THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

Consistent Physical-to-Virtual Mapping in Digital Twins

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Date: 7 August 2025

Chair: Prof. Yuanqing Zheng, PolyU

Examiners: Prof. Christian Becker, University of Stuttgart

Prof. Xiaohua Jia, CityU

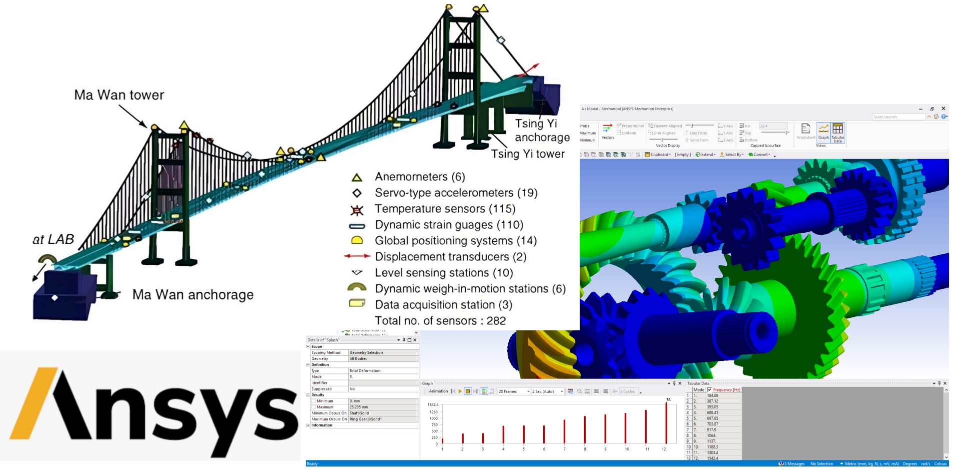
Supervisor: Prof. Jiannong Cao, PolyU

Outline

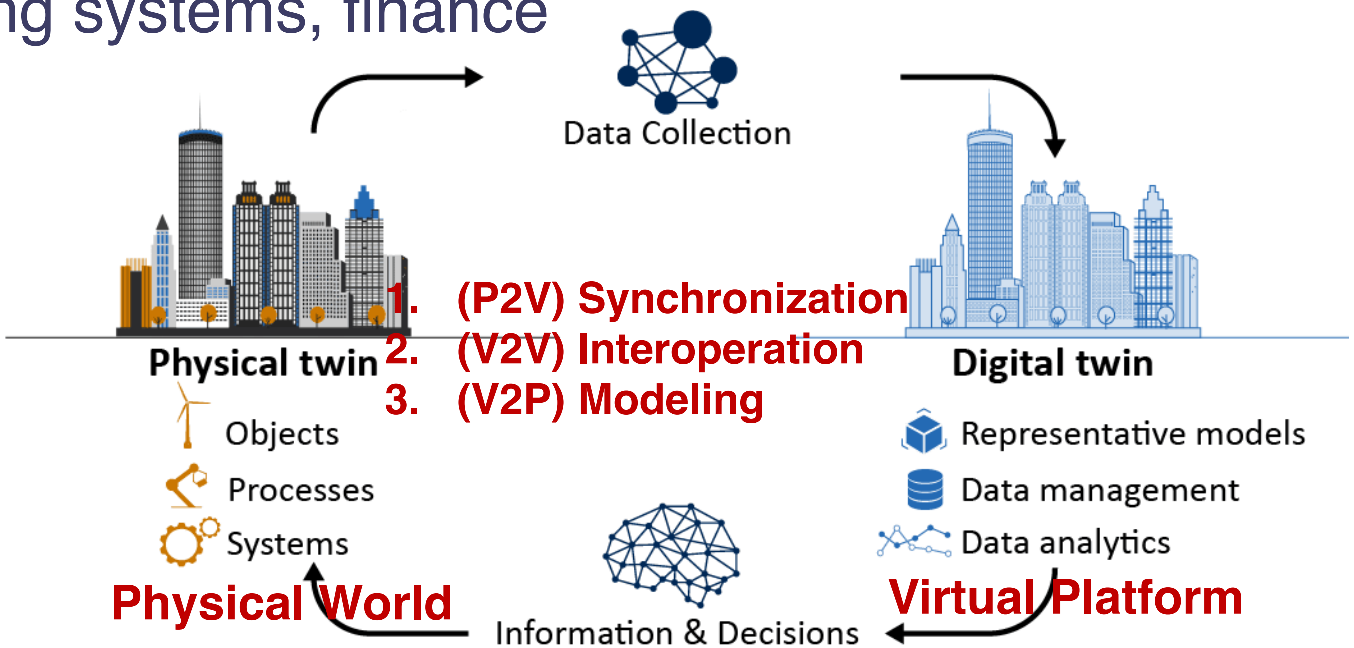
- Introduction of Digital Twins
- Problems, Existing Works, and Challenges
  - Digital Twin Synchronization
  - Digital Twin Interoperation
- My PhD Research
- Research Contributions
  - PolyVerse: An Edge-based Digital Twin Platform with Physical-to-Virtual Projection
  - ChainTwin: Trustworthy Digital Twin Synchronization
  - MAP: Efficient and Scalable Blockchain-based Digital Twin Interoperation
- Summary and Future Directions

Digital Twin is Promising

- Simulation is important for industrial applications
  - Static and offline features lead to low-accuracy (fidelity) modeling
- **Digital Twin (DT):** connected system that maps physical objects into virtual replicas (twins) by real-time data and advanced modeling methods
  - Promising interdisciplinary research directions between CS and Engineering
  - Healthcare, education, computing systems, finance



Traditional Simulator



Digital Twin Workflow

Mihai S, Yaqoob M, Hung D V, et al. Digital twins: A survey on enabling technologies, challenges, trends and future prospects[J]. IEEE Communications Surveys & Tutorials, 2022, 24(4): 2255-2291.

Research Gaps and Problems in Digital Twin

- Three processes of digital twins: **(P2V)synchronization**, **(V2V)interoperation,** and **(V2P)modeling**
- **Most of existing works**: find accurate algorithm-level modeling methods
  - Reinforcement learning, LLM, game theory, etc
- A significant and fundamental system-level problem is unsolved: **DT consistency**
  - The state of twins should be updated strictly according to its physical objects
  - Cross-platform processes: **synchronization** and **interoperation** are vulnerable to inconsistency
  - Affect the overall accuracy

Mobility-Aware Service Provis
Replica Placements
Yuncan Zhang; Weifa Liang; Zichuan
IEEE Transactions on Mobile Computi
Year: 2024 | Volume: 23, Issue: 12 |
Cited by: Papers (14)
Abstract HTML

Semi-Distributed Network Fau
in Highly Dynamic Heterogene
Fengxiao Tang; Linfeng Luo; Zhiqi Gu
IEEE Transactions on Mobile Computi

Deep learning for hybrid 5G services in mobile edge computing systems: Learn from a digital twin
R Dong, C She, W Hardjawana, Y Li… - IEEE Transactions on …, 2019 - ieeexplore.ieee.org
… a digital twin of the real network environment. As shown in [14], a digital twin is a virtual digital … With the help of a digital twin, we can compute the energy consumption, delay, and packet …
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Digital twin-aided intelligent offloading with edge selection in mobile edge computing
T Do-Duy, D Van Huynh, OA Dobre… - IEEE Wireless …, 2022 - ieeexplore.ieee.org
… study a mobile edge computing (MEC) architecture with the assistance of digital twin (DT) … -ofThings (IoT) devices intelligently offload computing tasks to multiple MEC servers to reduce …
☆ 保存 99 引用 被引用次数：153 相关文章 所有 7 个版本

Adaptive digital twin for vehicular edge computing and networks
Y Dai, Y Zhang - Journal of Communications and Information …, 2022 - ieeexplore.ieee.org
… To elaborate the integration of digital twin and VEC, we consider a digital twin empowered VEC offloading problem which aims to minimize the total time consumption of all vehicles. In …
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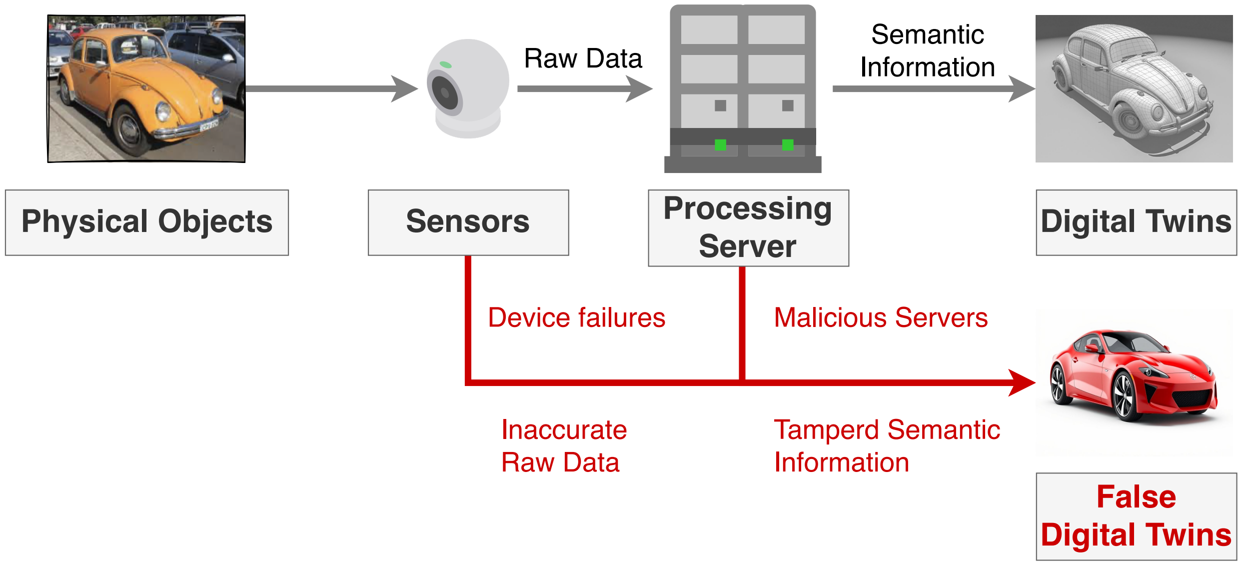
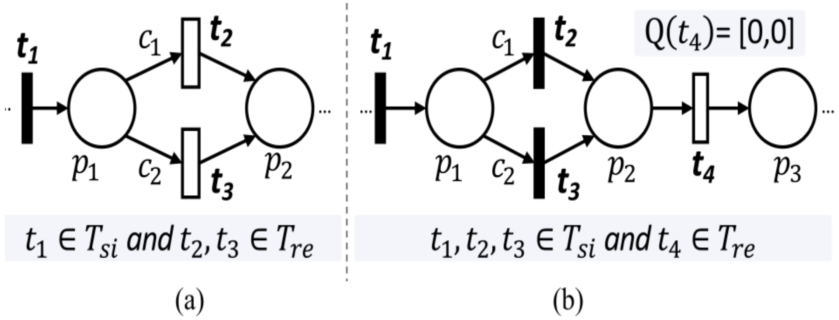
Search results of digital twin in Google Scholar



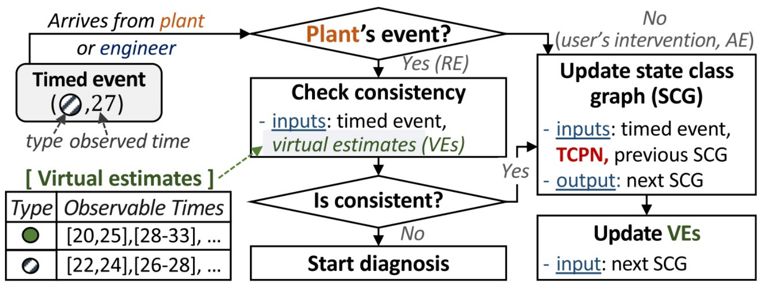
Existing Works: Digital Twin Synchronization

- **Definition**: update the states of physical objects to digital twins (sensors, database, etc) in real-time
  - Checkpoint-triggered
    - Update the digital twin periodically (time/event)
  - Rule-based
    - Check if the updates follow pre-defined rules
  - Data-driven
    - Adaptively detect anomaly from historical records using data-driven methods

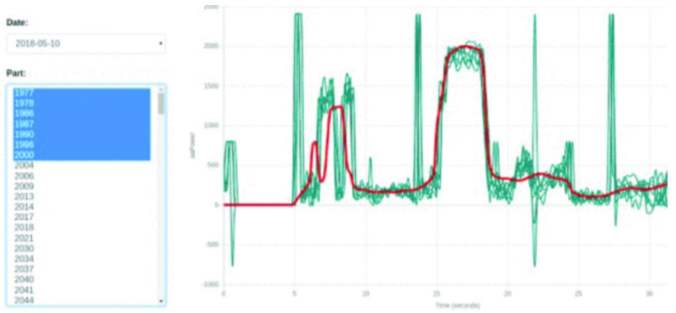
Limitation: Assume the sensors are honest
Problem: How to sync. DT in adversarial environment (e.g., sensor spoofing, failures)?
Challenges:
1. Limited observation ability (virtual platforms)
2. Heterogeneity (sensors and data processing method)



Checkpoint-triggered



Rule-based



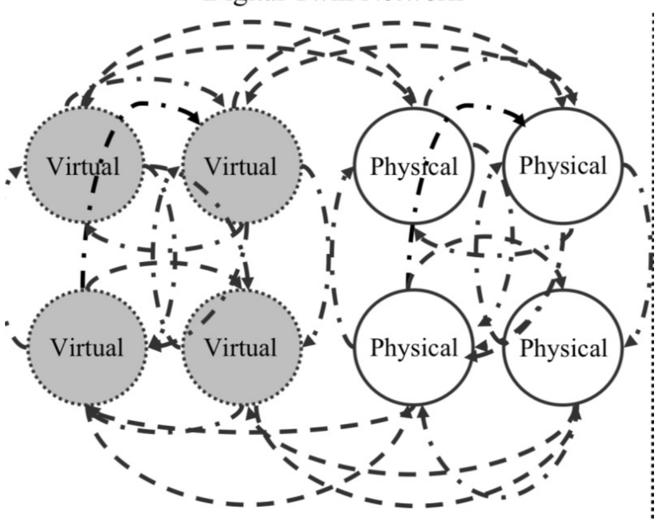
Data-driven

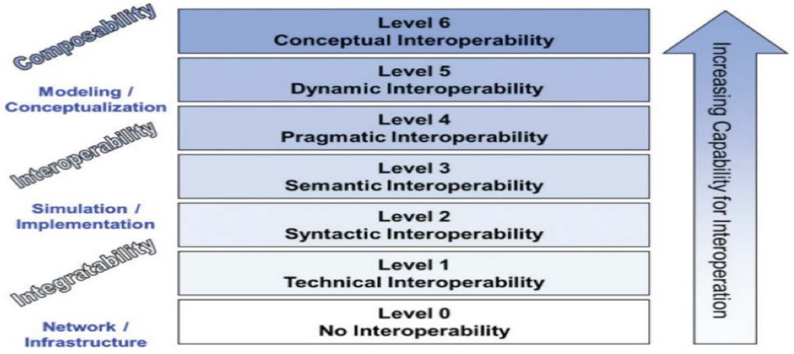
Alcaraz C, Lopez J. Digital twin: A comprehensive survey of security threats[J]. IEEE Communications Surveys & Tutorials, 2022, 24(3): 1475-1503.

Existing Works: Digital Twin Interoperation

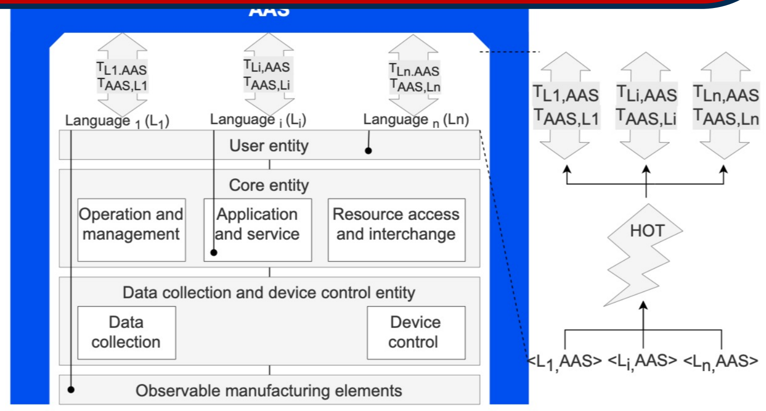
- **Definition**: untrusted digital twin systems operate DT from each other (compose, retrieval, sharing, tracing, etc)
  - Standardization
    - Pre-defined software, data format, communication proto
  - Transformation-based
    - Translating diverse files/models using rules/AI models v
    - E.g., Asset Administration Shell (AAS) to Digital Twins D

Limitation: Require trust and costly
Problem: How to operate DT across heterogenous systems without centralized trust?
Challenges:
1. Efficiency (operation cost)
2. Scalability (system integration cost)





Standardization

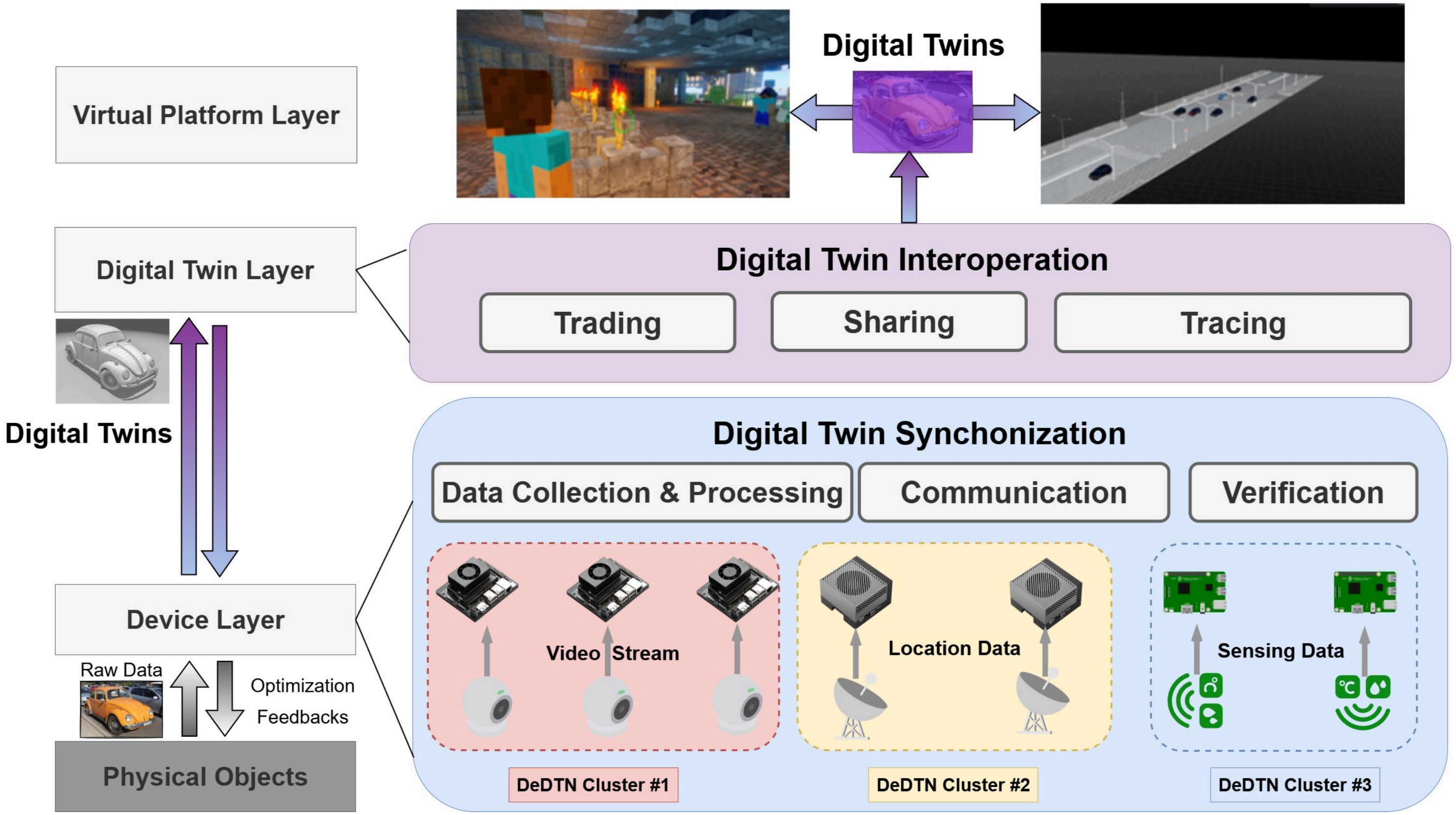


Transformation

Klar R, Arvidsson N, Angelakis V. Digital twins' maturity: The need for interoperability[J]. IEEE Systems Journal, 2023, 18(1): 713-724..

My PhD Research

- **Research objectives**
  - System and protocols ensure the consistency of digital **synchronization** and **interoperation** while preserving scalability and efficiency
  - Consistency be verified by stakeholders without centralized trust



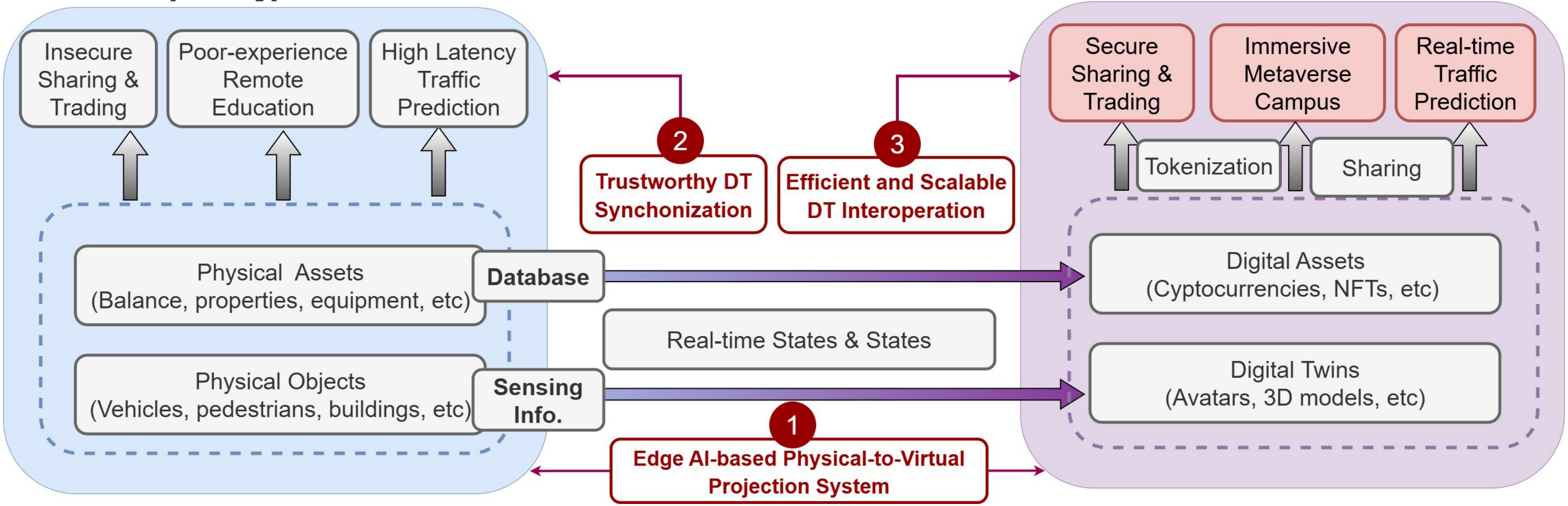
Trustworthy and Insteroperable Digital Twins

Consistency

Massive Objects in Adversarial Environment

Research Framework

- **Consistent physical-to-virtual mapping in digital twins**
  - **An Edge AI based physical-to-virtual DT projection system provides basic framework and functional support**
  - **Trustworthy DT synchronization (P2V)**
  - **Efficient and scalable DT interoperation (V2V)**
  - **Real-world prototypes to evaluate and test functionalities**



Yinfeng Cao, Jiannong Cao, Baoxia Du, and Ruidong Li(2025). "Decentralized Digital Twin Network". IEEE Communications Magazine.

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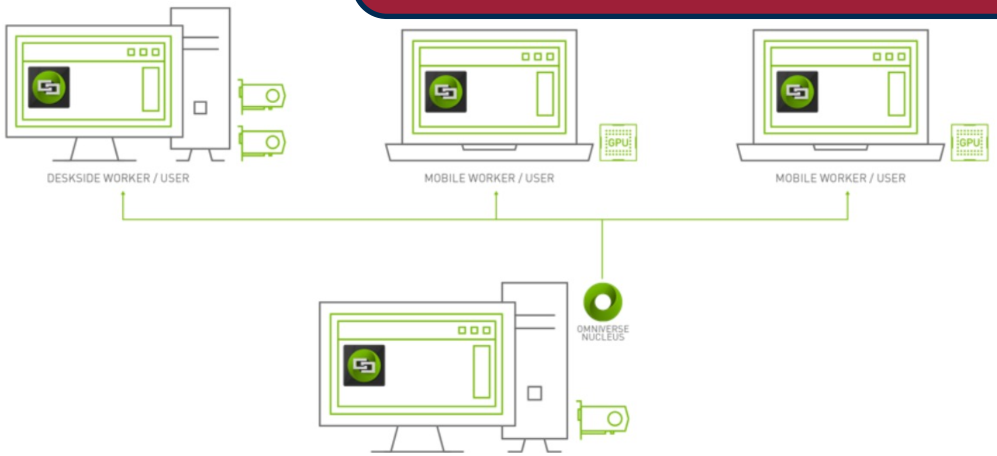
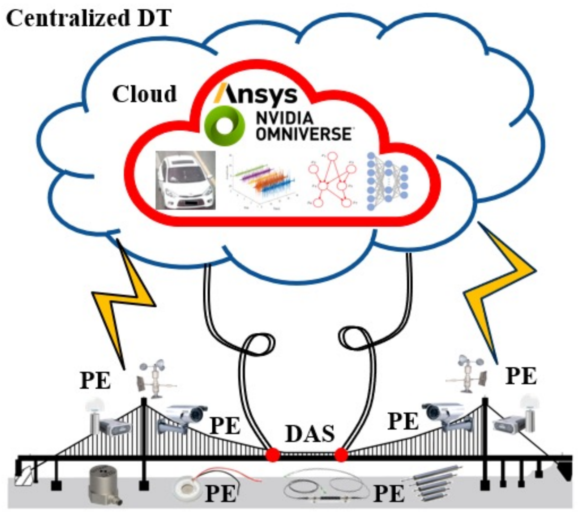
PolyVerse: Motivation

- **Digital twin system requires sensing and data processing capabilities for physical objects**
  - Existing systems (such as Nvidia Omniverse, Ansys) are based on centralized cloud platform for simulation cooperation
  - Only support manual uploads digital twin data with **high latency** and **labor work.**
- **Timeliness and scalability are important**
  - Physical objects / assets can be massive and distributed (such as pedestrians)

An end-to-end physical-to-virtual digital twin projection system are still missing

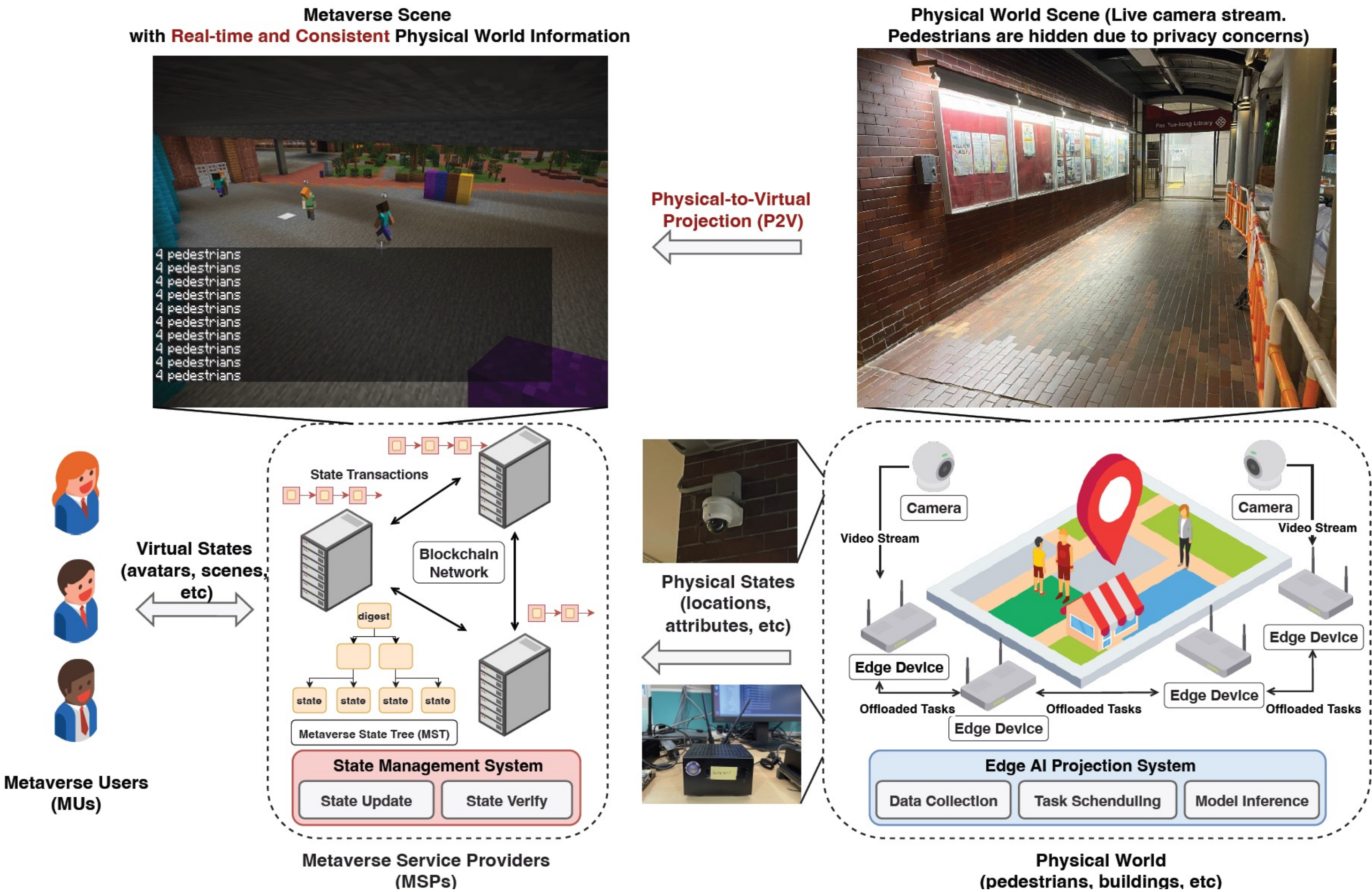


Nvidia Omniverse



Cloud-based Architecture

- **New system architecture enabling real-time and scalable physical-to-virtual projection**
  - **Real-time Edge AI projection system**
    - Senses and extracts physical states of objects with on-device processing
  - **Digital Twin Semantic communication**
    - Transmits state data to virtual platform
  - **Blockchain network**
    - Synchronizes and stores the states between physical and virtual



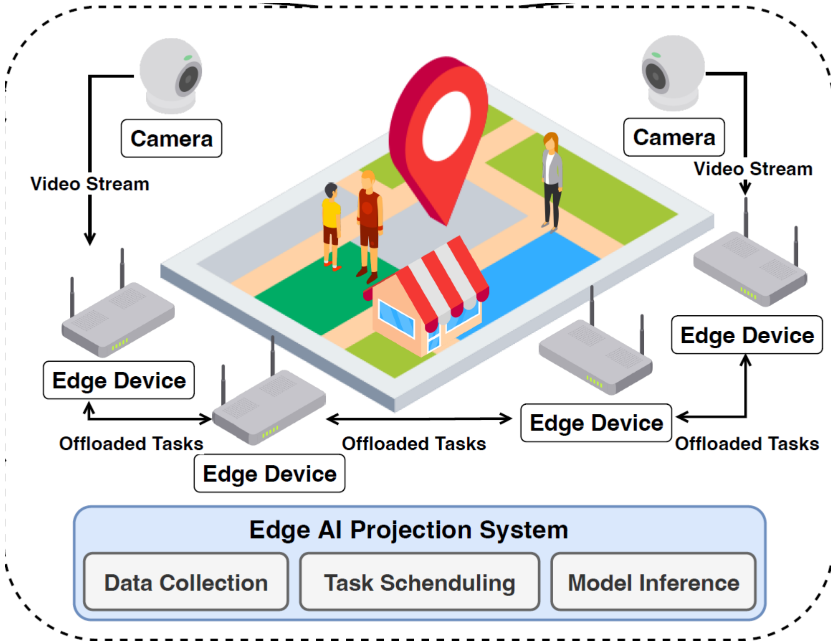
PolyVerse System architecture

Yinfeng Cao, Jiannong Cao, Zeyang Cui, Dongbin Bai, Mingjin Zhang, Long Wen. (2024). "PolyTwin:Edge Blockchain-empowered Trustworthy Digital Twin Network for Metaverse". The 2nd Annual IEEE International Conference on Metaverse Computing, Networking, and Applications (IEEE MetaCom 2024)

Yinfeng Cao, Jiannong Cao, Dongbin Bai, Zhiyuan Hu, Kaile Wang, Mingjin Zhang (2023). PolyVerse: An Edge Computing-Empowered Metaverse with Physical-to-Virtual Projection. IEEE International Conference on Intelligent Metaverse Technologies and Applications (iMETA2023), 18-20 September 2023, Tartu, Estonia. Best Paper Award Nomination

Real-time Edge AI Projection System

- Using Edge AI to infer the physical states (e.g., pedestrian locations) and attributes (e.g., appearances) in real-time
  - Tasks and raw data are processed on edge devices without uploading to cloud servers to reduce **latency**
- Edge devices collaboratively execute tasks to further minimize the latency
  - A task offloading algorithm considering **dynamic** workloads



System Overview

$$L_k = \sum_{i=1}^{M} x_{ik} \cdot T_{ik} + \sum_{i=1}^{M} x_{ik} \cdot \frac{T_d^k}{PS_i} + \sum_{j=1}^{M} y_{jk} \cdot \frac{T_r^k}{PS_j} + \sum_{i=1}^{M} \sum_{j=1}^{M} x_{ik} \cdot y_{jk} \cdot \frac{D_{d,r}^k}{R_{i,j}} \cdot \sigma(i-j)$$

Target Function (min.)

Algorithm 1: PolyVerse Joint Stream and Task Scheduling Heuristic (PolyHeuristic)

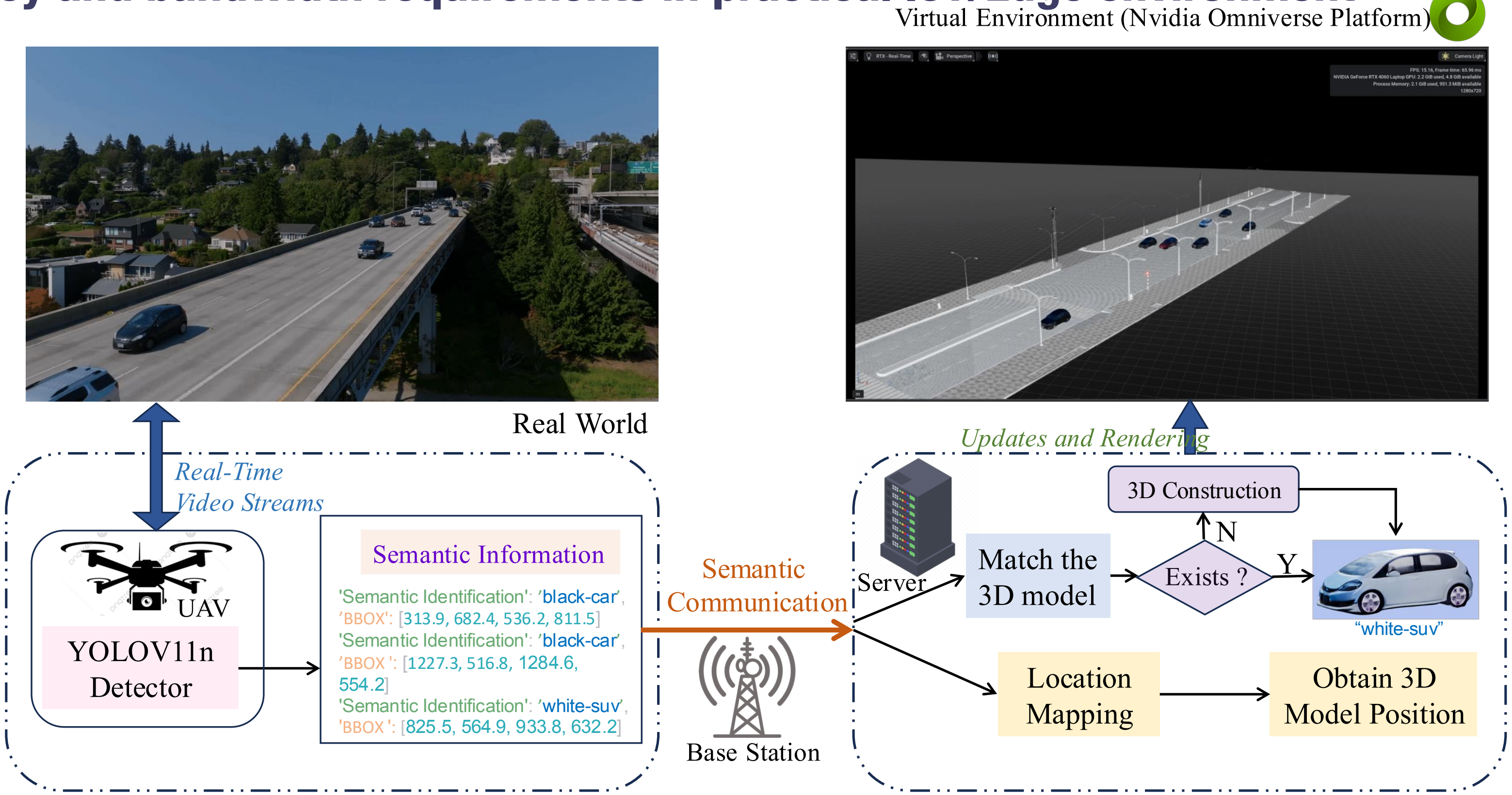
Input: Video stream V, computation capacity $\{PS_i\}_{i=1}^{M}$ and available resource $\{R^j_{avail}\}_{j=1}^{M}$
Output: Video and task allocation policy x_{ik} and y_{ik}

Create stream priority I in descending workload;
for $t \leftarrow 1$ *to* I **do** // Stage 1
  for *each device* $i \leftarrow 1$ *to* M **do**
    if $R^j_{avail} > R^{det}_{req}$ **then**
      Calculate $t^i_{exec} = T_{ik} + \frac{T_{d,k}}{PS_i}$;
    end
  end
  Select device i^* with the shortest execution time $i^* = min_i\{t^j_{exec}\}$;
  $x_{i^*,k} \leftarrow 1$, update $R^{i^*}_{avail}$ for device i^*;
end
for $t \leftarrow 1$ *to* I **do** // Stage 2
  for *each device* $i \leftarrow 1$ *to* M **do**
    if $R^j_{avail} > R^{reg}_{req}$ **then**
      Calculate $t^i_{exec} = x_{ik} \cdot \frac{D^k_{d,r}}{R_{i,j}} + \frac{T_{r,k}}{PS_i}$;
    end
  end
  Select device i^* with the shortest execution time $i^* = min_i\{t^j_{exec}\}$;
  Add i to candidate list $M_{deployed}$;
  if $V_{rest} \neq \emptyset$ **then**
    Schedule remaining streams by solving Eq. 8;
  end
  $y_{i^*,k} \leftarrow 1$, update $R^{i^*}_{avail}$ for device i^*;
end
return x_{ik}, y_{ik}

Task-Scheduling Algorithm

Semantic Communication Scheme for Digital Twin

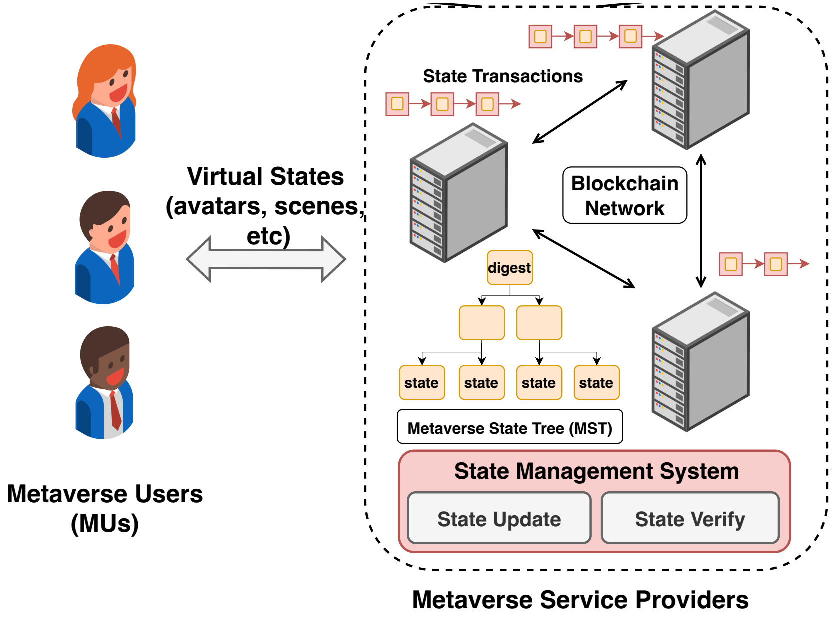
- **A digital twin communication scheme that only transmits extracted state and attributes to virtual platform**
  - **Raw data size in GB-level (such as raw video), while the semantic information only size in KB-level**
  - **Reduce latency and bandwidth requirements in practical IoT/Edge environment**

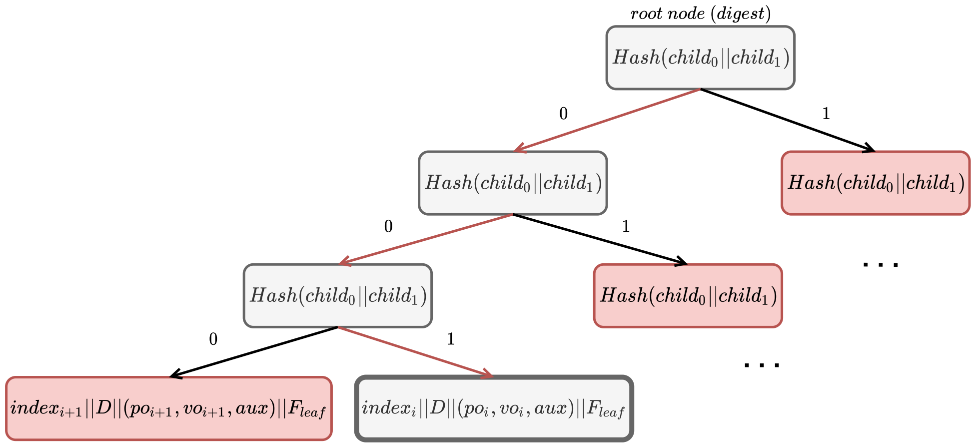


Digital Twin Semantic Communication

Digital Twin Chain

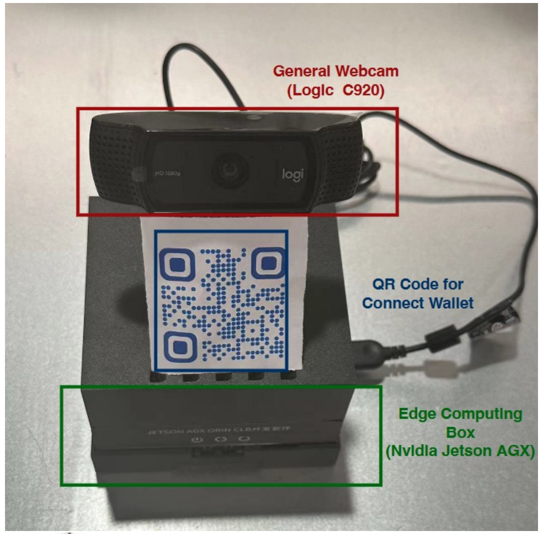
- Provide the consistency of generated digital twins from edge devices
  - Each edge device acts as a blockchain node
  - Upload and synchronize states within the blockchain network
  - (Remaining issues?)
- Merkle State Tree
  - A revised Merkle tree for accumulating states into one value to reduce the number of state transactions
  - Leaf nodes (contain states) are indexed according to scenes to improve search efficiency

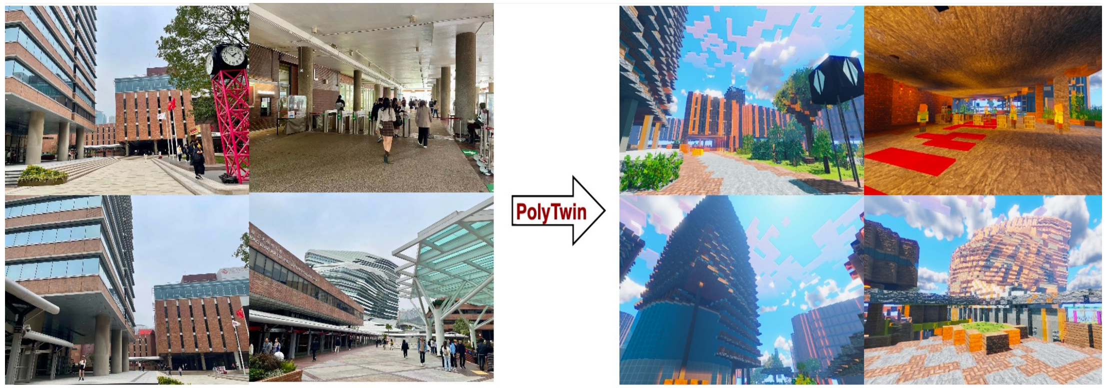




PolyVerse Prototype

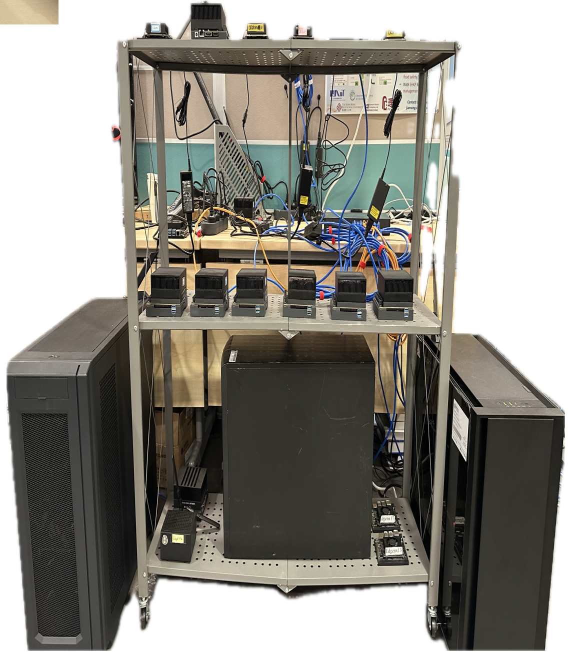
- Edge devices
  - Jetson AGX 16GB
  - Logitech C920 Webcam/Hikvision Webcam
  - Equipped with YOLO-based CV models
  - Customized drones
- Virtual platforms
  - RTX 3080Ti server rendering
  - Microsoft Minecraft
  - Nvidia Omniverse
- Scenarios
  - Pedestrian
  - Vehicle traffic





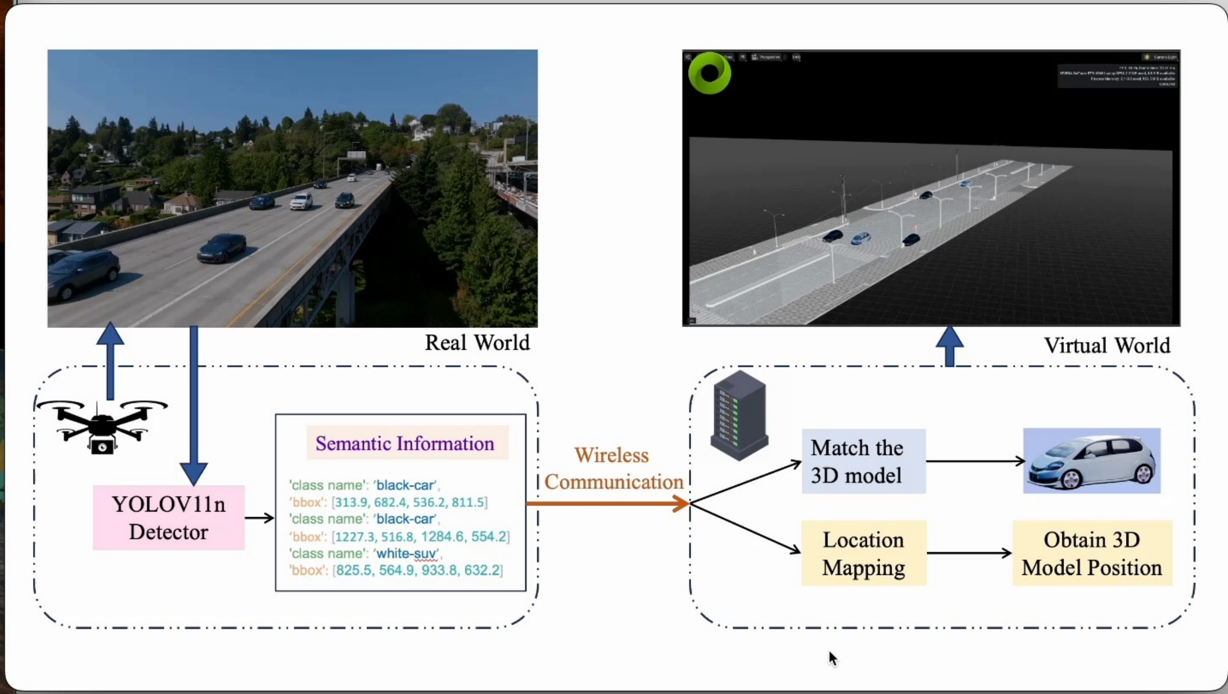
Campus of The HK PolyU

Virtual World of PolyCampus



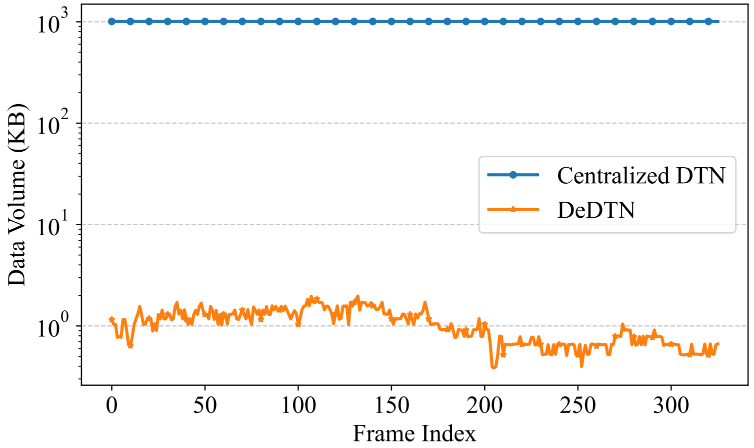
PolyVerse Prototype

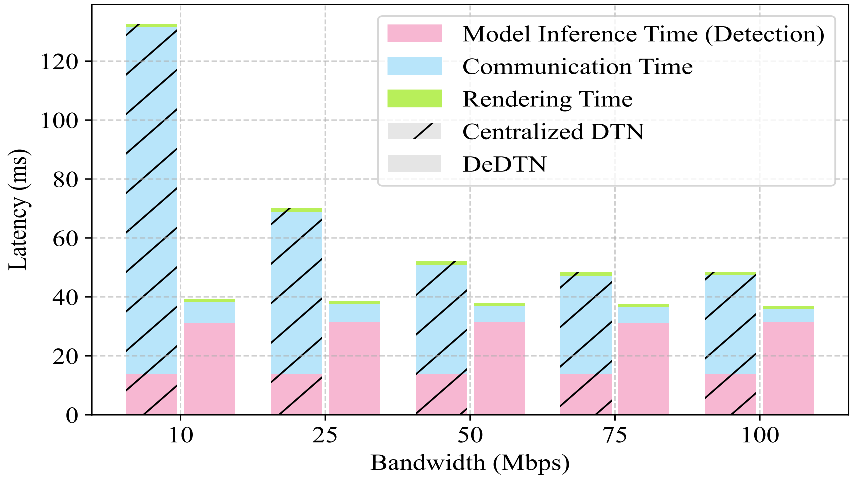
Screen Recording
2025-0...M.mov

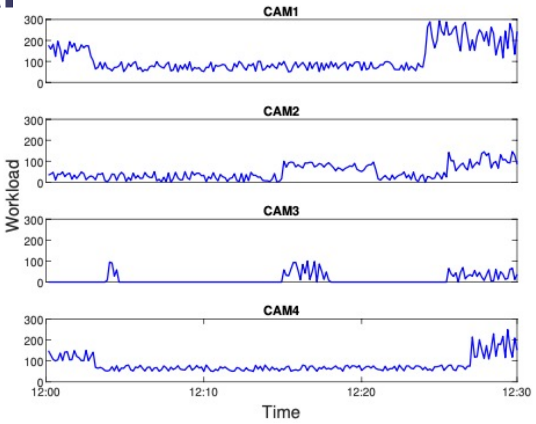


Performance Evaluation

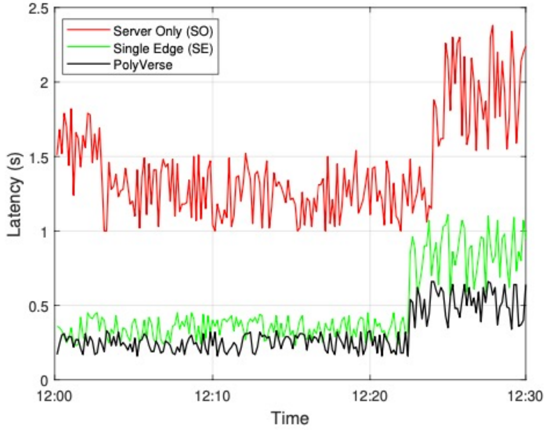
- **Metrics**
  - Latency of different phases
  - Data upload volume
- **Key results**
  - ~100 ms end-to-end latency
  - Reduce 95% data volume compared to traditional digital twin sync.



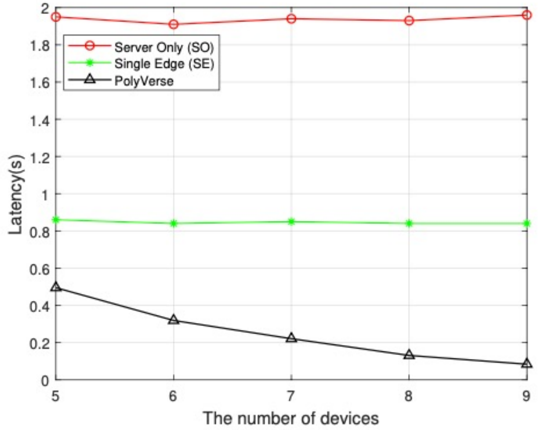




(a) Workload dynamics



(b) Latency vs. dynamic workload



(c) Latency vs. number of devices

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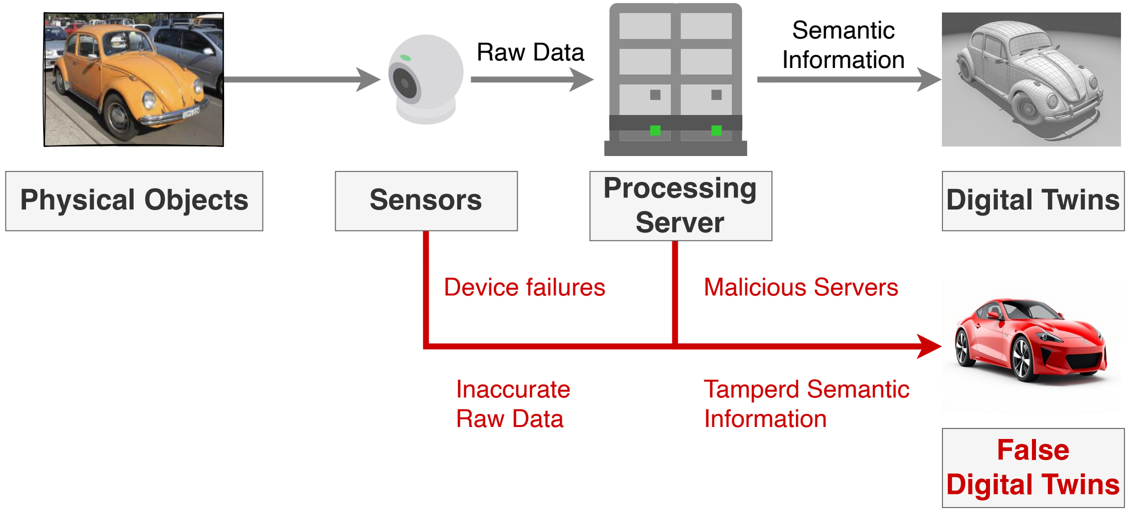
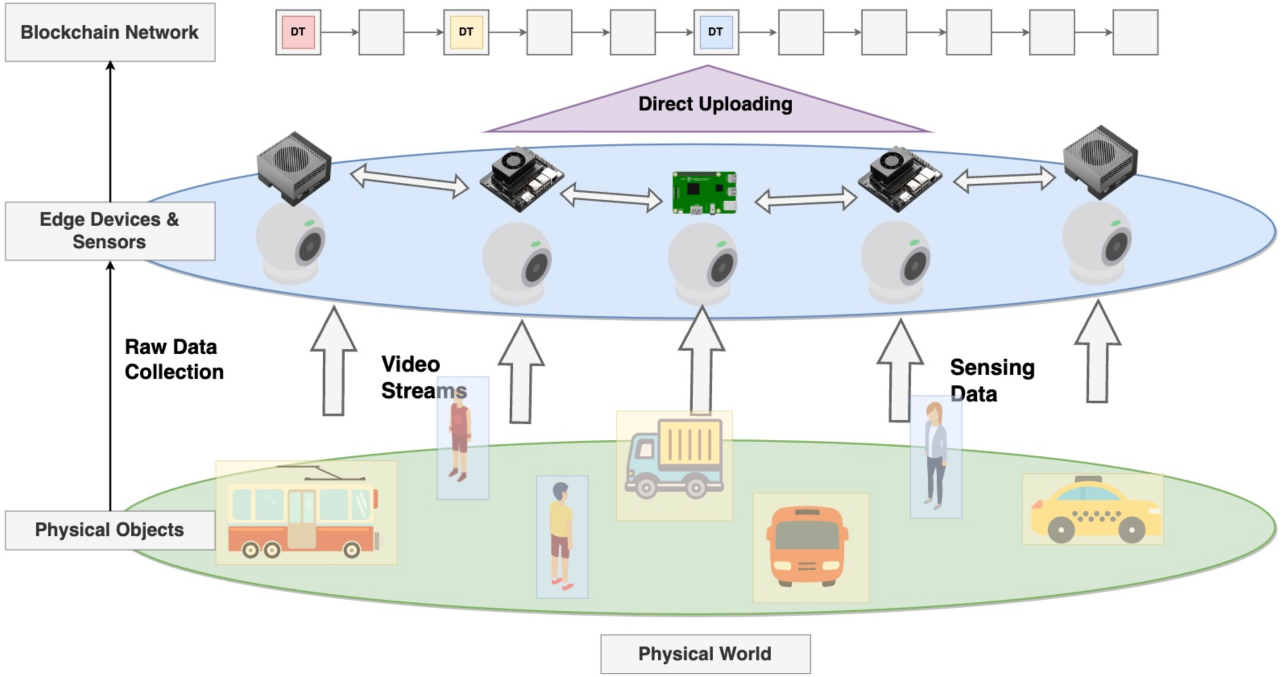
Trust Issues in Digital Twin Synchronization

- Digital twin synchronization is vulnerable in adversarial environment
- Existing blockchain-based approaches
  - Simply upload them on-chain
  - No verification between the extracted physical objects states before uploading
  - Only ensure the consistency after on-chain
  - Limited consistency guarantees

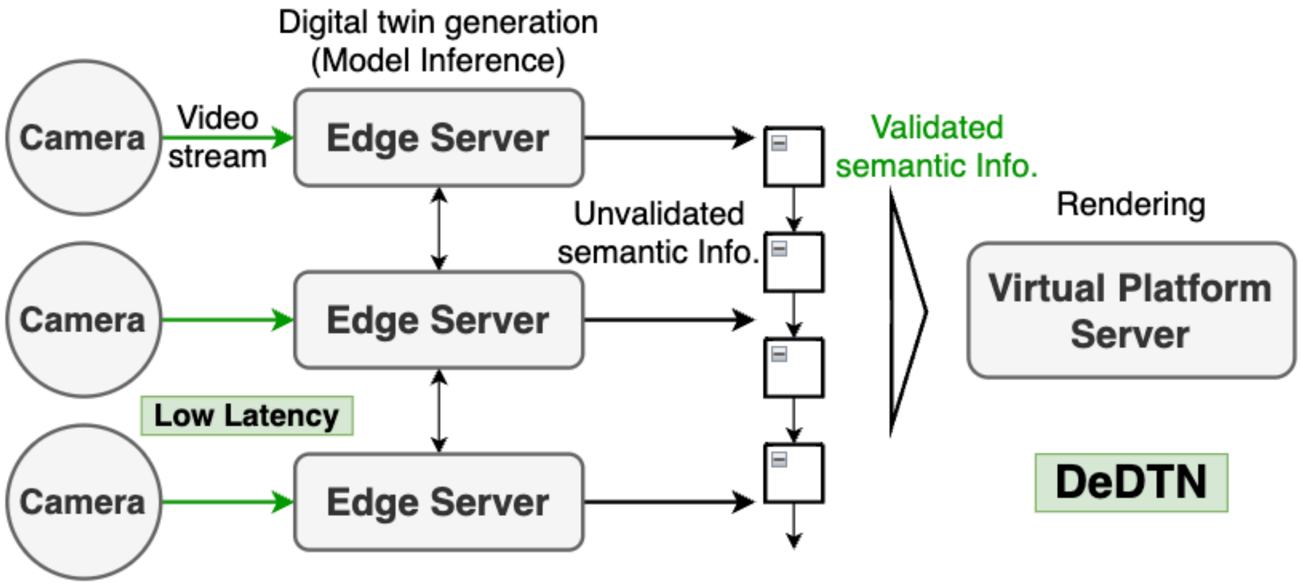




Suhail S, Hussain R, Jurdak R, et al. Blockchain-based digital twins: Research trends, issues, and future challenges[J]. ACM Computing Surveys (CSUR), 2022, 54(11s): 1-34.

Solution: ChainTwin

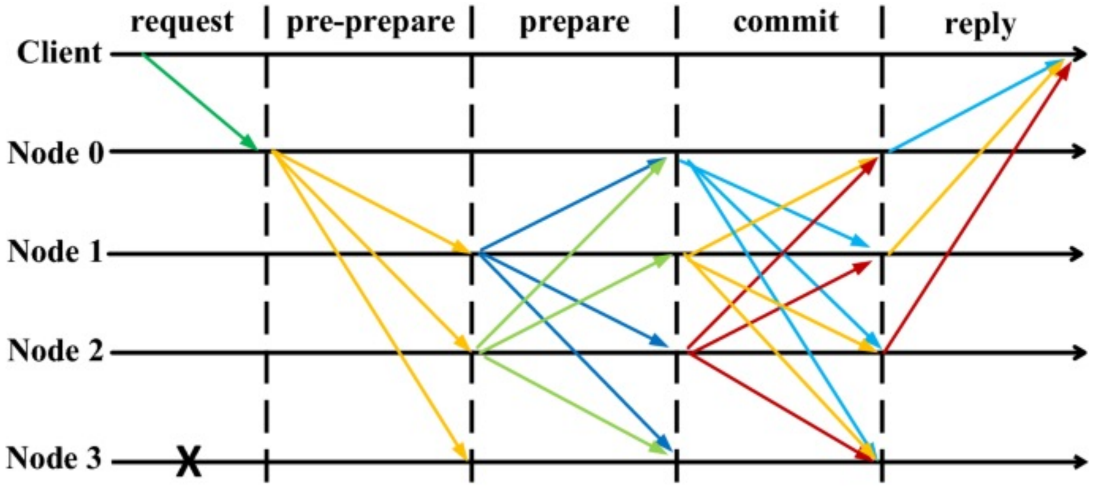
- Main Idea: Verify physical object states before uploading to blockchain nodes for consensus
  - After verification, the reached consensus in the blockchain network can actually guarantee the consistency of digital twins

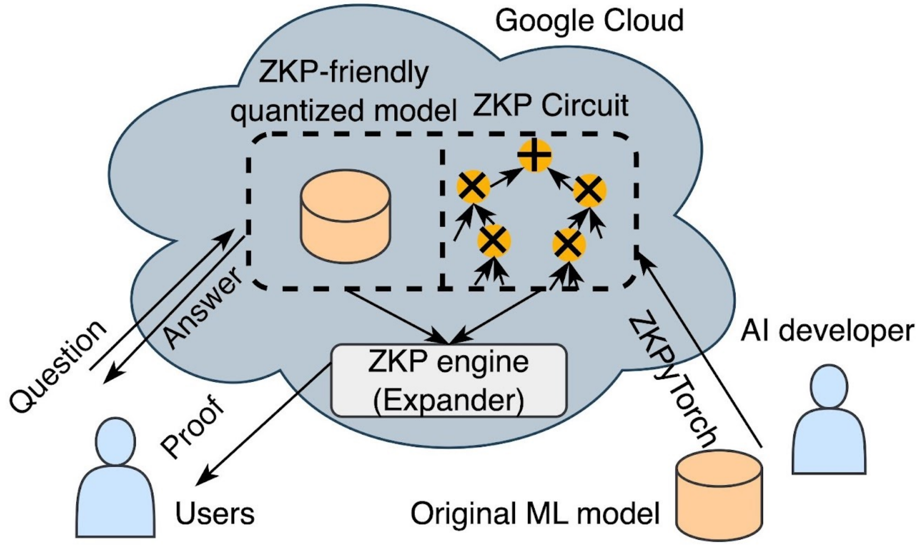


Yinfeng Cao, Jiannong Cao, Baoxia Du, Dongbin Bai, Mingjin Zhang, and Ruidong Li. (2025) "ChainTwin: Blockchain-based Trustless Digital Twin Generation and Cross-Domain Adoption". IEEE Transactions on Network Science and Engineering (Major Revision).
Yinfeng Cao, Jiannong Cao, Baoxia Du, and Ruidong Li(2025). "Decentralized Digital Twin Network". IEEE Communications Magazine.

Challenges

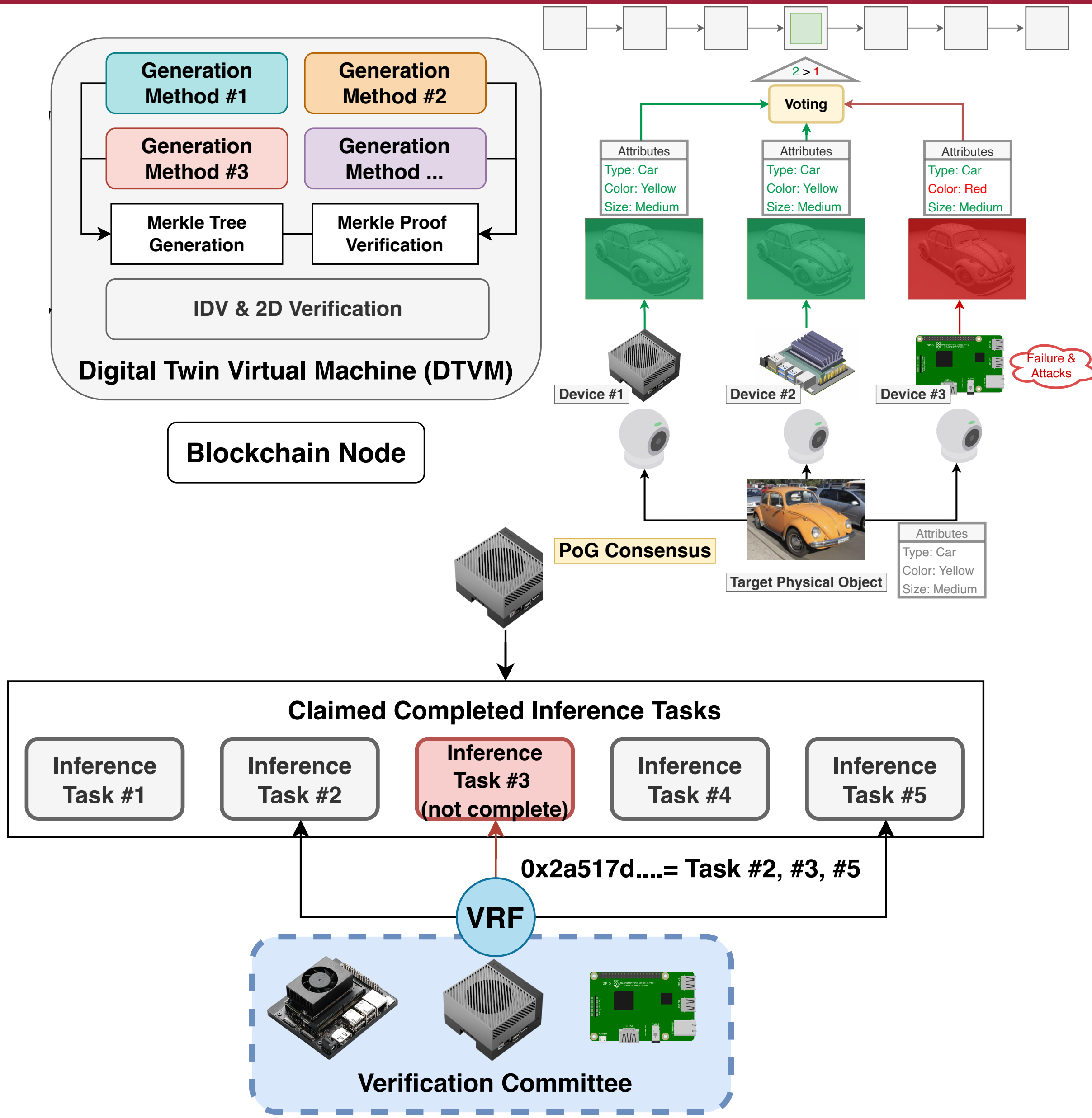
- Challenge 1: High computational costs for verifying DT states from AI models
  - Re-produce
  - Verifiable machine learning
  - LLM-as-a-Judge
- Challenge 2: High communication costs for all blockchain nodes to run verification
  - $O(N^2)$ complexity for BFT consensus





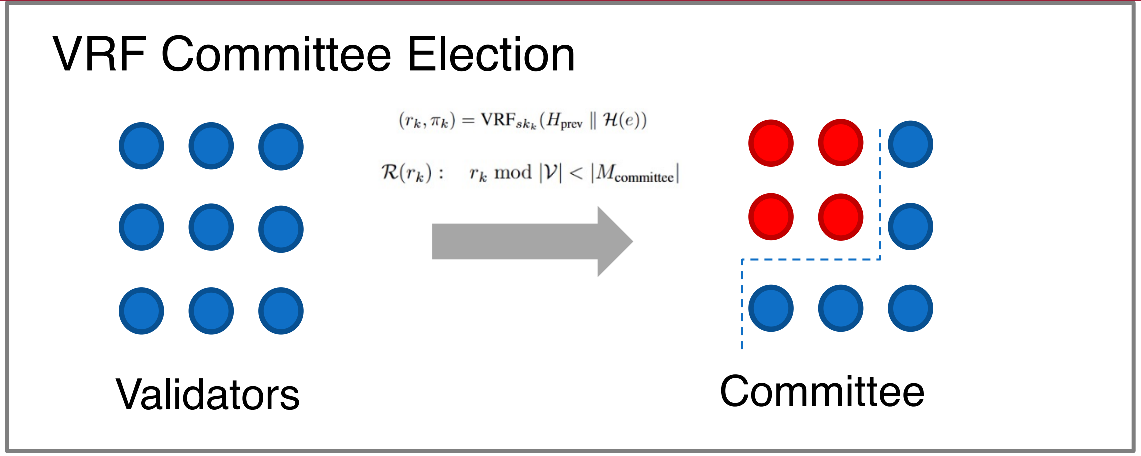
Tackle Challenge 1

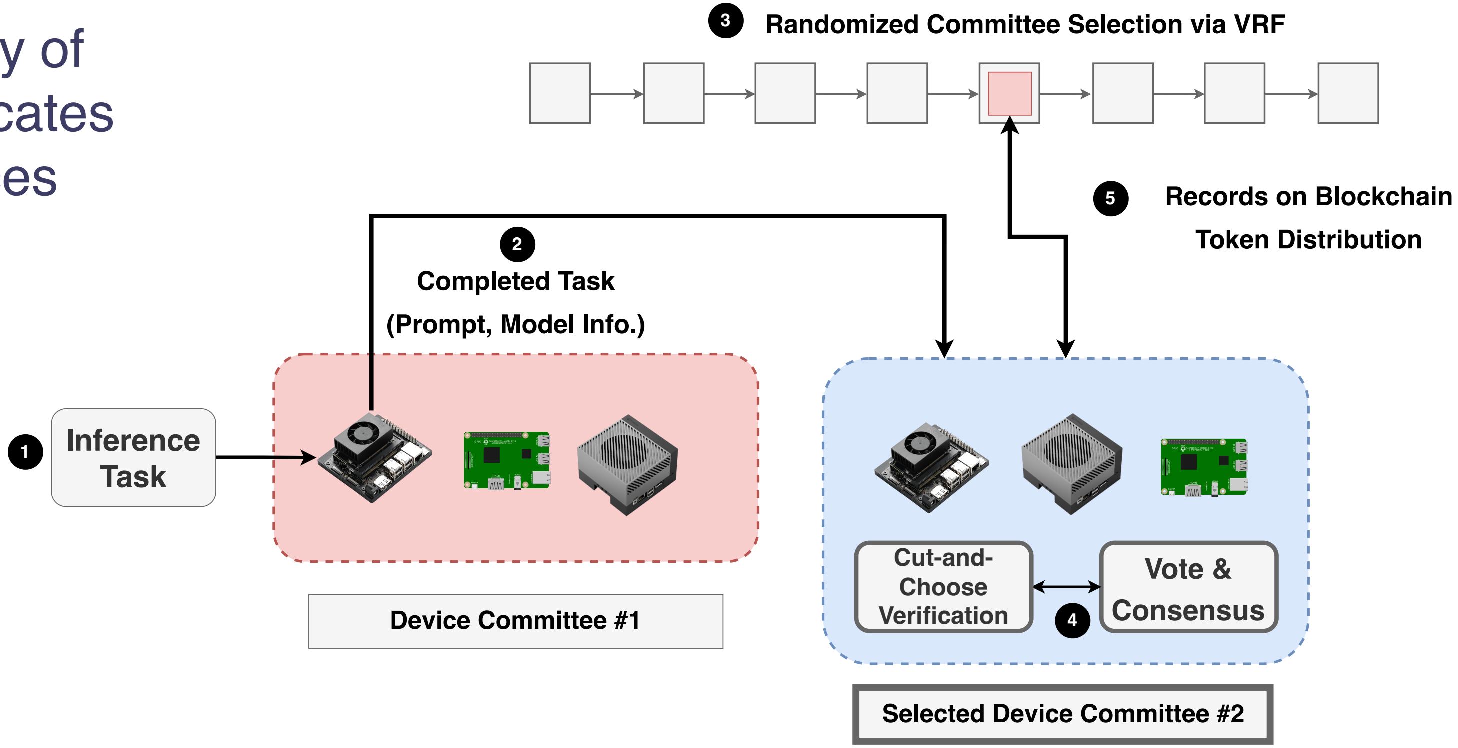
- **Digital twin generation machine**
  - Each device are equipped with multiple AI models
  - Overlapped cluster deployment mode
- **Cut-and-choose verification strategy**
- **(Which task needs to verify)**
  - Given a list of completed tasks to be verified, randomly choose the partial tasks to reproduce the inference results
  - If all the chosen tasks are reproduced, likewise, we can infer all tasks are correctly executed
  - **Benefits:** Further improves the verification efficiency by reducing the number of inference tasks to be verified



Tackle Challenge 2

- **Randomized committee selection**
- **(who run the verification)**
  - Randomly selected a qualifiable (i.e., devices able to observe the physical objects) sub-committee from validator pool to run the verification protocol
  - The consensus result from the majority of the randomly selected committee indicates the task integrity on all the other devices approximately
  - **Benefits:** Balance the efficiency and security



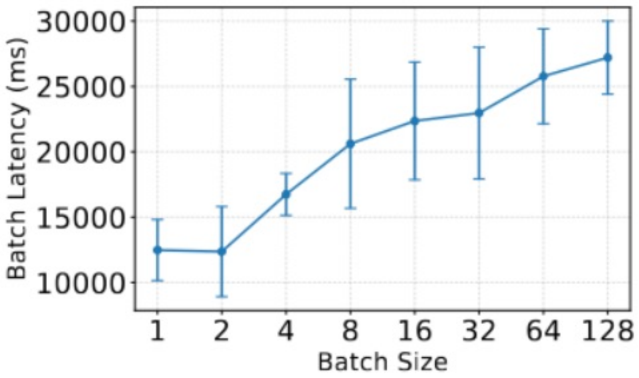


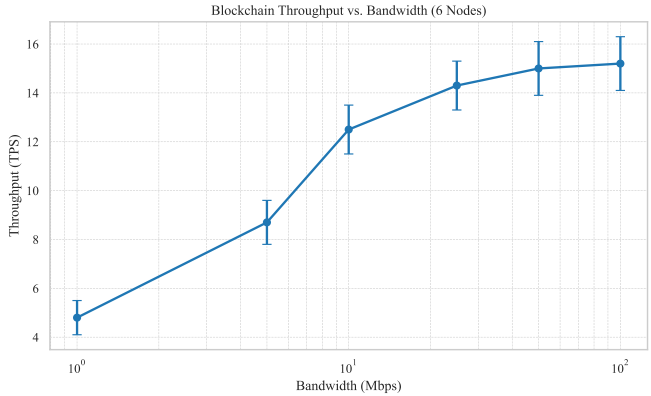
Experiments and Results

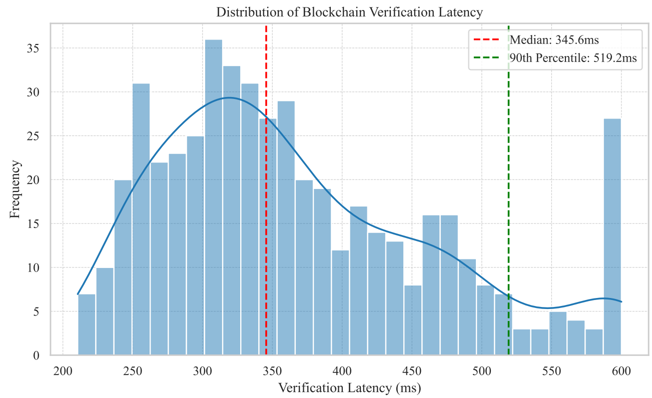
- Real-world prototype
- Verification protocols include
  - Reproduce
  - LLM-as-a-judge
- Metrics and results
  - Throughput (6 nodes, 100Mbps, 15 TPS)
  - End-to-end latency (MED 300ms for reproducing, 25000ms for LLM-as-a-judge)
  - The first protocol can verify physical objects

Worker	Device Location	Device Type	Quantity
1	Guangzhou, Panyu	NVIDIA RTX 2080 Ti	2
2	Kanazawa, Kakumamachi	NVIDIA RTX A4500	1
	Hong Kong, Hung Hom	NVIDIA RTX 4060 Ti	1
	Hong Kong, Hung Hom	NVIDIA RTX 3080 Ti	1
3	Hong Kong, Hung Hom	Jetson Orin NX (16GB)	3
	Hong Kong, Hung Hom	Jetson AGX Orin (32GB)	3
	Shenzhen, Luohu	Apple MacBook Pro (M3 Pro)	1
4	Hong Kong, Pokfulam	NVIDIA Tesla P100	2
5	Hong Kong, Sai Kung	NVIDIA RTX 4090	8
	Hong Kong, Hung Hom	NVIDIA RTX 3090	1
6	Hong Kong, Hung Hom	NVIDIA RTX 3090	1
	Hong Kong, Hung Hom	NVIDIA RTX 3090	1
7	Hong Kong, Sha Tin	NVIDIA RTX 3090	4
8	Hong Kong, Sha Tin	NVIDIA RTX 3060	1
	Hong Kong, Hung Hom	NVIDIA RTX 2060	1
9	Hong Kong, Hung Hom	NVIDIA RTX 3090	5
	Hong Kong, Hung Hom	NVIDIA RTX 3090 Ti	1
	Hong Kong, Hung Hom	NVIDIA Quadro GV100	2
10	Hong Kong, Hung Hom	NVIDIA Tesla A100	1
	Hong Kong, Hung Hom	NVIDIA RTX 4090	4

Geo-Distributed Heterogeneous devices







Performance Results

Outline

- Introduction of Digital Twins
- Problems, Existing Works, and Challenges
  - Synchronization
  - Interoperability
- My PhD Research
- Research Contributions
  - PolyVerse: An Edge-based Digital Twin Platform with Physical-to-Virtual Projection
  - ChainTwin: Trustworthy Digital Twin Synchronization
  - **MAP: Efficient and Scalable Blockchain-based Digital Twin Interoperation**
- Summary and Future Directions

Digital Twin Interoperability

- Digital twins need to be interoperable to be adopted in different platforms
  - Different platforms integrate diverse services
  - Operating and sharing among virtual platform, upper applications, etc.
  - E.g., metaverse, real-world asset (RWA),
- Traditional methods like standardization and transformation
  - Require centralized trust / not scalable for large-scale digital twin networks

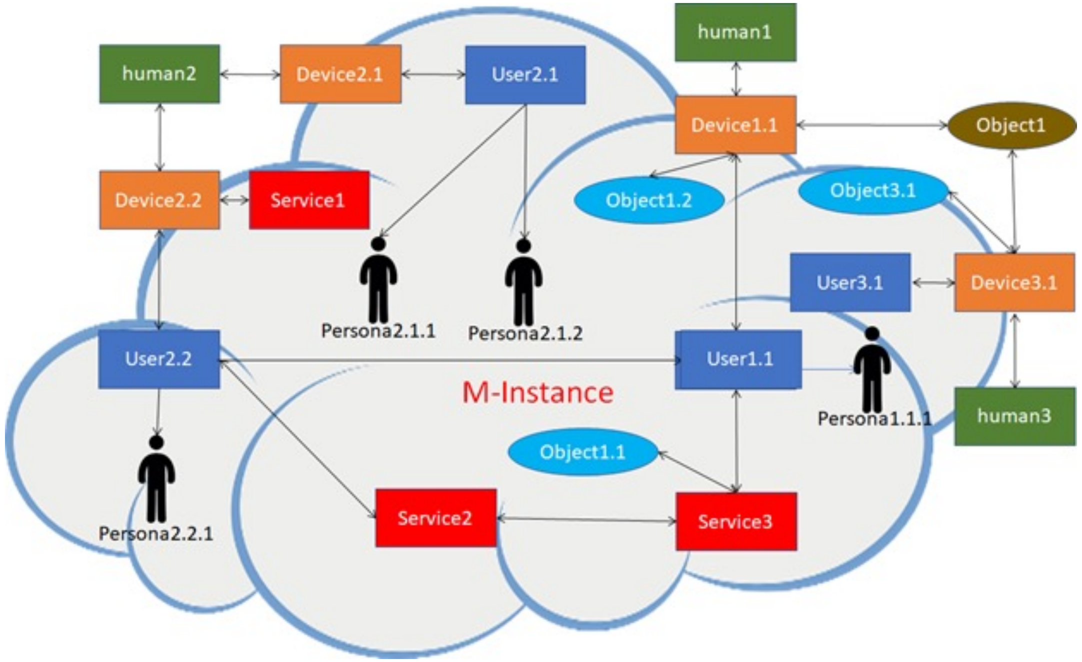
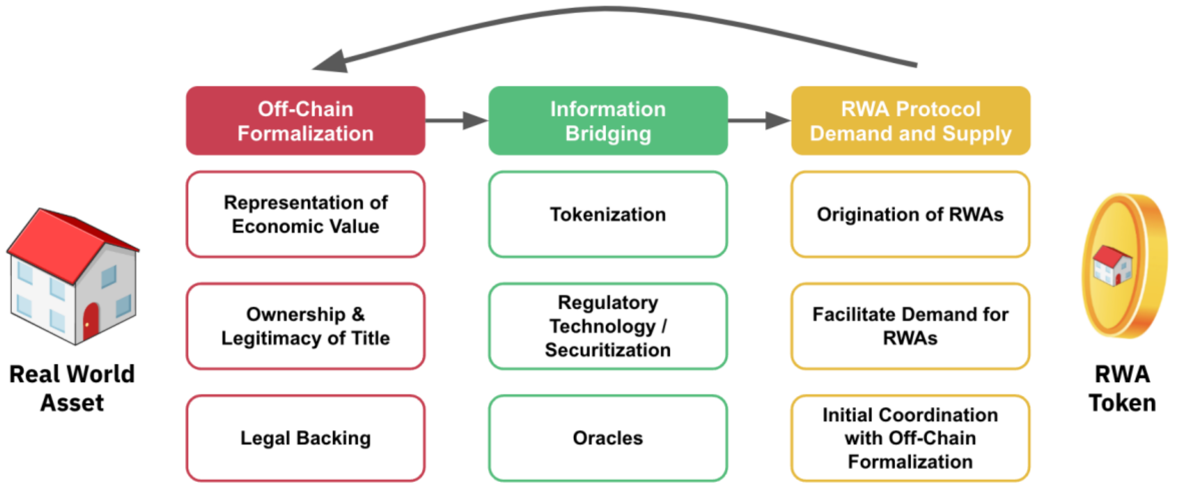


Figure 5: How RWA tokens become legitimate bearer assets

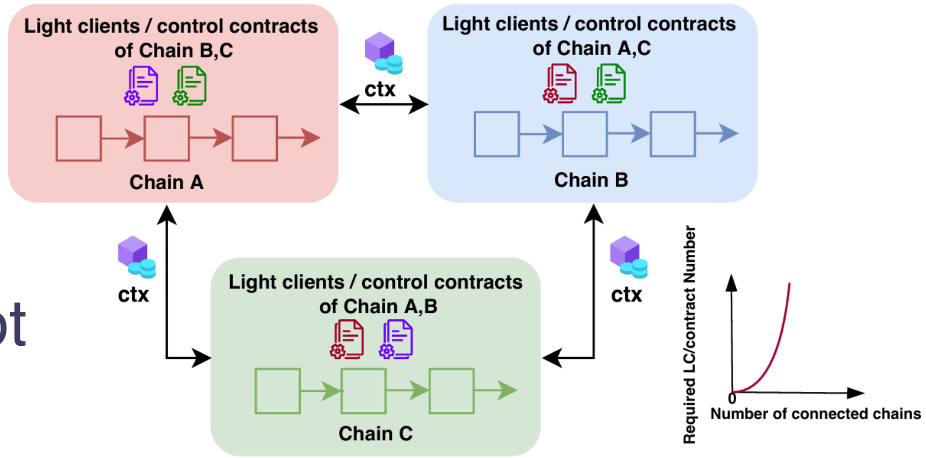


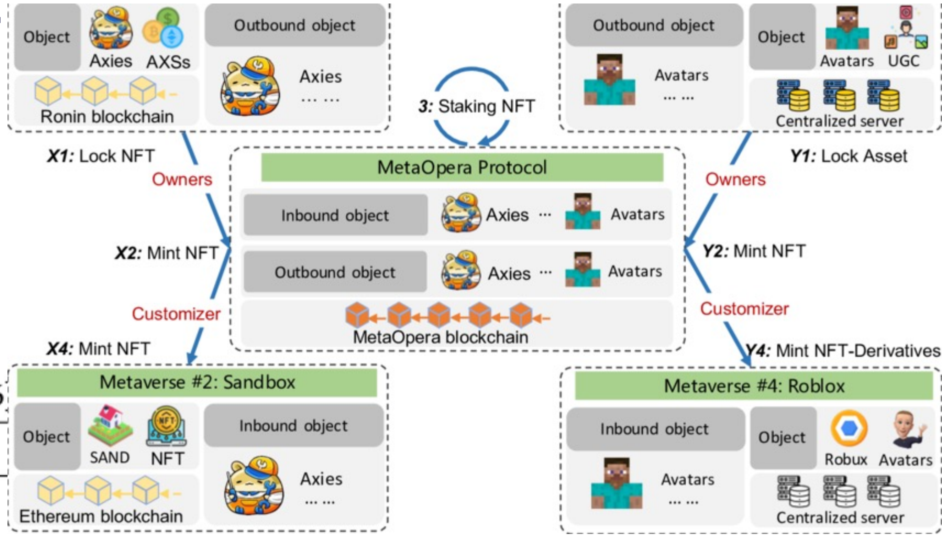
Source: Binance Research

Suhail S, Hussain R, Jurdak R, et al. Blockchain-based digital twins: Research trends, issues, and future challenges[J]. ACM Computing Surveys (CSUR), 2022, 54(11s): 1-34.

Challenges

- Blockchain-based interoperability solutions are promising
  - Tokenize the digital twins as tokens (e.g., NFT)
  - Secure data sharing
  - High transparency and traceability
- Challenge 1: Trust issues
  - Some blockchain interoperability protocols are not completely decentralized
- Challenge 2: High costs for running verification
  - High on-chain costs (light client-based bridges) or
  - off-chain costs (zk-based bridges)
  - Hard to scale: $O(N^2)$ smart contract pairs

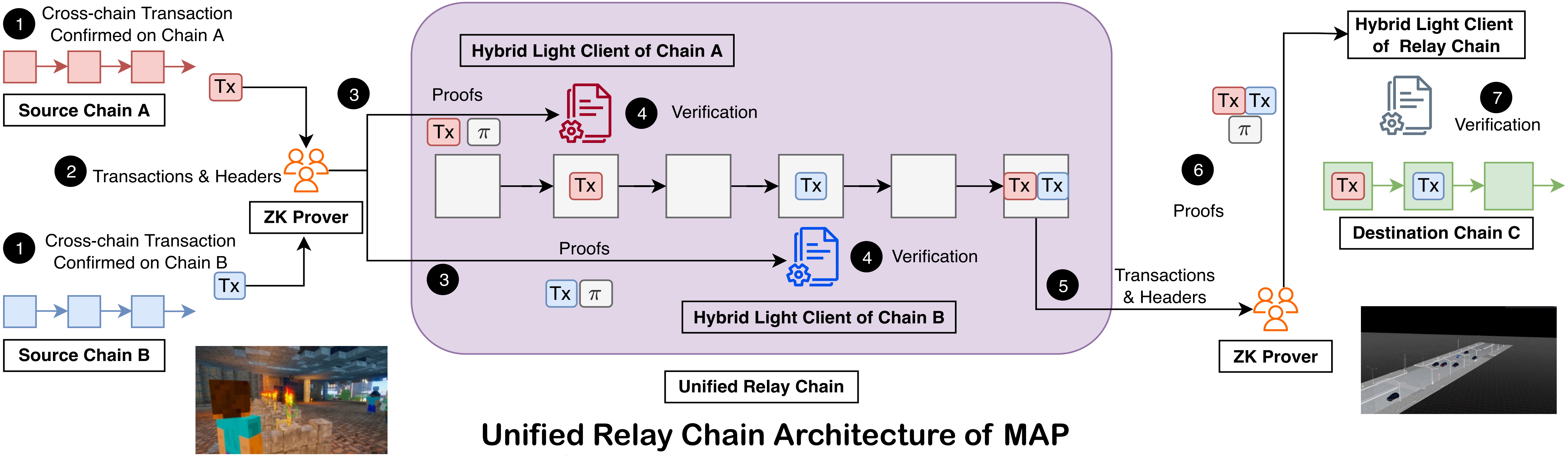




Solutions	Binance, CoinBase[3][9]	Multichain, Celer[28][10]	EthHTLC[7], Lighting[2]	Polkadot, Cosmos[44][18]	Horizon, LayerZero,[19][48]	zkRelay, zkBridge[43][46
Types	Notary	MPC	HTLC	BoB	LC	ZKLC
Security Models	Trusted	Semi-Trusted	Trustless	Trustless	Trustless	Trustless

Unified Relay Chain

- MAP: A blockchain-based interoperability protocol for cross-platform digital twins
  - Introduce a public PoS relay chain between source chain(SC) and destination chain (DC)
  - Integrate all SCs and DCs' the cryptographic primitives and algorithms in the VM
  - Deploy on-chain light clients of each other chains

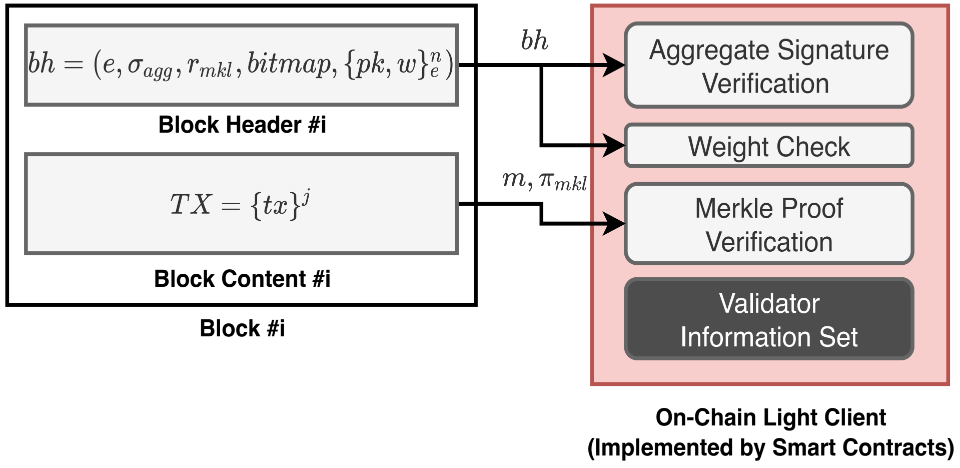


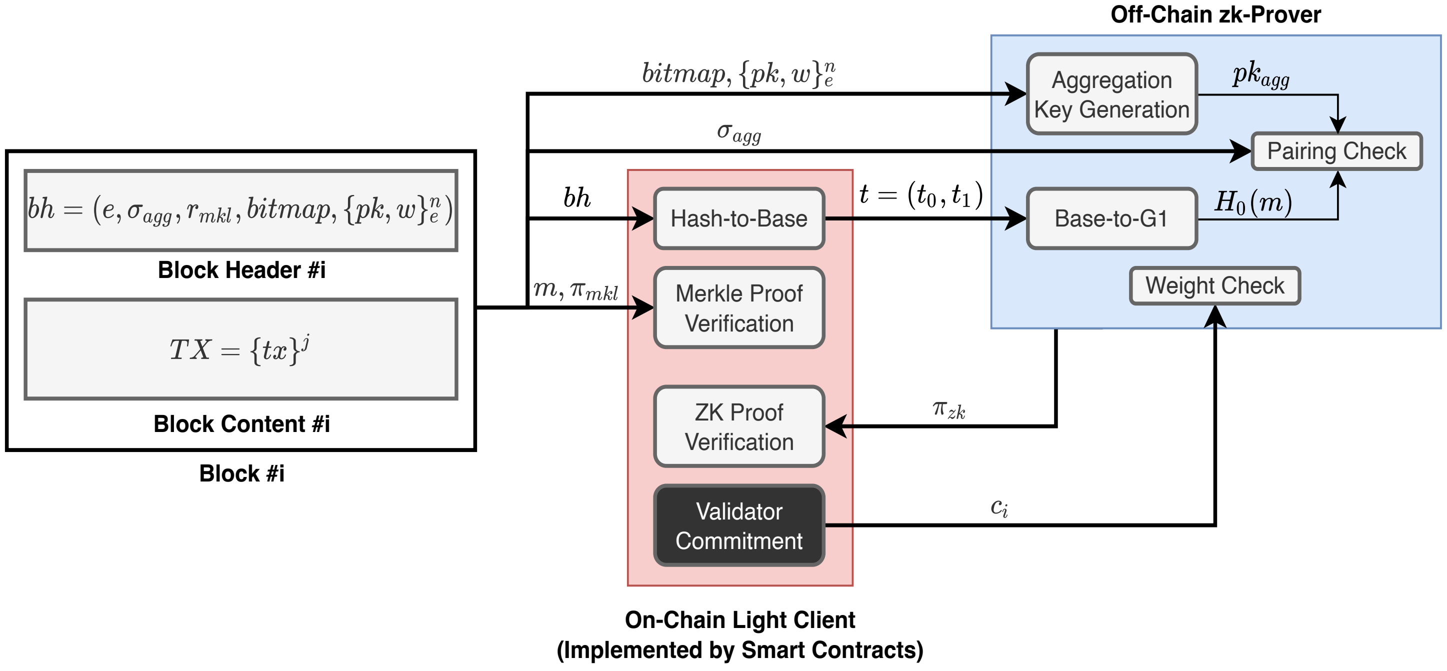
Unified Relay Chain Architecture of MAP

Yinfeng Cao, Jiannong Cao, Dongbin Bai, Long Wen, Yang Liu, and Ruidong Li(2025). "MAP the Blockchain World: A Trustless and Scalable Blockchain Interoperability Protocol for Cross-chain Applications". The ACM Web Conference 2025 (WWW 2025) Sydney, Australia.

ZK-based Hybrid Light Client

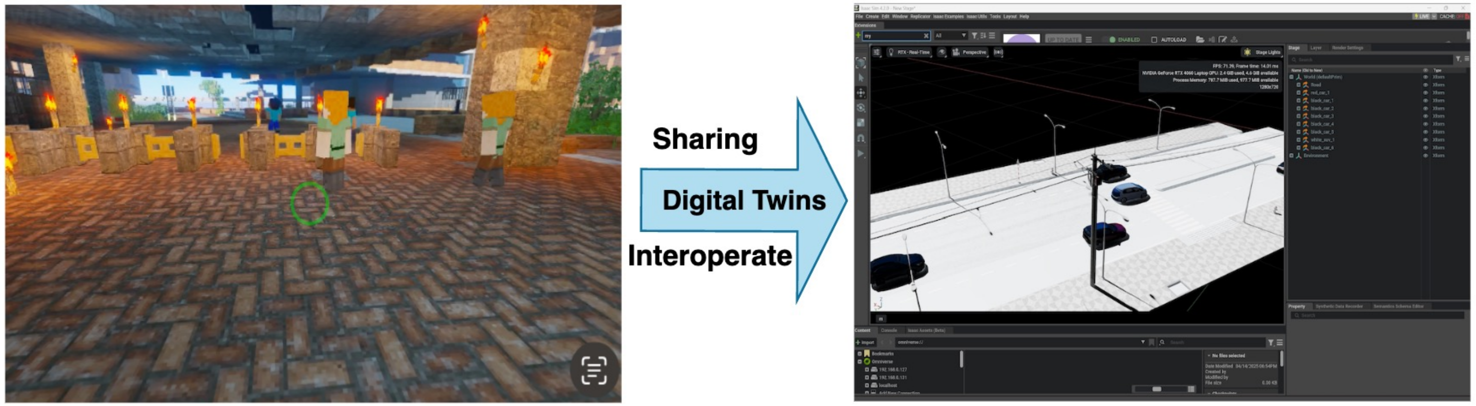
- Reduce and balance the on-chain cost and off-chain cost to achieve overall efficiency (i.e., PoS Aggregated Signature Verification on PoS Chain Headers)
  - Decouple the most expensive sig. verification workloads
  - Hash-related operations are executed on-chain
  - Curve operations are moved to off-chain zk prover





Performance

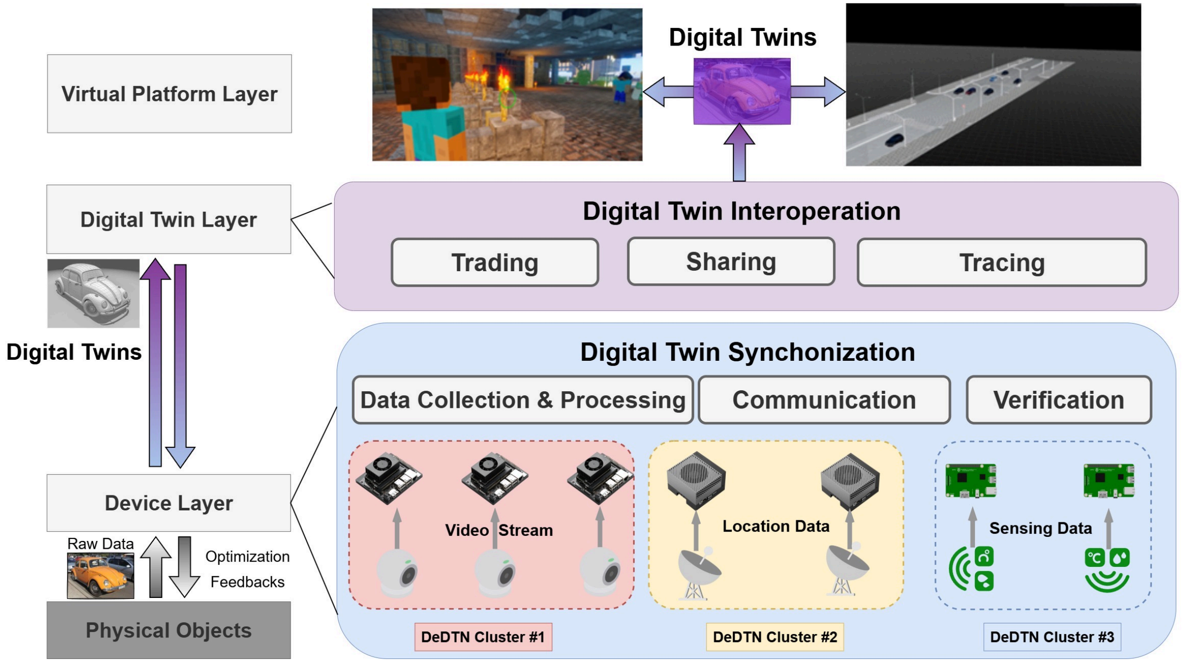
- **Two prototypes**
  - Cross-domain digital twin
  - RWA (token relay)
- **Metrics and results**
  - Reduced on-chain costs (~35%)
  - Reduced off-chain costs (~25%)
  - O(N) smart contracts for connecting N virtual platforms or chains



Evaluation Metrics	Centralized	Committee	Chain				
Solutions	Binance, CoinBase[3][9]	Multichain, Celer[28][10]	EthHTLC[7], Lighting[2]	Polkadot, Cosmos[44][18]	Horizon, LayerZero,[19][48]	zkRelay, zkBridge[43][46]	**MAP**
Types	Notary	MPC	HTLC	BoB	LC	ZKLC	**ZKLC+Relay**
Security Models	Trusted	Semi-Trusted	Trustless	Trustless	Trustless	Trustless	**Trustless**
On-chain Costs (gas)	N/A	0.5×10^6	1.5×10^6	0.8×10^5	1×10^6	0.3×10^6	**0.65×10^6 (35% ↓)**
Off-chain Costs (gates)	N/A	N/A	N/A	N/A	N/A	2×10^7	**1.57×10^7 (25% ↓)**
Latency	1s	310s	N/A	13s	227s	153s	**210s**
Complexity	$O(N)$	$O(N^2)$	$O(N^2)$	$O(N)$	$O(N^2)$	$O(N^2)$	**O(N)**

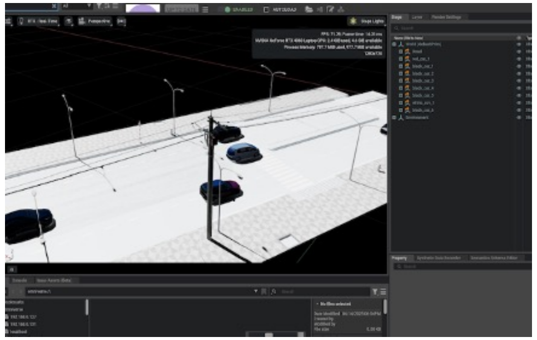
Summary of My PhD Contributions

- Study and solve a fundamental problem: DT consistency
  - PolyVerse: New end-to-end digital twin system leveraging blockchain and edge AI
  - ChainTwin: The first digital twin synchronization protocol that can verify physical objects against BFT
  - MAP: interoperability protocol with significantly improved performance
  - Deployed prototypes for different scenarios



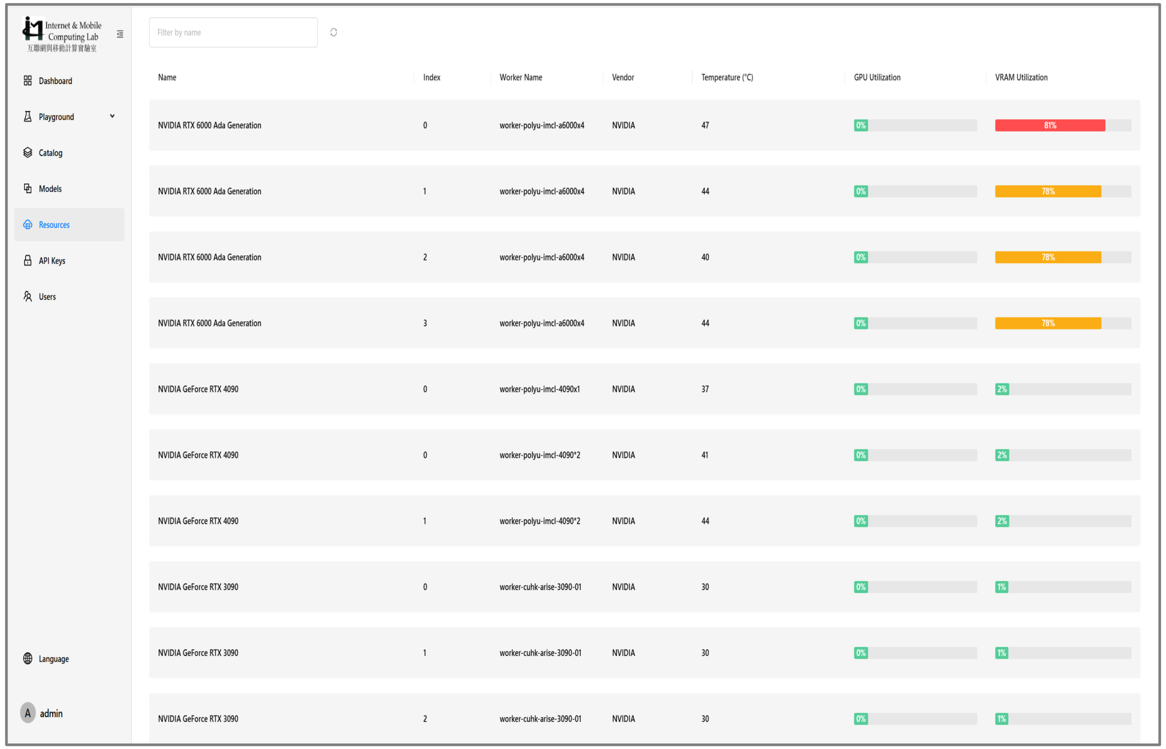
Trustworthy and Insteroperable Digital Twins

Massive Objects in Adversarial Environment

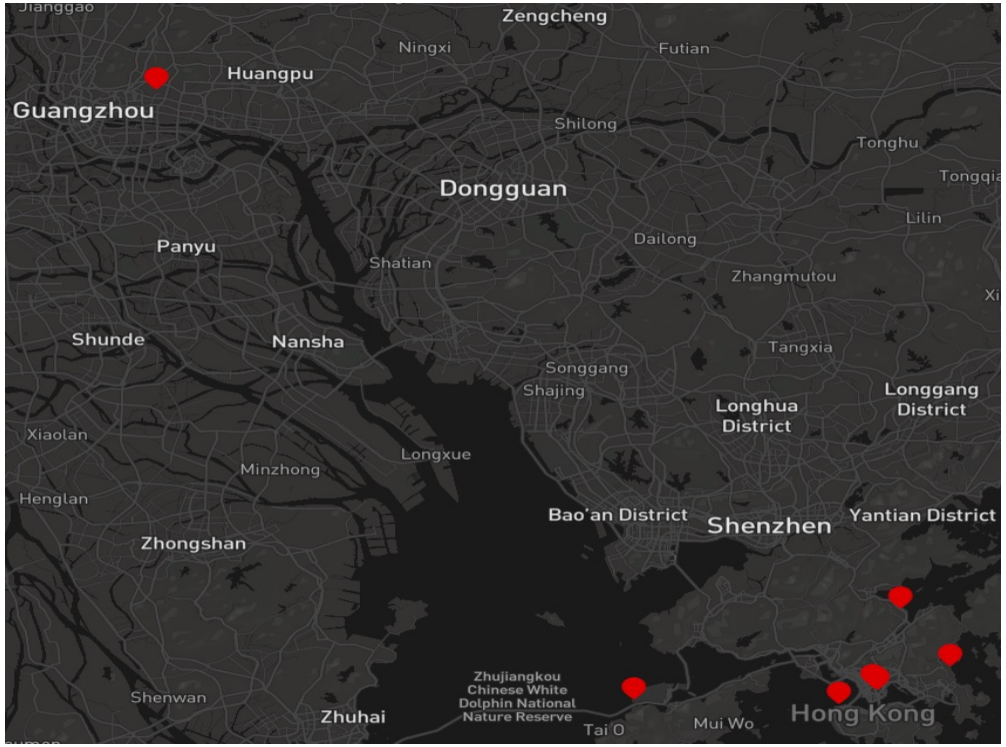


Future Works

- Geo-Decentralized Edge Digital Twin Platform
  - Extremely large-scale digital twin network (smart city, disaster management, campus)
  - Cross-region deployment
  - Decentralized and collaborative modeling and rendering



Name	Index	Worker Name	Vendor	Temperature (°C)	GPU Utilization	VRAM Utilization
NVIDIA RTX 6000 Ada Generation	0	worker-polyu-imcl-a6000x4	NVIDIA	47	0%	81%
NVIDIA RTX 6000 Ada Generation	1	worker-polyu-imcl-a6000x4	NVIDIA	44	0%	78%
NVIDIA RTX 6000 Ada Generation	2	worker-polyu-imcl-a6000x4	NVIDIA	40	0%	78%
NVIDIA RTX 6000 Ada Generation	3	worker-polyu-imcl-a6000x4	NVIDIA	44	0%	78%
NVIDIA GeForce RTX 4090	0	worker-polyu-imcl-4090x1	NVIDIA	37	0%	2%
NVIDIA GeForce RTX 4090	0	worker-polyu-imcl-4090*2	NVIDIA	41	0%	2%
NVIDIA GeForce RTX 4090	1	worker-polyu-imcl-4090*2	NVIDIA	44	0%	2%
NVIDIA GeForce RTX 3090	0	worker-cuhk-arise-3090-01	NVIDIA	30	0%	1%
NVIDIA GeForce RTX 3090	1	worker-cuhk-arise-3090-01	NVIDIA	30	0%	1%
NVIDIA GeForce RTX 3090	2	worker-cuhk-arise-3090-01	NVIDIA	30	0%	1%



Publications Related to Thesis

Conference papers:

1. Jingwen Liang, Jiannong Cao, Bo Yang, Dongbin Bai, Hongbo Liu, **Yinfeng Cao** (2025) Decentralized Physical Infrastructure Networks: Backgrounds, Architectures, Open Issues, and Case Studies. Submitted to IEEE Blockchain 2025.
2. Hongbo Liu, Jiannong Cao, Bo Yang, Dongbin Bai, **Yinfeng Cao**, Xiaoming Shen, Yinan Zhang, Jingwen Liang, Shan Jiang, Mingjin Zhang. (2025) “PolyEdge: A Blockchain-Based Decentralized Edge AI Platform". submitted to IEEE Blockchain 2025.
3. **Yinfeng Cao**, Jiannong Cao, Dongbin Bai, Long Wen, Yang Liu, and Ruidong Limodeling (2025). "MAP the Blockchain World: A Trustless and Scalable Blockchain Interoperability Protocol for Cross-chain Applications". The ACM Web Conference 2025 (WWW 2025) Sydney, Australia.
4. **Yinfeng Cao,** Jiannong Cao, Hongbo Liu, Zeyang Cui and Long Wen. (2024). "Eden: An Edge Computing Empowered Proof-of-Personhood Protocol for Anti-Sybil in Blockchain-based Metaverse". The 2nd International Conference on Intelligent Metaverse Technologies & Applications (iMETA2024) Best Paper Award Nomination.
5. **Yinfeng Cao,** Jiannong Cao, Zeyang Cui, Dongbin Bai, Mingjin Zhang, Long Wen. (2024). "PolyTwin:Edge Blockchain-empowered Trustworthy Digital Twin Network for Metaverse". The 2nd Annual IEEE International Conference on Metaverse Computing, Networking, and Applications (IEEE MetaCom 2024)
6. **Yinfeng Cao**, Jiannong Cao, Dongbin Bai, Zhiyuan Hu, Kaile Wang, Mingjin Zhang (2023). PolyVerse: An Edge Computing-Empowered Metaverse with Physical-to-Virtual Projection. IEEE International Conference on Intelligent Metaverse Technologies and Applications (iMETA2023), 18-20 September 2023, Tartu, Estonia. Best Paper Award Nomination

Publications Related to Thesis

Journal papers:

1. **Yinfeng Cao,** Jiannong Cao, Ruidong Li, “Blockchain Empowered Digital Twin Networks: Motivations, Fundamentals, Emerging Applications, and Open Challenges”, to be submitted to IEEE Communications Surveys & Tutorials
2. Hongbo Liu, Jiannong Cao, **Yinfeng Cao**, Dongbin Bai, Jinwen Liang, Ruidong Li. (2025) “EdenDID: An Edge Computing and Blockchain-based Decentralized Identity System for Web3 Applications and DePIN“. Cluster Computing (Minor revision).
3. **Yinfeng Cao**, Jiannong Cao, Baoxia Du, Dongbin Bai, Mingjin Zhang, and Ruidong Li. (2025) "ChainTwin: Blockchain-based Trustless Digital Twin Generation and Cross-Domain Adoption". IEEE Transactions on Network Science and Engineering (Major Revision).
4. **Yinfeng Cao**, Jiannong Cao, Baoxia Du, and Ruidong Li(2025). "Decentralized Digital Twin Network". IEEE Communications Magazine.

thank you

We sincerely appreciate your presence and listening!