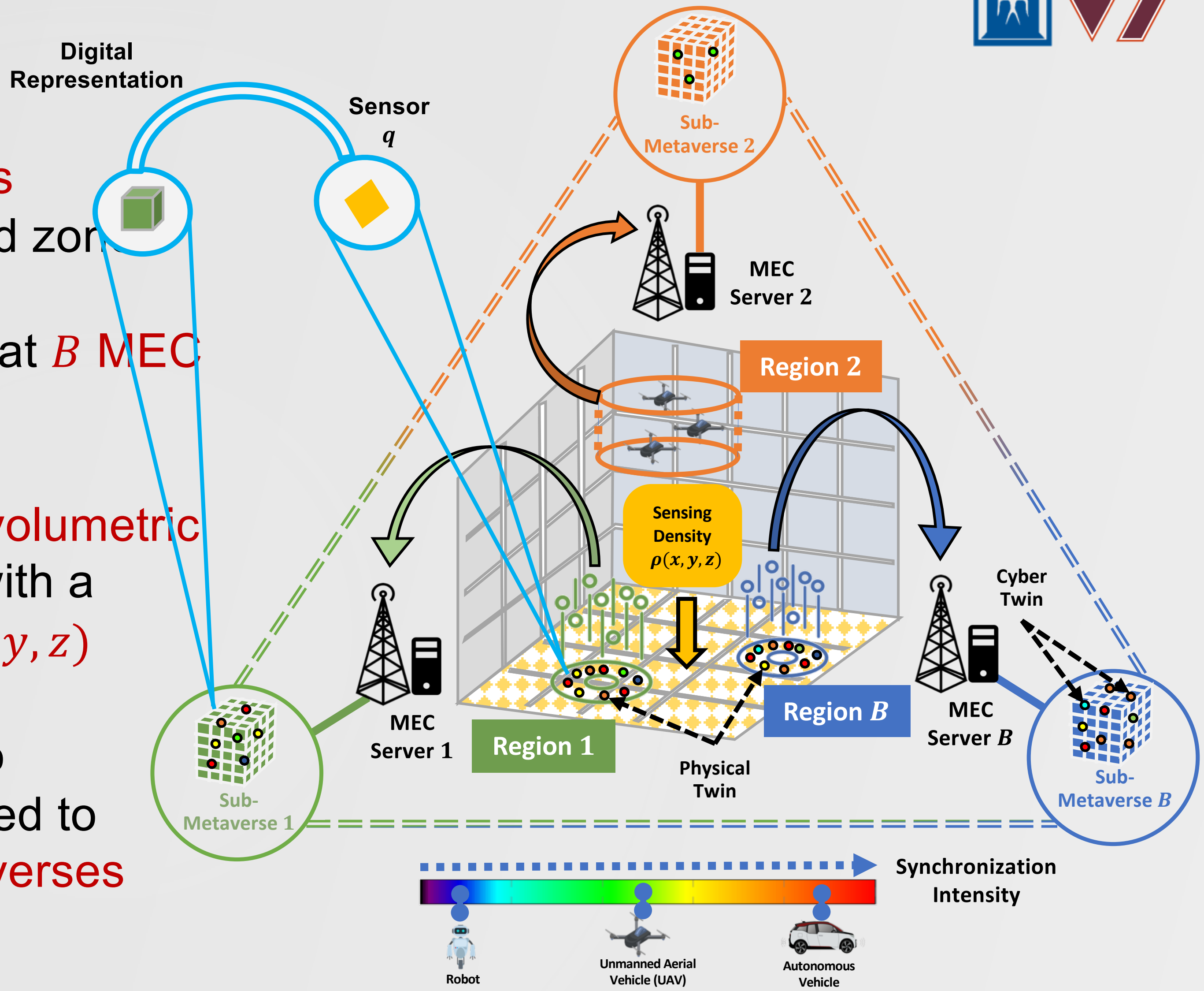
- Previous work tried to address synchronization in wireless edge networks, however they consider:
  - ➢ DTs synchronization only ➔ fail to consider metaverse synchronization
  - ➢ Metaverse synchronization only ➔ fail to consider DT synchronization
  - ➢ Consider a centralized metaverse approach ➔ cannot accommodate the DTs residing at the edge

- Distributed metaverse ➔ synchronization of both DTs and sub-metaverses at the edge

- **<u>To bridge the gap</u>:** investigating the joint synchronization of DTs and sub-metaverses in a distributed metaverse framework, while orchestrating the interplay between them at the edge

System Model

- Consider K DT applications operating in a 3D real-world zone
- PTs are replicated as CTs at B MEC servers
- The zone is scaled with a volumetric sensing density $\rho(x, y, z)$ with a probability distribution $g(x, y, z)$
- The zone is partitioned into A regions, that are teleported to MEC servers as sub-metaverses



System Model (Cont'd)

- Time to upload data generated within Δ from sensor q to MEC server b:

$$t_{q,b}^{\text{com}}(Q_b) = \frac{\Delta\epsilon}{R_{q,b}(Q_b)}\rho(x,y,z)$$

Rate from sensor q to MEC b

Infinitesimal volume

$$R_{q,b}(Q_b) = \frac{W_b^s}{Q_b}\log_2\left(1 + \frac{h_{q,b}\xi_q}{\sigma_b^2}\right)$$

Total sensors connected to MEC server b

- Time to render sensor q at MEC server b:

$$t_{q,b}^{\text{cmp}}(Q_b, \psi_b^s) = \frac{\Lambda\Delta\epsilon}{\psi_b^s}Q_b\rho(x,y,z)$$

Topological complexity

Metaverse synchronization resources

- Total time to synchronize sensor q with its digital counterpart:

$$t_{q,b}^{\text{sync}}(Q_b, \psi_b^s) = t_{q,b}^{\text{com}}(Q_b) + t_{q,b}^{\text{cmp}}(Q_b, \psi_b^s)$$

- **Sub-synchronization time** to synchronize region a_b:

$$T_b(Q_b, \psi_b^s) = \iiint_{a_b} t_{q,b}^{\text{sync}}(Q_b, \psi_b^s)g(x,y,z)\,dx\,dy\,dz$$

System Model (Cont'd)

- Time to upload data from PT k to MEC server b:

$$\tau_{k,b}^{\text{com}} = \frac{D_k}{r_{k,b}} \longleftrightarrow r_{k,b} = W_k \log_2\left(1 + \frac{h_{k,b}\zeta_k}{\sigma_b^2}\right)$$

Data of p_k

Bandwidth for DT k

- Time to execute the action by CT c_k at MEC server b:

$$\tau_{k,b}^{\text{cmp}}(\phi_b^k) = \frac{\Gamma_k D_k}{\phi_b^k}$$

Twin complexity

DT computing resources

- **Twinning synchronization time** of DT k:

$$\tau_{k,b}^{\text{sync}}(\phi_b^k) = \tau_{k,b}^{\text{com}} + \tau_{k,b}^{\text{cmp}}(\phi_b^k)$$

Goal: Effectively partition the regions and associate DTs to:

- **Minimize *sub-synchronization time* between the real and digital worlds**
- **Satisfy the synchronization intensity requirements of DTs**

Problem Formulation

- Our goal is to optimize the following problem:

$$
\begin{aligned}
\min_{a_b, b\in\mathcal{B}, \psi, \Phi} \quad & \frac{1}{B}\sum_{b\in\mathcal{B}} T_b(Q_b, \psi_b^s), \\
\text{s.t.} \quad & \tau_{k,b}^{\text{sync}}(\phi_b^k) \le \frac{1}{\mu_k} \quad \forall k \in \mathcal{K}, \forall b \in \mathcal{B}, \\
& \psi_b^s + \sum_{k=1}^{K} \phi_b^k \le \Psi_b \quad \forall b \in \mathcal{B}, \\
& \sum_{b\in\mathcal{B}} x_{k,b} \le 1 \quad \forall k \in \mathcal{K}, \\
& x_{k,b} \in \{0,1\}, \quad \forall k \in \mathcal{K}, \forall b \in \mathcal{B} \\
& \bigcup_{b\in\mathcal{B}} a_b = \mathcal{Z}, \\
& a_i \cap a_j = \emptyset \quad \forall i,j \in \mathcal{A}, i \ne j,
\end{aligned}
$$

Regions

MEC resources for metaverse synchronization

Association variable

DT association and computing resource allocation

DT synchronization intensity

- Solving this problem is challenging as:
  - It involves a set of **mutually correlated regions**
  - Region partitioning is dependent on the **distribution of DTs** and their **synchronization intensities**

Proposed Solution:
Optimal Transport Theory

- Optimal transport (OT) can provide the optimal mapping, *from the sensors to the MEC servers*, which determines the region partitions that yield the minimal sub-synchronization time

- Under given resource allocations, our problem is reduced to a region partitioning problem:

$$
\begin{aligned}
\min_{a_{b,b\in\mathcal{B}}} \quad & \frac{1}{B}\sum_{b\in\mathcal{B}} \iiint_{a_b} L(g(x,y,z))F(\boldsymbol{\omega},\boldsymbol{\kappa}_b) \\
& \times g(x,y,z)\,dx\,dy\,dz, \\
\text{s.t.} \quad & \bigcup_{b\in\mathcal{B}} a_b = \mathcal{Z}, \\
& a_i \cap a_j = \emptyset \quad \forall i,j \in \mathcal{A}, i \neq j.
\end{aligned}
$$

Sensor coordinates

BS coordinates

$$L(g(x,y,z)) = Q\Delta\epsilon^{q,b} \iiint_{a_b} g(x,y,z)\,dx\,dy\,dz$$

$$F(\boldsymbol{\omega},\boldsymbol{\kappa}_b) = \frac{\rho(\boldsymbol{\omega})}{W_b^s \log_2\left(1+\frac{\beta(\boldsymbol{\omega},\boldsymbol{\kappa}_b)}{\sigma_b^2}\right)} + \frac{\Lambda\rho(\boldsymbol{\omega})}{\psi_b^s}$$

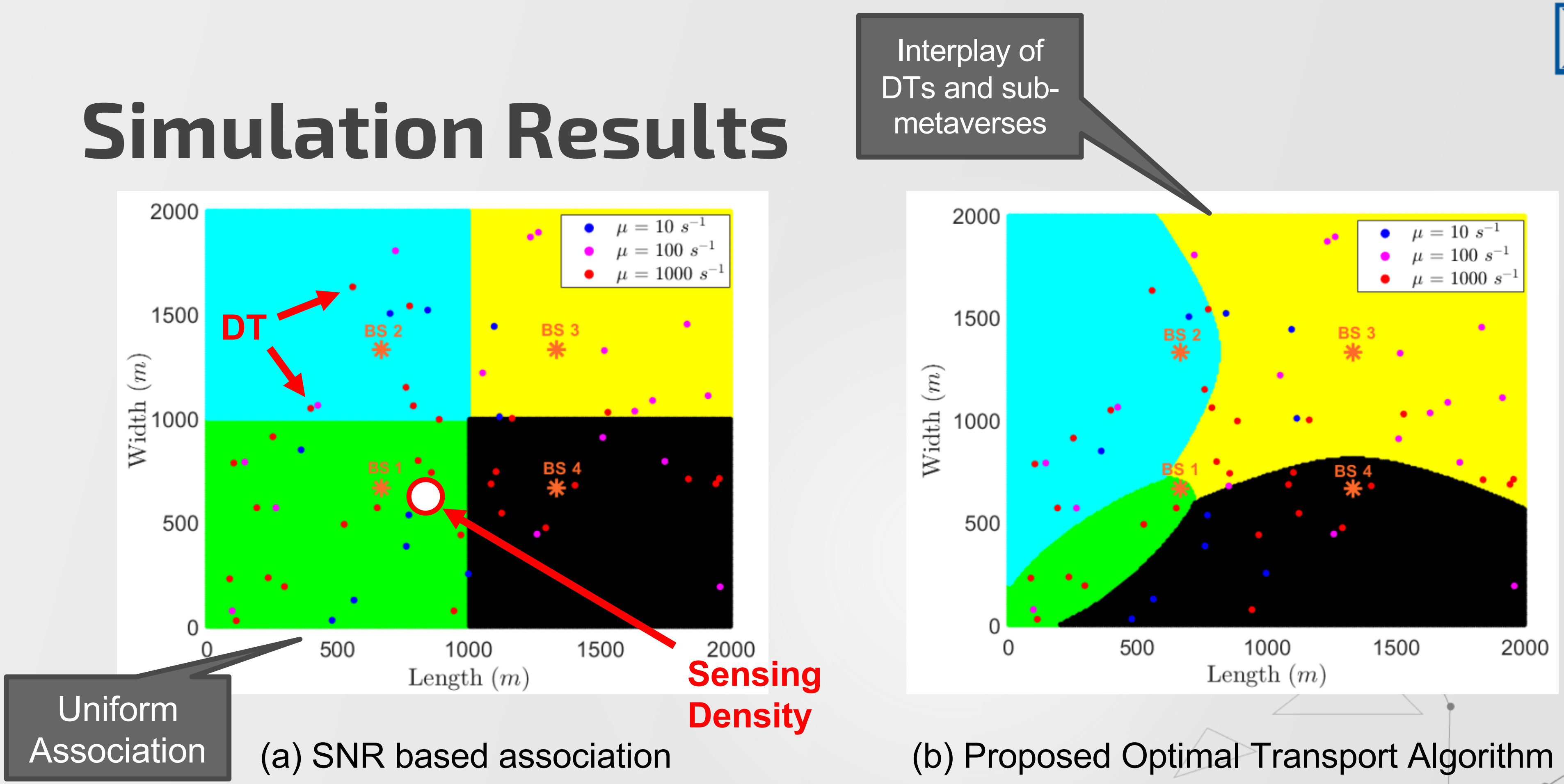
Proposed Solution (Cont'd)

- The *optimal regions partitioning* is given by the following map:

$$a_b^* = \left\{ \boldsymbol{\omega} = (x, y, z) \middle| \ \alpha_b F(\boldsymbol{\omega}, \boldsymbol{\kappa}_b) \leq \alpha_j F(\boldsymbol{\omega}, \boldsymbol{\kappa}_j), \forall j \neq b \in \mathcal{B} \right\}$$

- After determining the optimal regions, associate the DTs within each region a_b to MEC server b
- Provide the DTs connected to each MEC server with the sufficient computing resources to meet synchronization intensity requirements
- Assign the remaining resources for sub-metaverse synchronization
- Iterate this procedure until the average sub-synchronization time which allows satisfying all DTs synchronization requirements is reached

Simulation Results



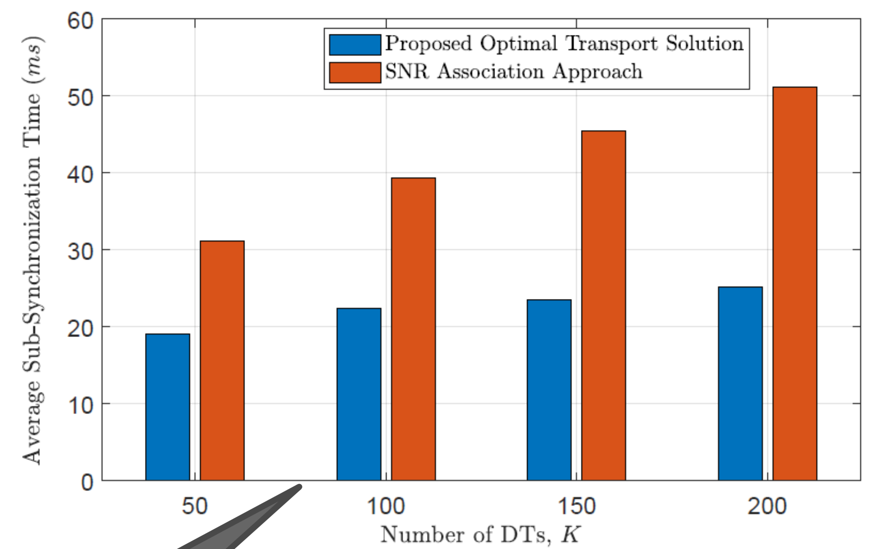
(a) SNR based association

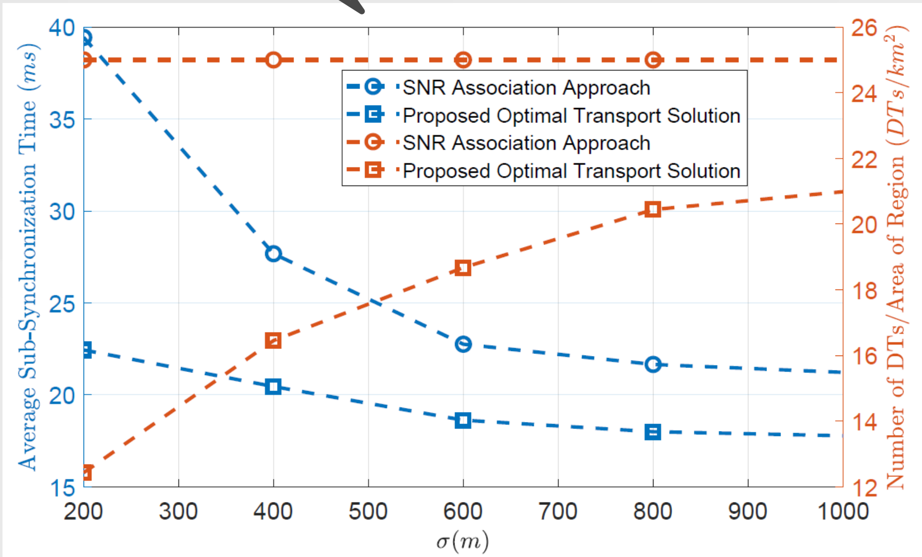
(b) Proposed Optimal Transport Algorithm

- Our approach provides a *tradeoff between DTs and sub-metaverses association* to guarantee minimal sub-synchronization time

Simulation Results

Tradeoff DTs and sub-metaverses





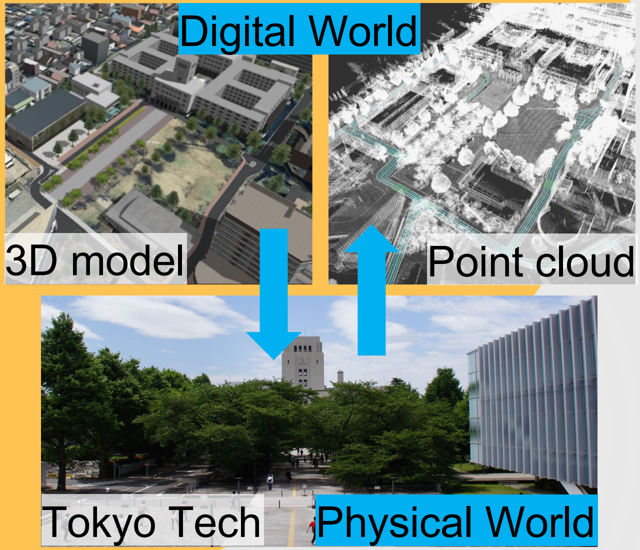
Considering DTs, resources, and sensing distribution

- ❑ The proposed approach achieves a 25.75% lower average sub-synchronization time for all values of σ

Next Steps

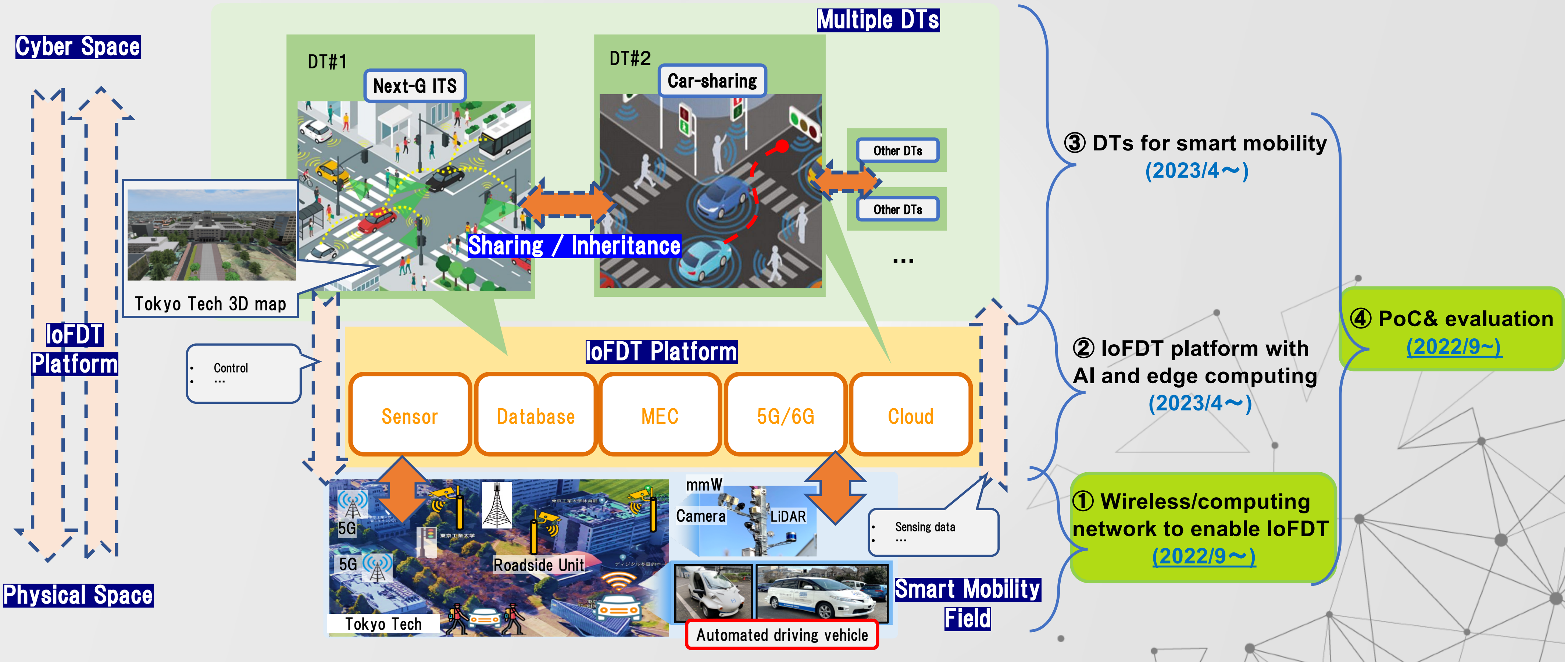
- Journal Paper: Continual Graph Neural Networks for an IoFDT over a Distributed Wireless Metaverse
  - Leverage CL as a tool to preserve the synchronized twinning process in a **non-stationary** scenario
  - Facilitate the continuous update process of DTs through Continual graph neural networks
- Conference Paper: Multi-view Generative AI for Ultra Predictive Digital Twins in the Metaverse
  - Develop a multi-view learning approach to predict future states of DTs connected through the IoFDT
  - This work is fundamental to hold experimental trials at Tokyo Tech on a vehicular DT application testbed

How do we demonstrate and validate the interaction between the physical and digital world?

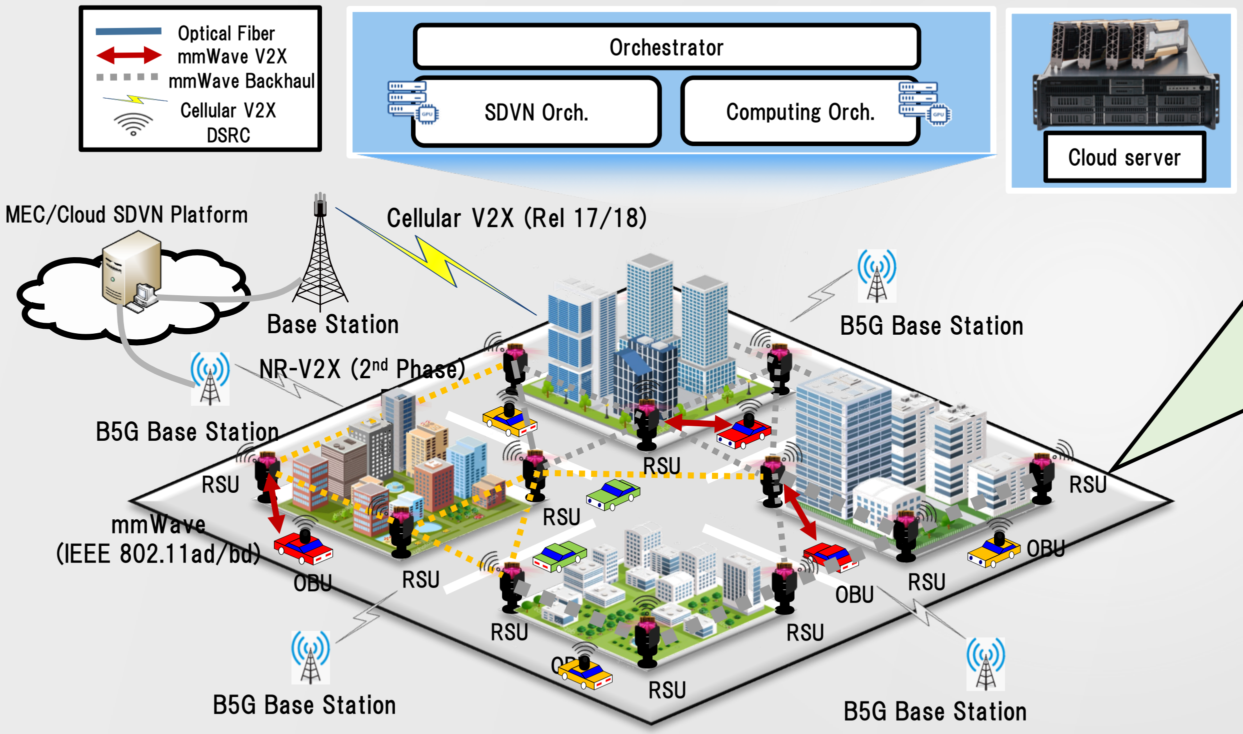


How do we jointly design, implement, and tune the network/computing hardware, topology, and protocols for DTs?

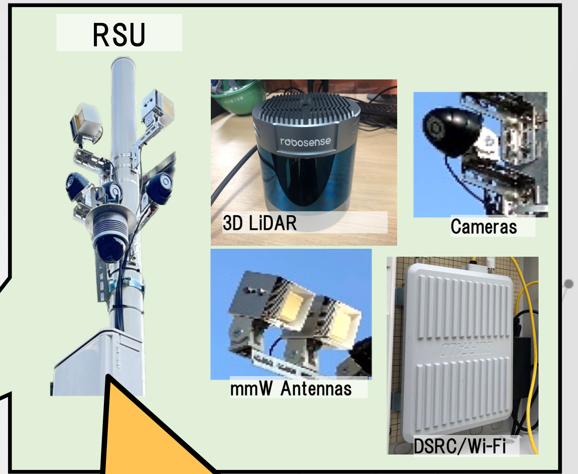
Overview of PoC Implementation of IoFDT



Ookayama B5G/6G Wireless & Computing Networks for Smart Mobility



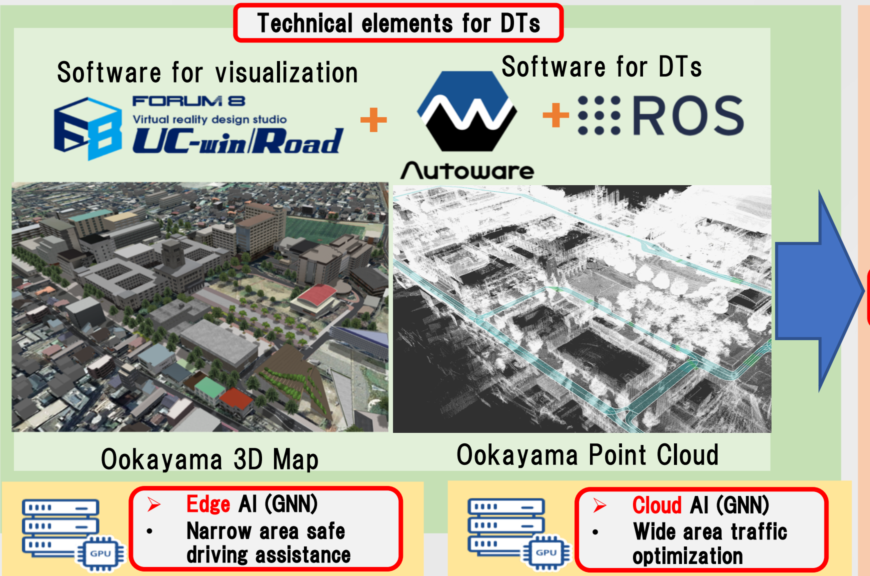
Heterogeneous SDVN & Edge/cloud computing network

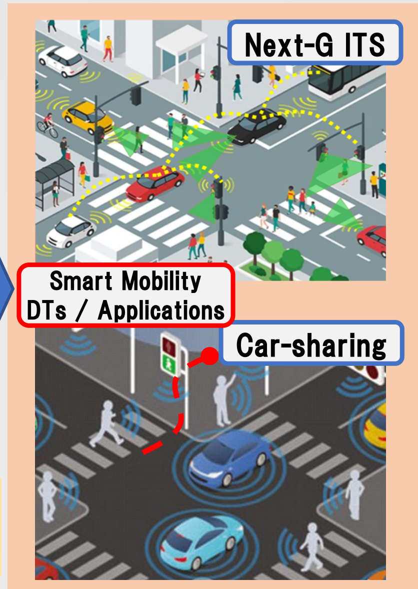


Introduce Jetson AGX Orin to RSU

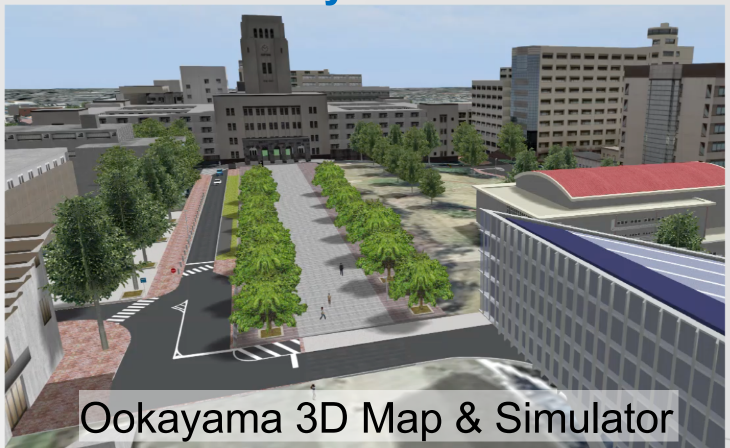
・Edge computing for mobility DTs
・Edge computing for FL

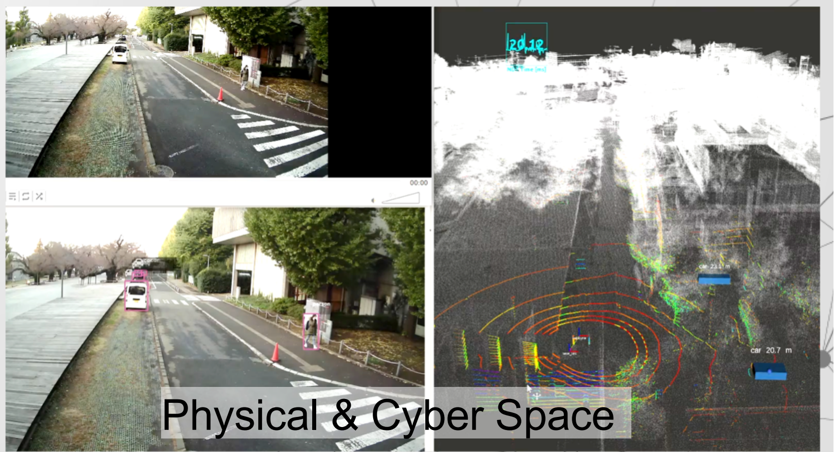
Ookayama DT for Smart Mobility





Preliminary Demo Videos



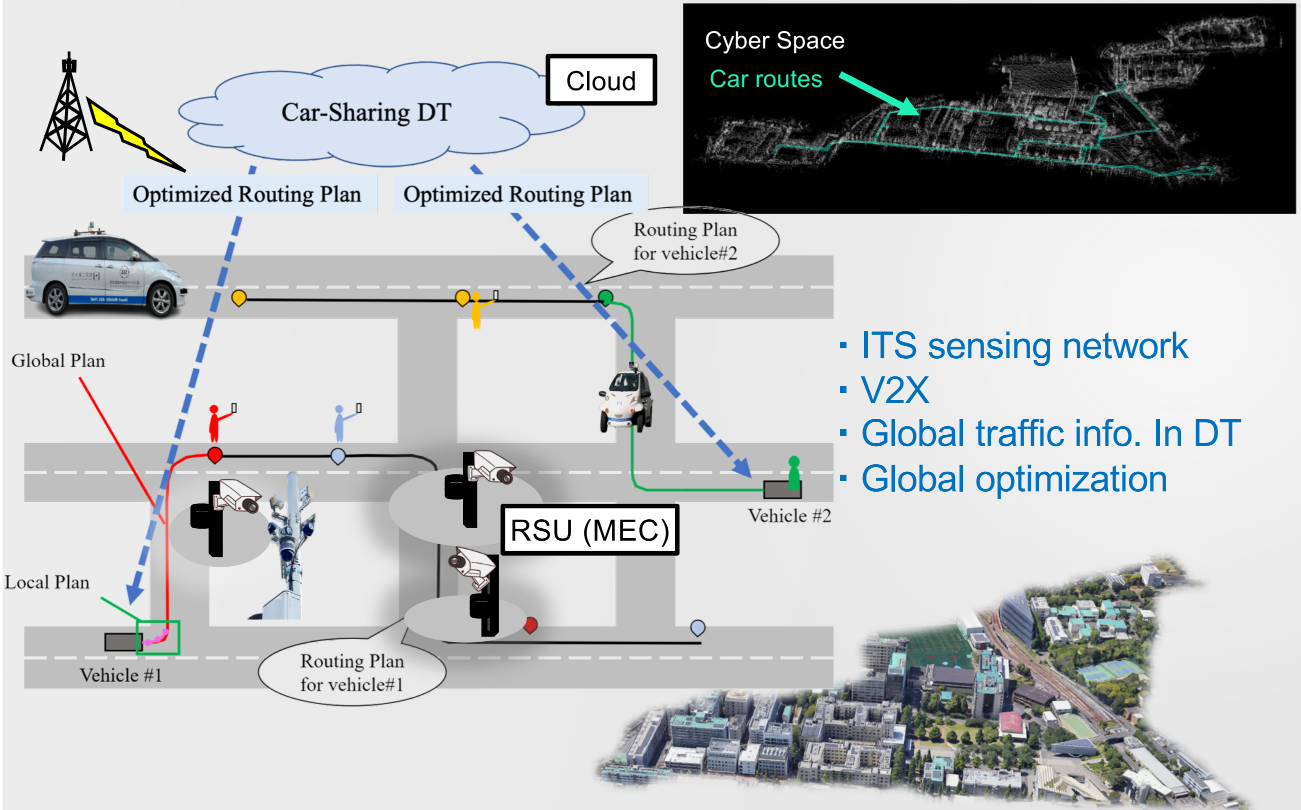


Tokyo Tech (from google map)

Ookayama DT for smart mobility empowered by cloud/edge computing

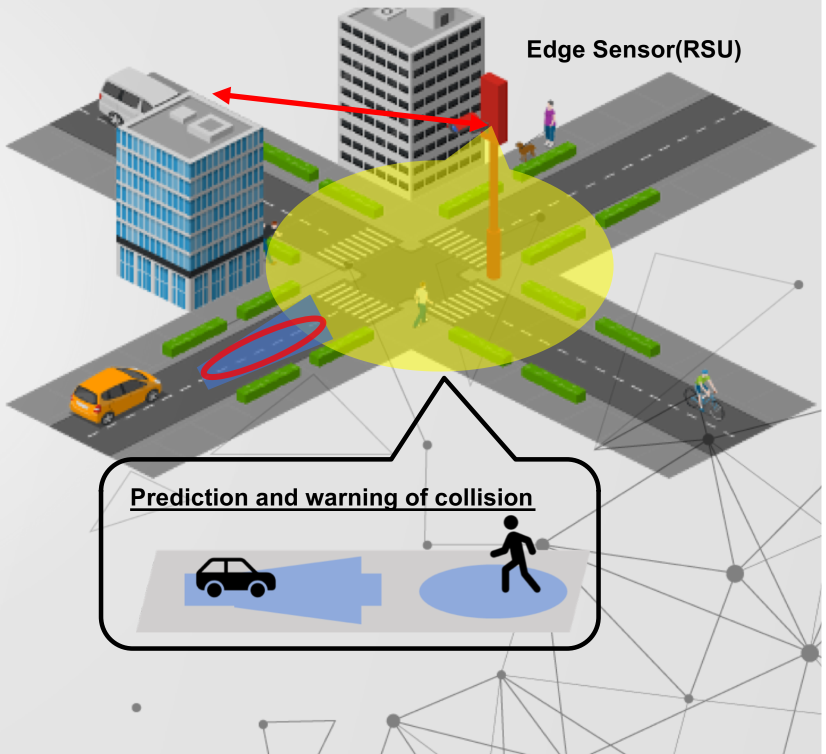
Mobility DTs for Demo and Evaluation

- Car-sharing system for automated cars



- ITS sensing network
- V2X
- Global traffic info. In DT
- Global optimization

- Next Generation ITS for collision avoidance



Collaborative Activities

- In-person meeting at IEEE VTC-Fall 2022 (kick off of project)
- We have been conducting monthly meetings
- Mr. Nonomura Kazuma visited Virginia Tech in January 2023
  - ➢ Discuss recent work: *Reshape Car-Sharing System for Super Smart Society: A Digital Twin-Based Method and Implementation*
  - ➢ This work will be a fundamental for our future work on the vehicular DT application testbed
- Joint publications (IEEE ICC, two ongoing magazines, one ongoing journal)
- Planned mutual visits in the next year or so to further foster collaborations

Conclusions

Communication Innovations

New communication approaches to today's wireless networks must take place:

- New network management techniques
- DT-oriented communication mechanisms

Computing Innovations

The convergence of computing and communications will require innovations at the computing level

- Edge-based designs
- Computing resource management
- Slashing computing latency

AI Innovations

Creating the IoFDT requires re-engineering data-driven approaches to:

- Knowledge-driven techniques that enable "growing" the IoFDT
- Lifelong Continual Learning that learn bit-by-bit

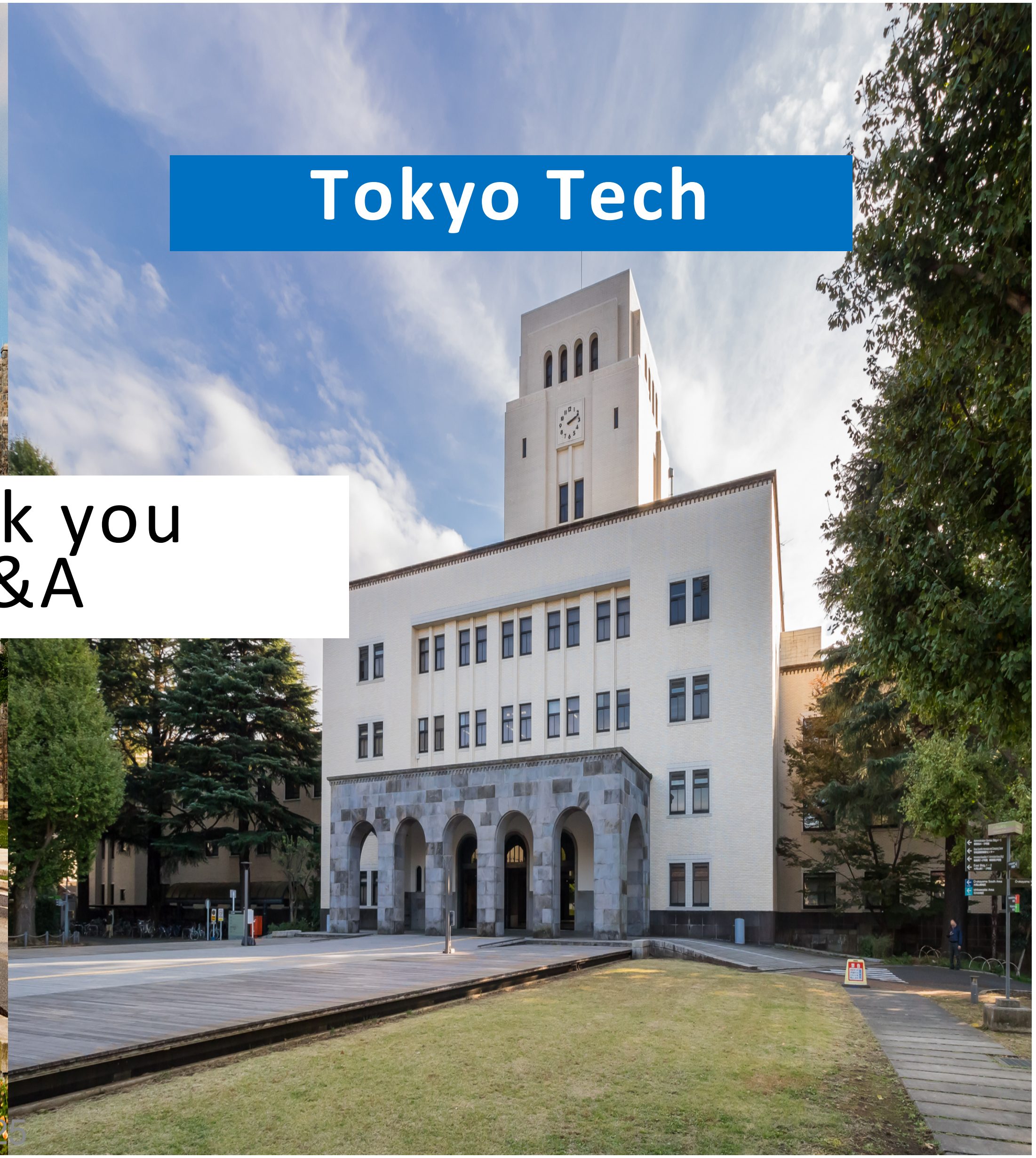
Experimental Innovations

Key experimental challenges must be addressed:

- Joint design and implementation of hardware, topology, and protocols
- Cross-system integration of different types of DTs
- PoC implementation of practical application/service for evaluation

Virginia Tech

Tokyo Tech



Thank you
Q&A