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This talk is not about research aimed to improve ICN performance, but rather research conducted from **the perspective of an ICN "user."**

ICN Service Mesh for plug-and-play ICN

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DePIN: Decentralized Physical Infrastructure Network
Co-Digital Twin: Co-creation of Digital Twin

Introduction

- Dawn of **Web3** Era
  - From Centralized Internet to **Decentralized Internet**
  - Users can manage and operate their own data

- Network infrastructure also follows trend toward decentralization
  - Spread of **decentralized network storage**
    - InterPlanetary File System (IPFS) becomes de facto standard
    - (Broadly defined) Information-Centric Network is adopted as network protocol
    - Data access using content identifiers
  - Emergence of **Decentralized Physical Infrastructure Network (DePIN)**
    - Building and maintaining decentralized infrastructure using Distributed Ledger Technologies
    - Infrastructure management **based on sharing economy** business model

Introduction (cont.)

- ICN could become a good network protocol to support various Web3 applications

- Web3 applications
  - Decentralized network storage
    - IPFS adopt ICN but not pure ICN like CCN/NDN
  - Distributed computing & In-Network Computing
  - AI Agent (Network for AI)
    - AI Agent could be a kind of Service Function Chaining
  - Trust Network for DePIN
  - **DePIN-based Co-Digital Twin** (our current main activity)

ICN implementation from the user's Perspective

- While there are several ICN implementations, **few implementations have reached the level of providing an API**
- **Difficulty of developing applications** based on ICN
- Developers **must implement ICN functionality** in addition to the application itself
  - Ideally, communication functions should be transparent to the application
  - Upper layers should not be aware of processing or protocols of lower layers
  - It should be possible to seamlessly replace the protocols used in existing applications
    - If applying ICN requires reimplementing the application, there is no motivation to use ICN
- Is it possible to implement ICN in **a plug-and-play manner**?

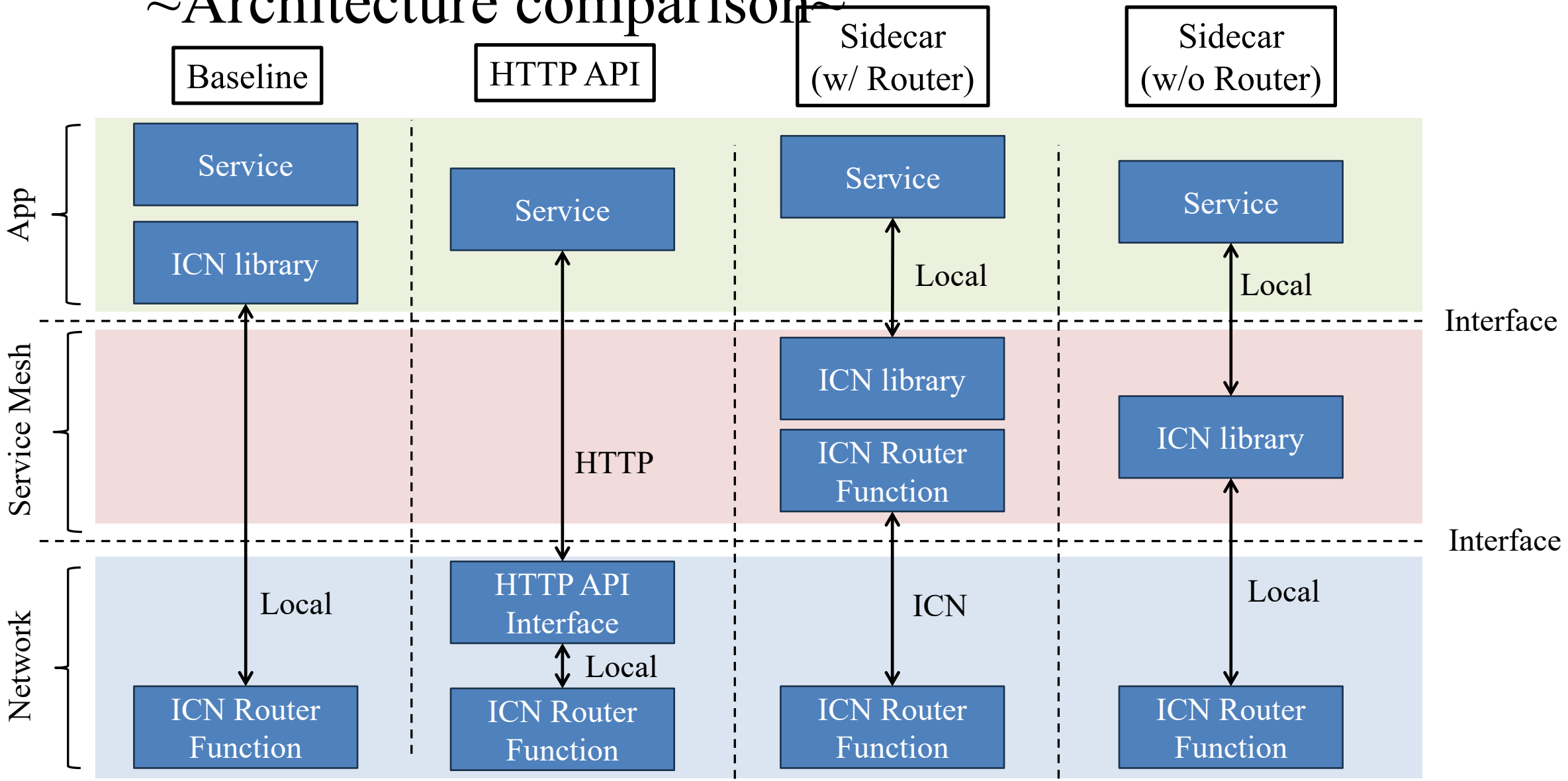
H. Saito, K. Kanai, H. Nakazato, “Development and Evaluation of ICN Service Mesh using NDN Function Chaining”, IEEE CCNC 2024.

ICN Service Mesh ~Motivation and goal~

- **Service Mesh** is one of cloud-native technologies
  - It mediates communication between (micro) services and resolves operational challenges related to communication
    - Traffic control
    - Fault tolerance
    - Security and access control
    - Observability
  - Istio/Envoy is a current de facto standard
    - Primarily supports HTTP
- ICN Service Mesh aims to **provide ICN functionality transparently** to applications
  - (Aim to) enable plug-and-play utilization of ICN functionality
  - (Aim to) achieve autonomous and distributed network control
  - (Aim to) realize a trusted networks

H. Saito, K. Kanai, H. Nakazato, “Development and Evaluation of ICN Service Mesh using NDN Function Chaining”, IEEE CCNC 2024.

ICN Service Mesh ~Architecture comparison~

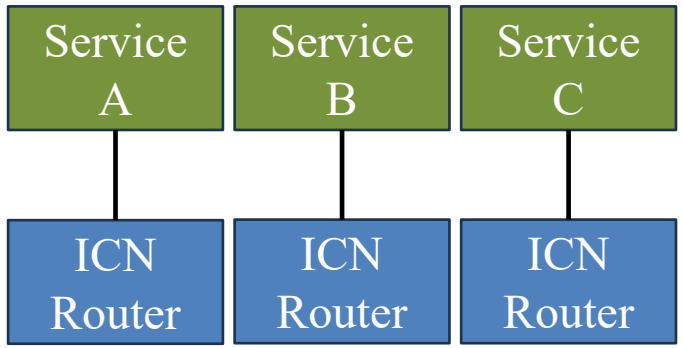


H. Saito, K. Kanai, H. Nakazato, “Development and Evaluation of ICN Service Mesh using NDN Function Chaining”, IEEE CCNC 2024.

ICN Service Mesh ~Deployment comparison~

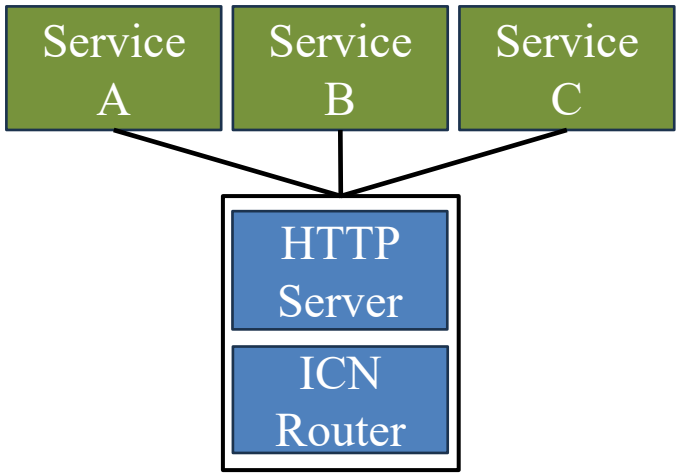
※ICN Router: ICN Router Function (e.g., Packet forwarding demon)

Baseline



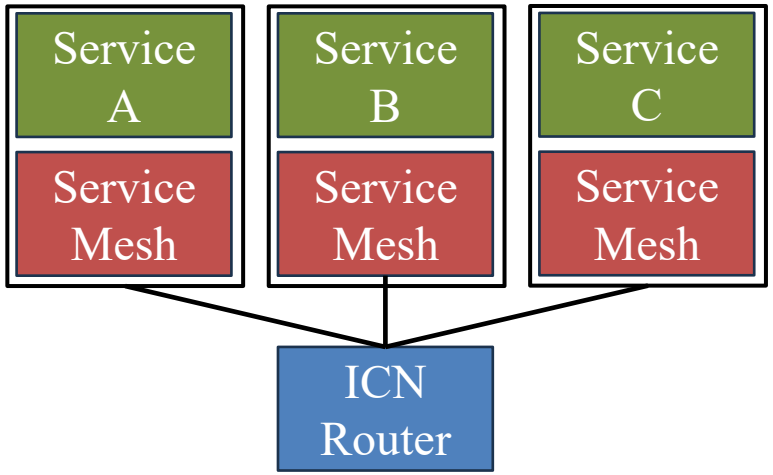
- ✓ ICN Router is required for each service
- ✓ Scalability issue

HTTP API



- ✓ ICN Router **can be shared** among services
- ✓ **HTTP server resources** are required

Sidecar (w/ Router) / Sidecar (w/o Router)

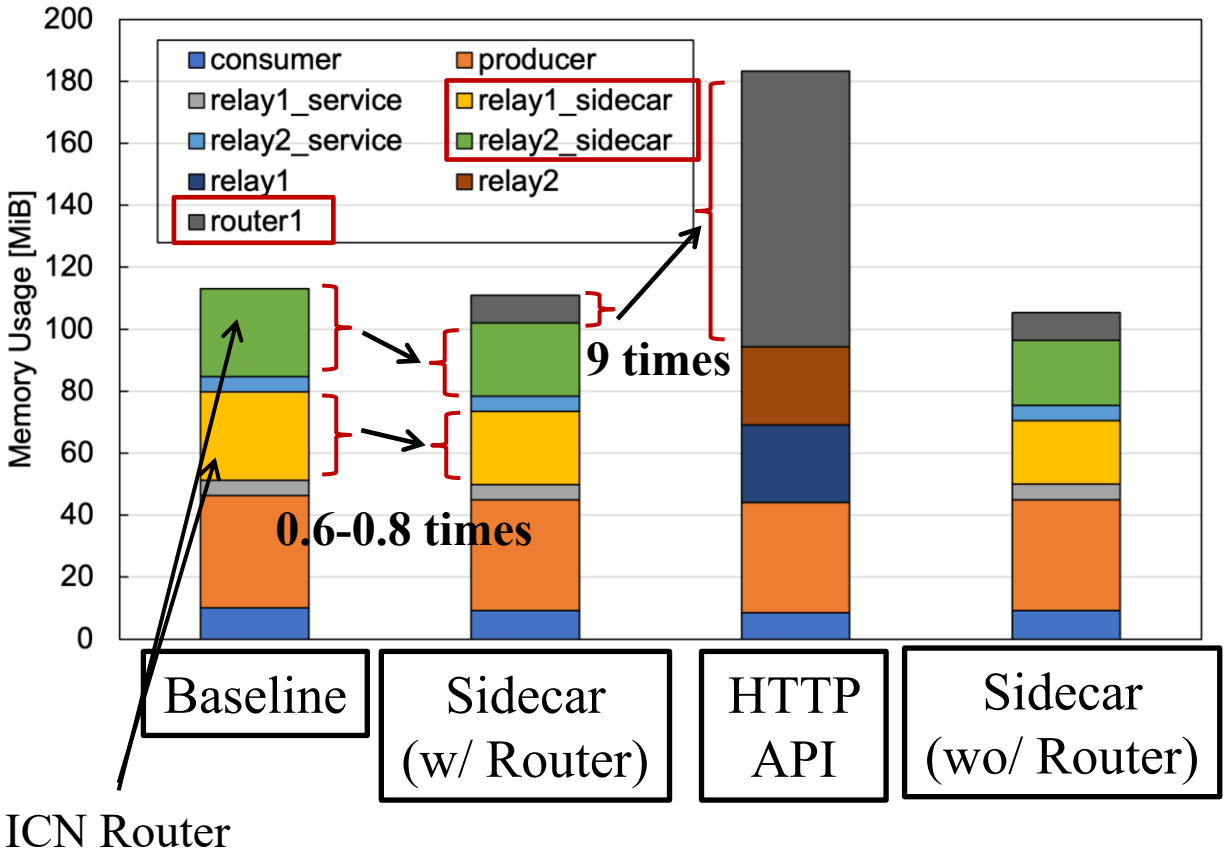


- ✓ ICN Router **can be shared** among services
- ✓ **Service mesh resources** are required

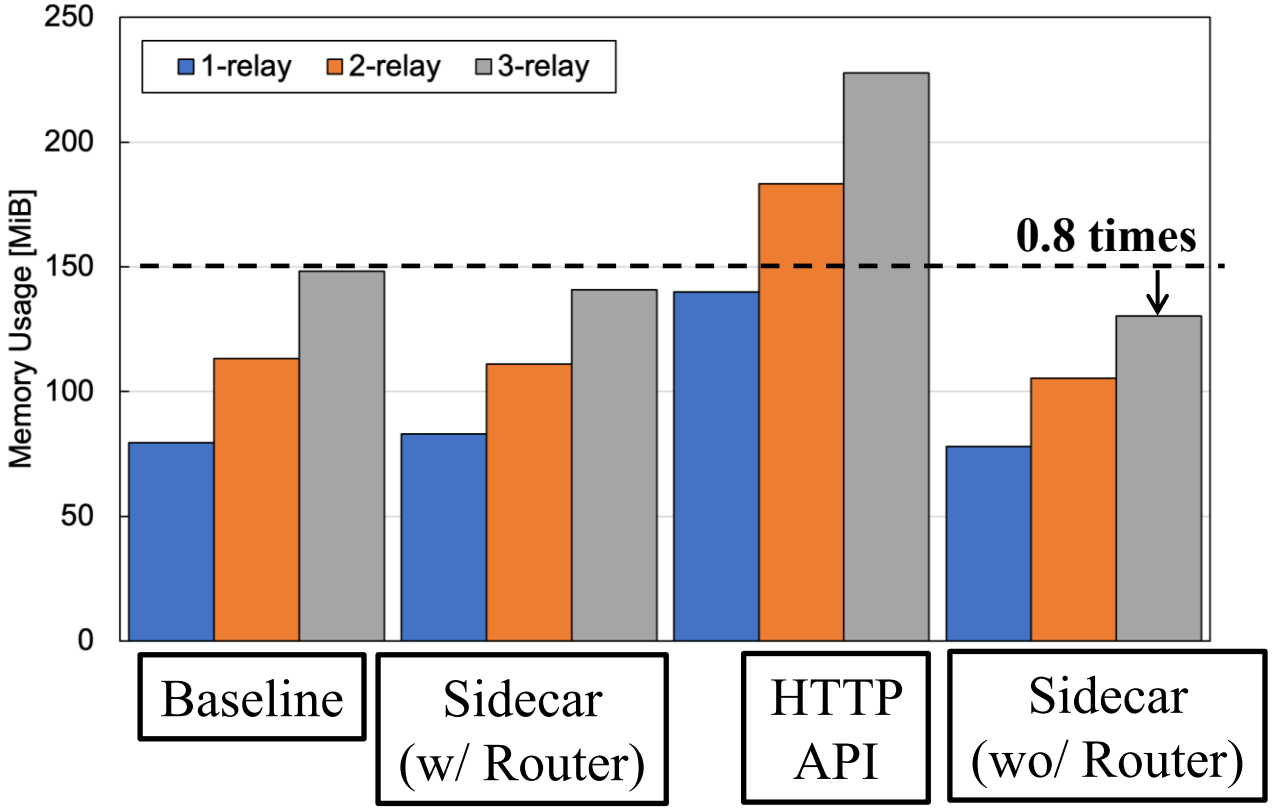
H. Saito, K. Kanai, H. Nakazato, “Development and Evaluation of ICN Service Mesh using NDN Function Chaining”, IEEE CCNC 2024.

ICN Service Mesh ~Performance comparison~

Deploy two services



Deploy from one to three services



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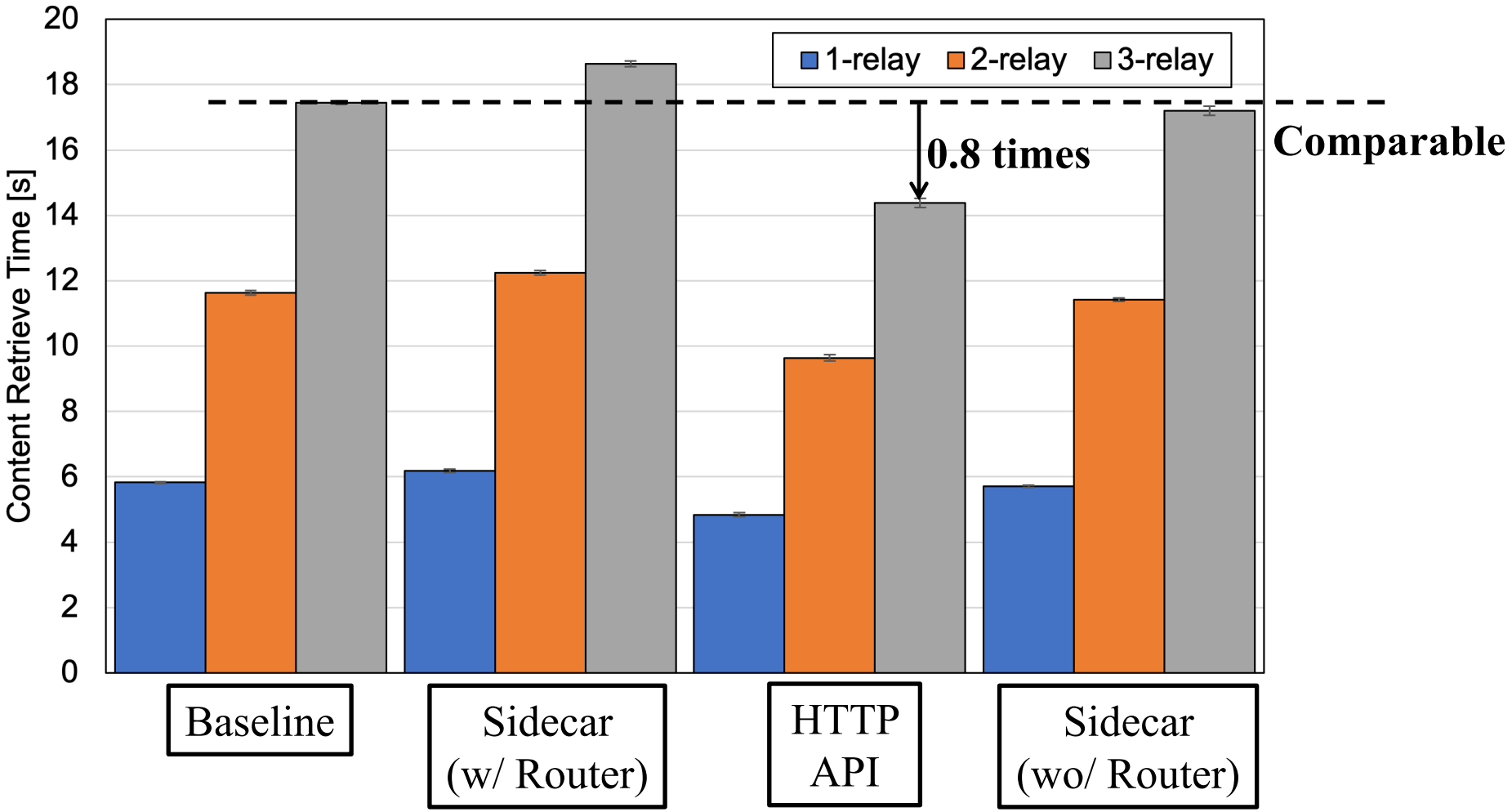
ICN Service Mesh ~Performance comparison~



DePIN-based “Co-”Digital Twin

Supported by NICT

to collect, update and share the latest digital twin data

K. Kanai, et al., “D2EcoSys: Decentralized Digital Twin EcoSystem Empower Co-Creation City-level Digital Twins”, IEICE Trans on Comms. 2023

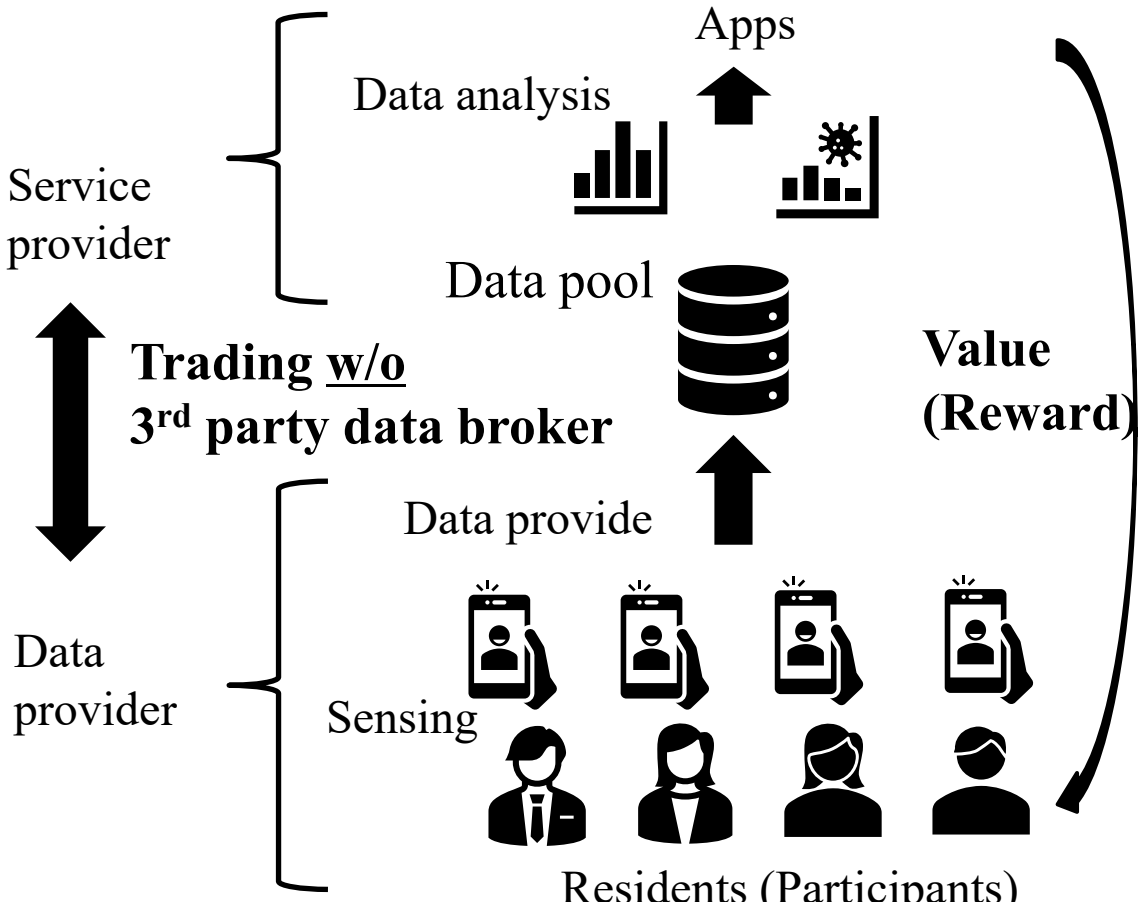
Problem statement

- **A (city-level) digital twin** is a critical enabling technology to construct a smart city that helps improve citizens' living conditions and quality of life
  - Future city planning, traffic simulation, disaster simulation, and wireless network simulation
- Research and development regarding **the digital replica city** are on-going in worldwide
  - **Only focus on creating the 3D city model**
  - There are **no mechanism** how to **maintain a "sustainable" and "up-to-date" digital twin** on a large scale
- **Lack a mechanism to involve various key players**, such as data providers, service providers, and application developers.
- The mechanism, "**ecosystem**," is essential for constructing the digital replica city and producing various city applications

DePIN-based “Co-”Digital Twin ~ Our vision ~

Co-: Co-creation

➢ Keep **up-to-dating** digital twin by **participatory sensing** (a.k.a. crowd sourcing)



◆ Point 1
- **City residents** play a crucial role **as a data provider**

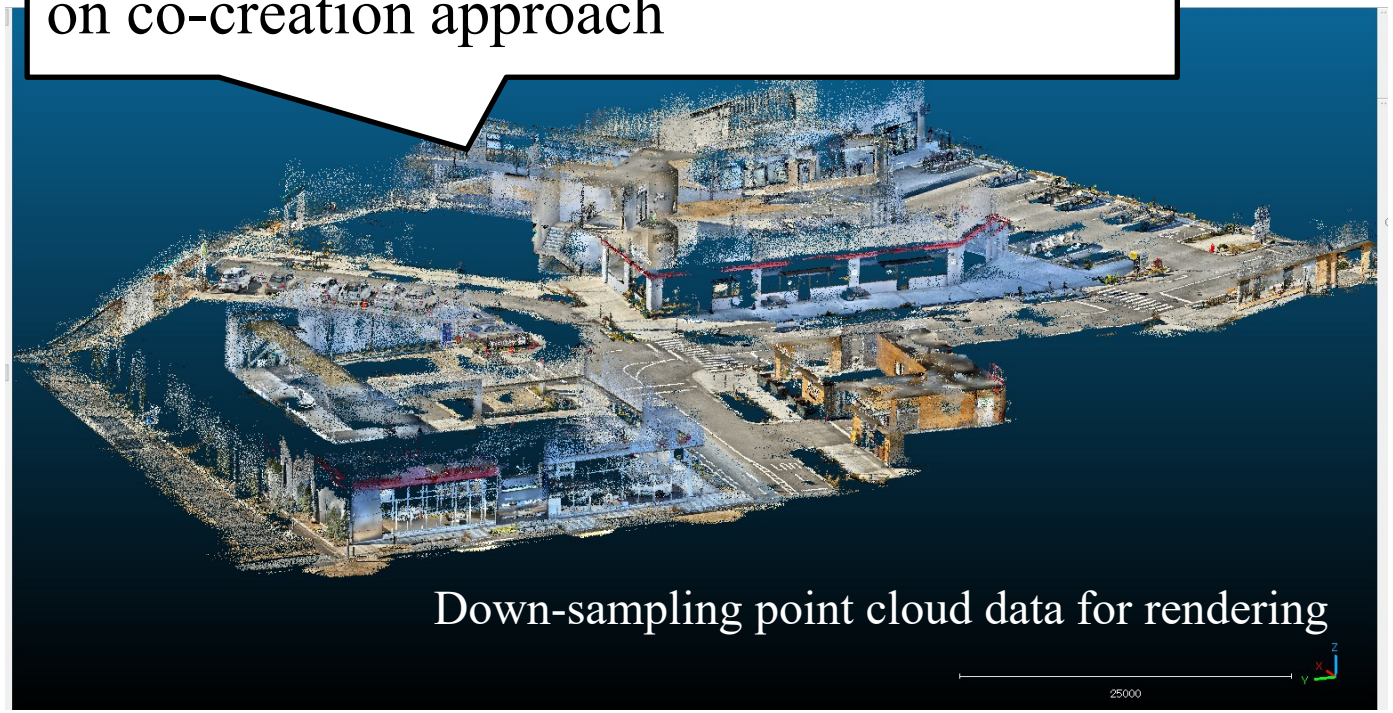
◆ Point 2
- **Without 3rd party data provider**, the provided data by the residents are distributed or traded with the service provider

◆ Point 3
- **Reward from service provider is an incentive** to residents to collect more data

Feasibility of Co-Digital Twin

- **3D point cloud data** is captured by **iPad**'s LiDAR sensors
- Collect 3D point cloud data by **6 participants** with their own iPad
- Merge them to one point cloud data as **a 3D map**

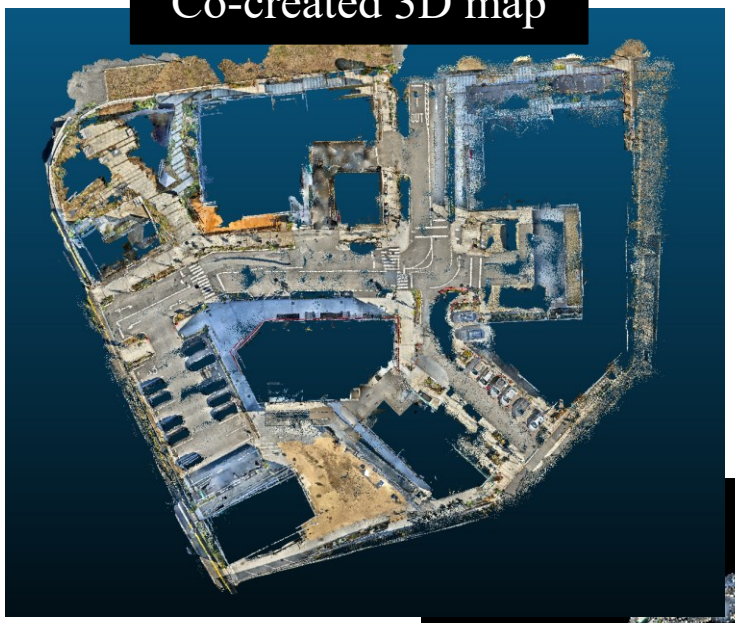
Create a **modest 3D map** using iPad based on co-creation approach

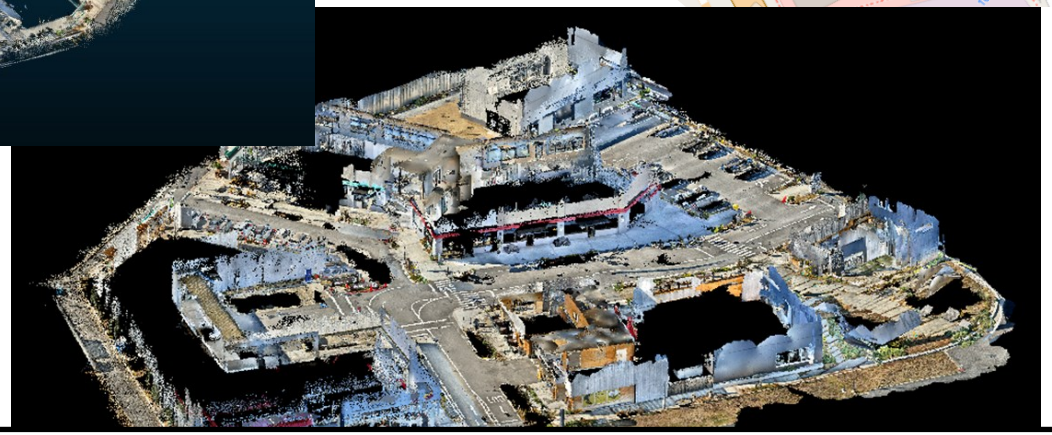


Feasibility of Co-Digital Twin

- Point Cloud collection experiment at KOIL 16 Gate, Kashiwanoha in Japan

Co-created 3D map





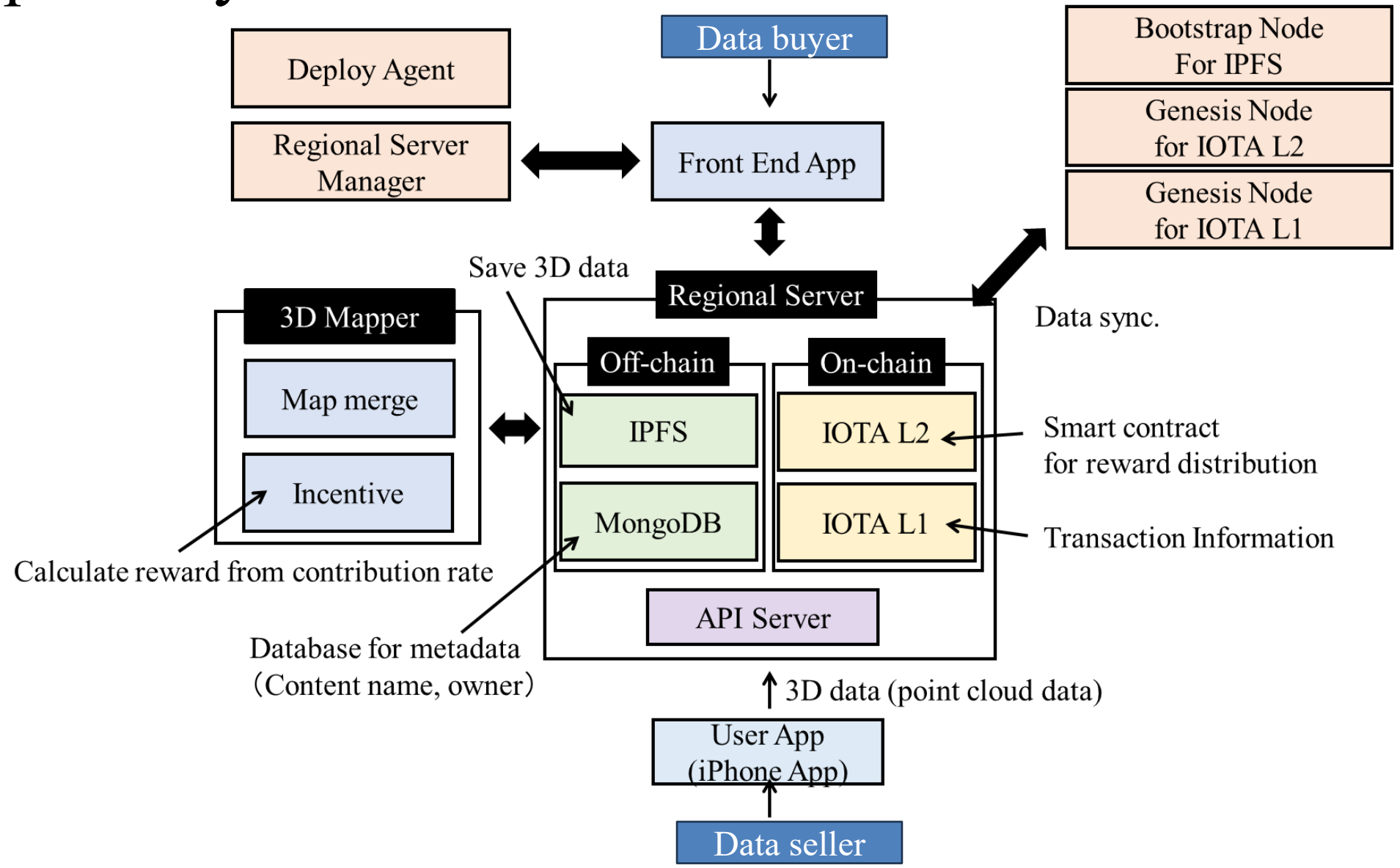
OpenStreetMap

Local floor map

Visually confirm that our co-created 3D map has nearly equivalent accuracy to existing maps (OpenStreetMap and local floor map)

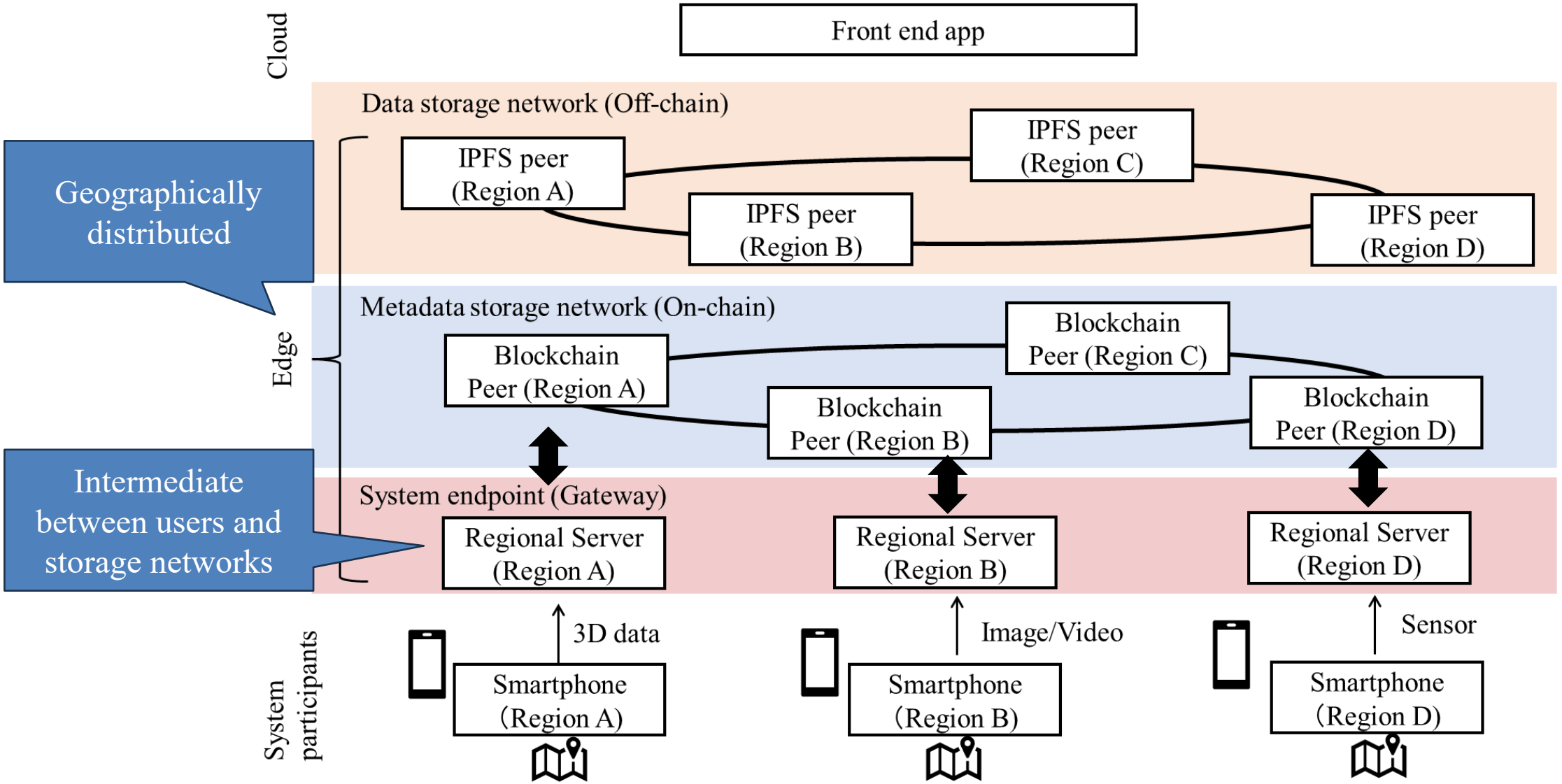
K. Kanai, et al., “Self-expanding City-level Digital Twin using Blockchain and IPFS”, WIND 2024.

Proposed system architecture ~function blocks~



K. Kanai, et al., “Self-expanding City-level Digital Twin using Blockchain and IPFS”, WIND 2024.

Proposed system deployment



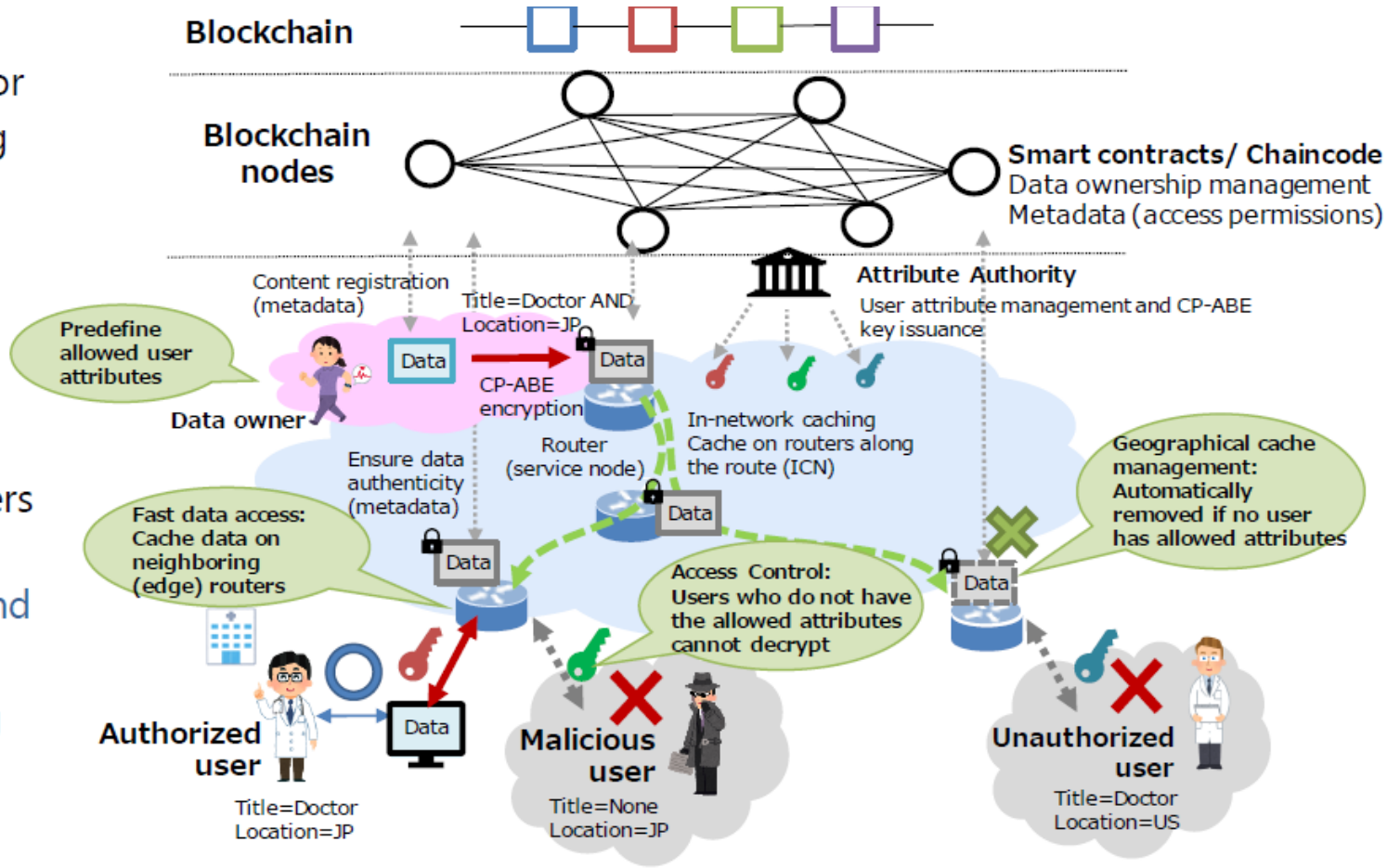
Two technical issues facing the proposed system

- **Issue 1: Security for IPFS**
  - **Content Identifier (CID) Concealment**
    - If the Content Identifier (CID) registered with IPFS is leaked to the outside, the data can be freely accessed
  - Content Encryption
    - Since the data is not encrypted, anyone who obtains it can decode it
  - This is **a critical issue for the purpose of buying and selling content**

- **Issue 2: Storage network performance**
  - **Content persistence**
    - While data is stored based on geographic information for each regional server, only the (single) node under that regional server can be used
    - No data replicated and **single point of failure**
  - **Effective storage utilization**
    - There is no management based on distributed data storage or storage utilization rates
    - Due to the current system architecture specifications, a distributed storage network has not been established

Detailed architecture of UCINC

- Approach: User-centric in-network caching for off-chain storage by leveraging ICN's caching feature and utilizing a database for storage
- Key features
  - Security and privacy: Ciphertext-policy attribute-based encryption (CP-ABE) → fine-grained data access control
  - Geographical limitation: cache data in routers within permitted areas and close to authorized users → efficient data transfer and high-performance data download
  - Availability: high data availability by caching data in multiple intermediate routers



H. Yamanaka, Y. Teranishi, Y. Hayamizu, A. Ooka, K. Matsuzono, R. Li, and H. Asaeda, "User-centric In-network Caching Mechanism for Off-chain Storage with Blockchain," Proc. IEEE ICC, June 2022
H. H. Hlaing, Y. Hayamizu, Y. Teranishi, and H. Asaeda, "Design and Implementation of User-centric In-network Caching Mechanism for Off-chain Storage with Blockchain," IEICE ICN研究会 2024. [online]: https://www.ieice.org/cs/icn/?page_id=2710

Solving problems using UCINC and ICN Service Mesh

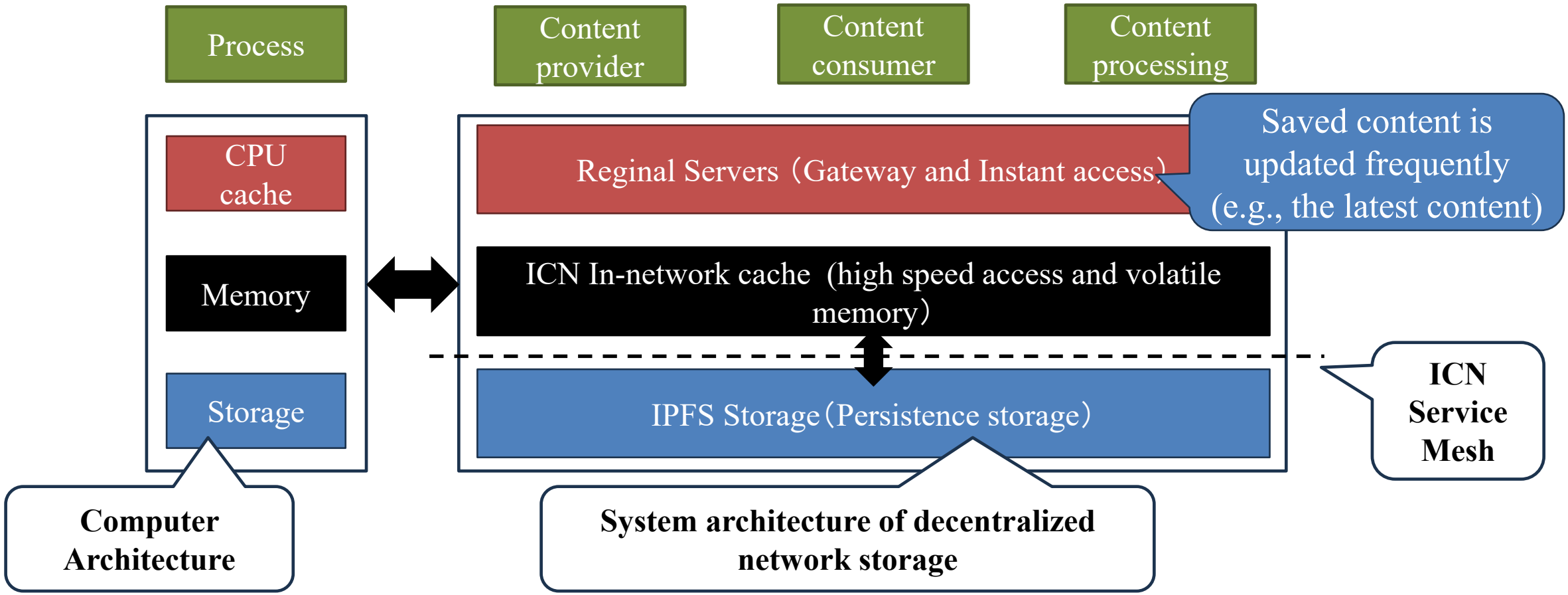
- **Issue 1: Security for IPFS**
  - Content encryption and Content ID concealment
    - Resolving the challenge by maintaining confidentiality through access permissions **using UCINC** (mainly attribute-based encryption (CP-APE) capability)
    - Concealment of Content ID by converting Content ID in accordance with certain rule **at the service mesh layer**

- **Issue 2: Storage network performance**
  - Efficient storage utilization and content persistence
    - Resolving challenges through **high-speed access utilizing network caching with UCINC**
  - **Accelerating content search in IPFS using ICN**

- Issue 3: Implementation challenges for achieving Issues 1 and 2
  - Code modifications are required for the application, IPFS, and ICN
  - **Minimizing code modifications** to each application by **applying the Service Mesh**

Decentralized network storage using ICN and IPFS

◆An illustration of the proposed system using an analogy with computer storage devices



Reference: M. Ma, H. Nakazato, “An Application of Named Data Network on InterPlanetary File System,” IEEE CCNC 2024.

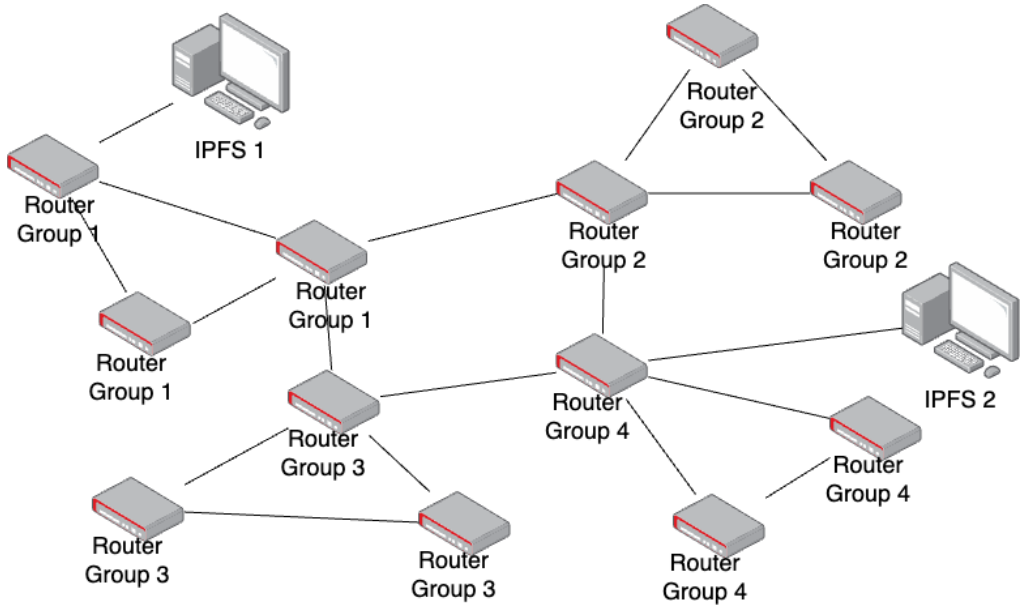
Methodology for integrating ICN into IPFS

- IPFS data discovery has **two searching steps** based on Kademlia algorithm
  - **Search for Peer ID** that have the requested content
  - **Search for connection information** (i.e., IP address) of Peer ID
  - Pairs of PeerIDs and ContentIDs are managed in a table called the **Provider Record**
  - Provider Records are exchanged only between neighboring nodes

- IPFS routing protocol is **relaced from Kademilia to ICN**
  - Provider Record is distributed using ICN protocol
  - IPFS data discovery can achieve only one step
    - ICN's routing table enables direct discovery of Provider Records within the network

Reference: M. Ma, H. Nakazato, "An Application of Named Data Network on InterPlanetary File System," IEEE CCNC 2024.

Performance Evaluations of ICN-based IPFS



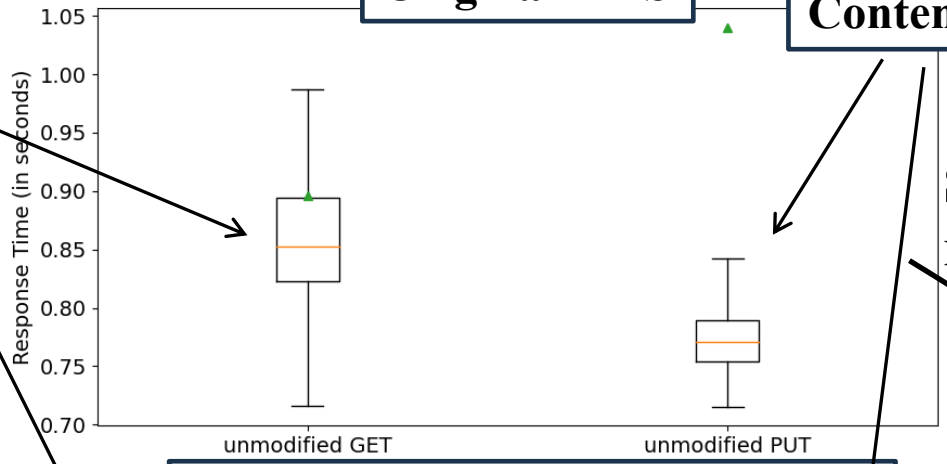
Test network topology

Original IPFS

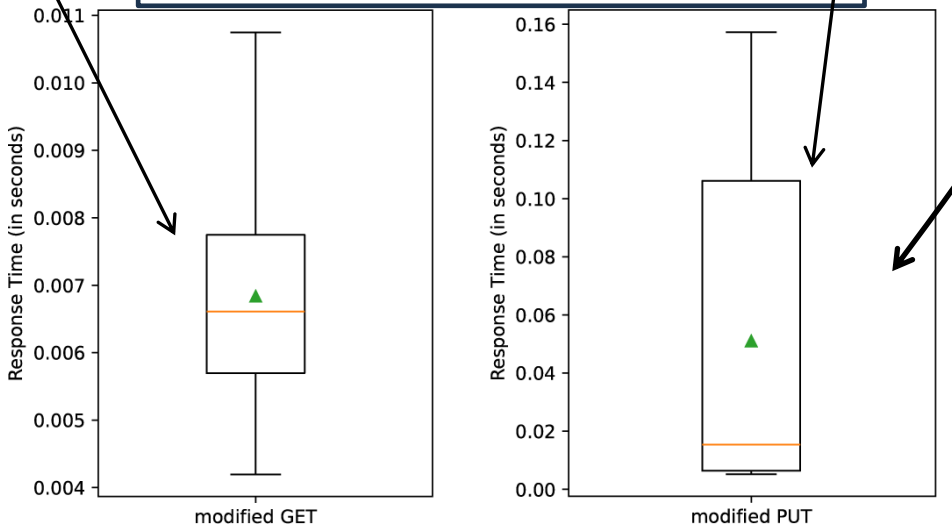
Content publish

Content retrieve

Significantly improvement



ICN-based IPFS



Our next step

- Effective use of **In-Network Cache**
  - Caching Provider Records
  - Caching content itself

- **Integration with UCINC**
- Implementation as a distributed network storage system

Conclusions

- Introduction to ICN Service Mesh
  - Architecture
  - Deployment
  - Performance evaluations

- Introduction to DePIN-based Co-Digital Twin
  - Our vision
  - System architecture
  - ICN and IPFS integrations to realize decentralized network storage