Leverage Vehicles to Build a Multi-D Resource Network for Smart Cities

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What is a smart city?

- Wikipedia
  - “The smart city concept integrates information and communication technology (ICT) and various physical devices connected to the Internet of Things (IoT) network to optimize the efficiency of city operations and services and connect to citizens.”
  - There is no standard terminology, but it does spell out a few things
    - ✓ ICT (data, information, communications, networking)
    - ✓ IoT (sensing)
    - ✓ Efficiency (resource optimization)
    - ✓ Operations & services
  - Need to be added explicitly
    - ✓ Computing (processing and AI/ML)
    - ✓ Storage (caching, buffering, memory, storage)
    - ✓ Security and privacy (Security by Design & Privacy by Design)

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Hong Kong Vision of Smart Cities

- En route to city modernization- Mission of Hong Kong Smart City Blueprint 2.0 (12/2020)
  - To make people happier, healthier, smarter and more prosperous, and the city greener, cleaner, more livable, sustainable, resilient and competitive
  - To provide better care for the elderly and youth and foster a stronger sense of community.
  - To enable the business to capitalize on Hong Kong's renowned business-friendly environment to foster innovation, transform the city into a living lab and test bed for development
  - To make the business, people, and Government more digitally enabled and technology savvy
  - To consume fewer resources and make Hong Kong more environmentally friendly, while maintaining its vibrancy, efficiency, and livability

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Smart Hong Kong Blueprint 2.0

- How to achieve the vision
  - Smart *-feature in multi-dimensional (Multi-D) space
  - Smart Mobility
  - Smart Living/aging
  - Smart Environment
  - Smart People
  - Smart Government
  - Smart Economy
  - (Smart grid)

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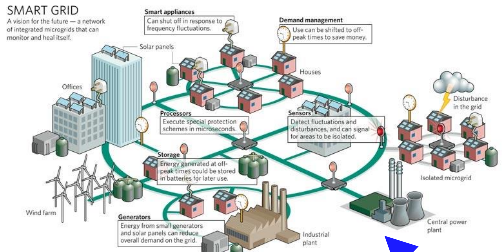
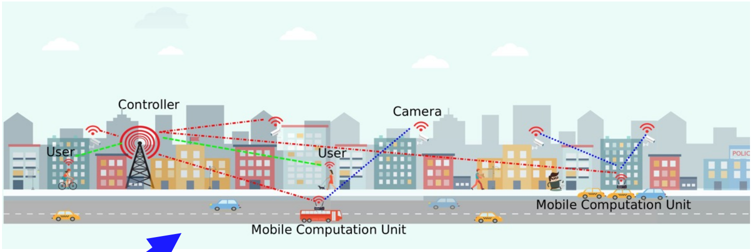
Wireless Intelligence & Networked Things Laboratory (WINET)

IoT+ICT+AI/ML： Sensing + Communications + Computing + Control



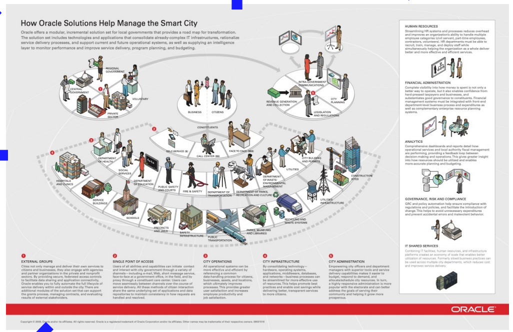
smart grid

smart transportation

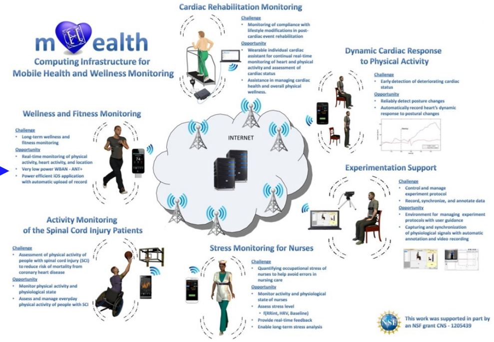


smart public safety

smart community

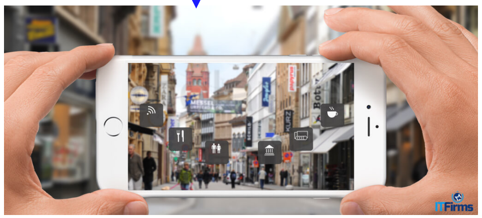


smart city



smart health

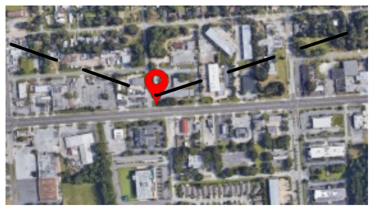
smart social



smart life

smart environment

Use case: interactive video surveillance for public safety (edge/cloud)



Anomaly detection (e.g., Amber alerting/criminal tracking)

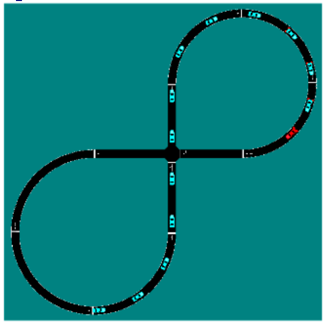
Analysis at local police station

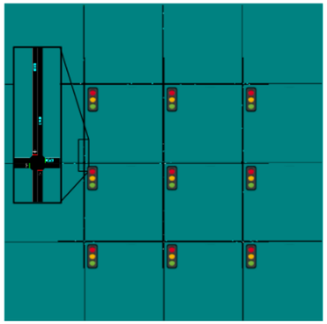
Inconclusive but suspicious?

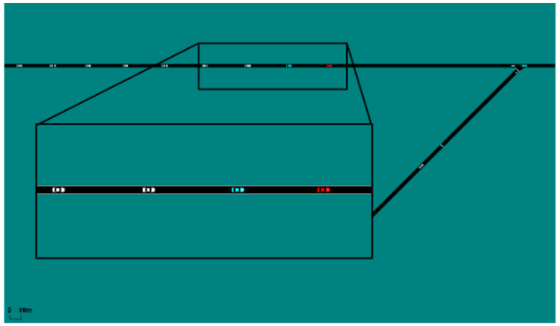
Further analysis at city police department

Use case: Smart Mobility

- "eSIMs identify individual vehicles, encrypt communications, and ensure secure global car connectivity for intelligent vehicle systems."
- Autonomous driving regulates traffic


(a) Figure Eight


(b) Grid


(c) Merge

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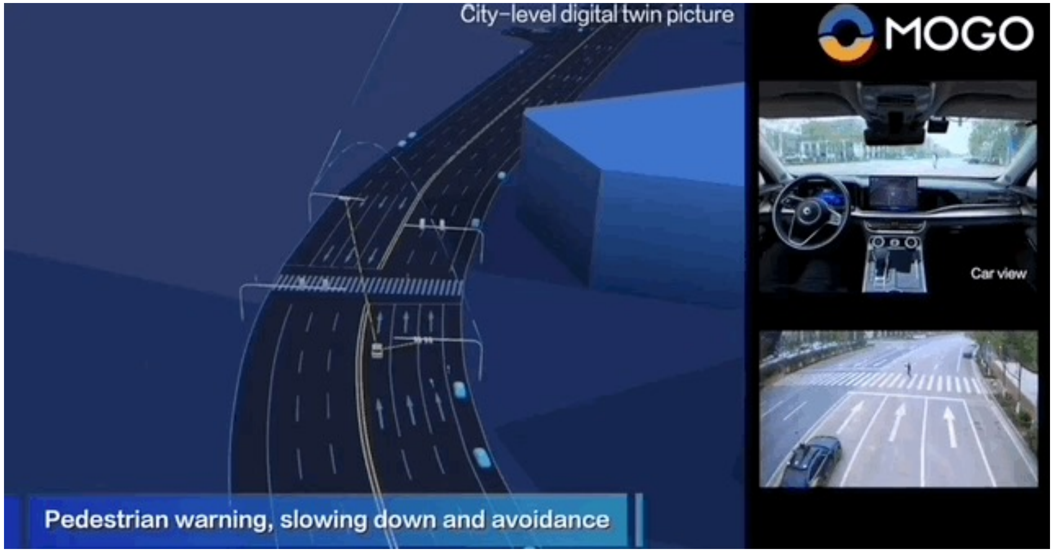
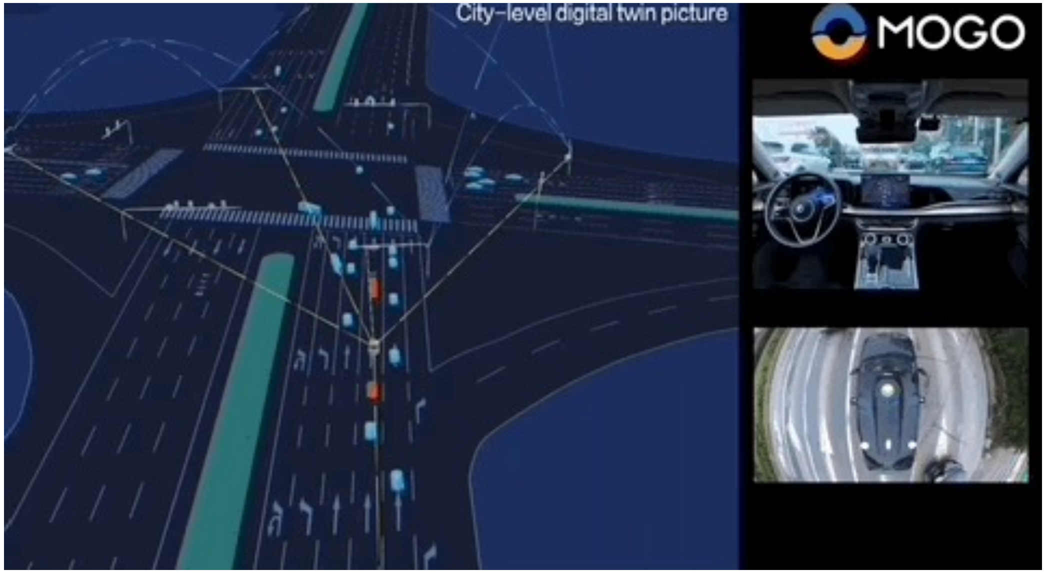
Networked Driving of Non-sensing Vehicles

- Mogo AI Digitalized Roads





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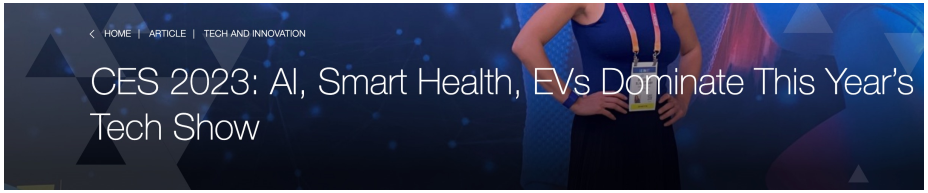
Use case: smart health in vehicles

- In-vehicle health monitoring
  - ➢ Fatigue detection
  - ➢ Sudden episodal health problems (e.g., heart attack)
  - ➢ In-vehicle wellbeing
  - ➢ vital sign monitoring
- City residents' health monitoring
  - ➢ smart aging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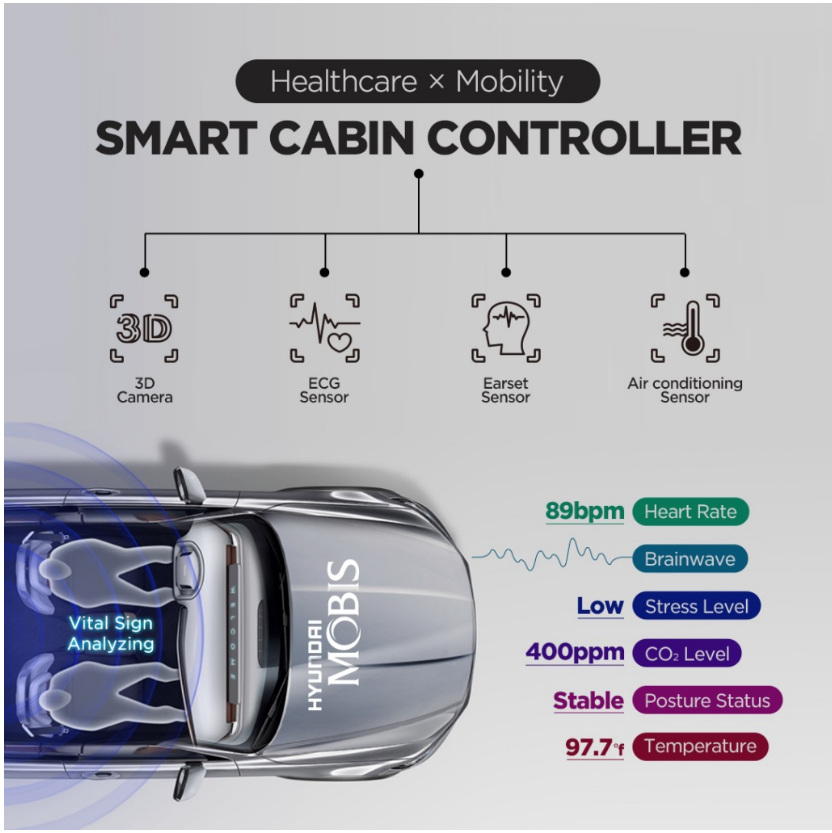
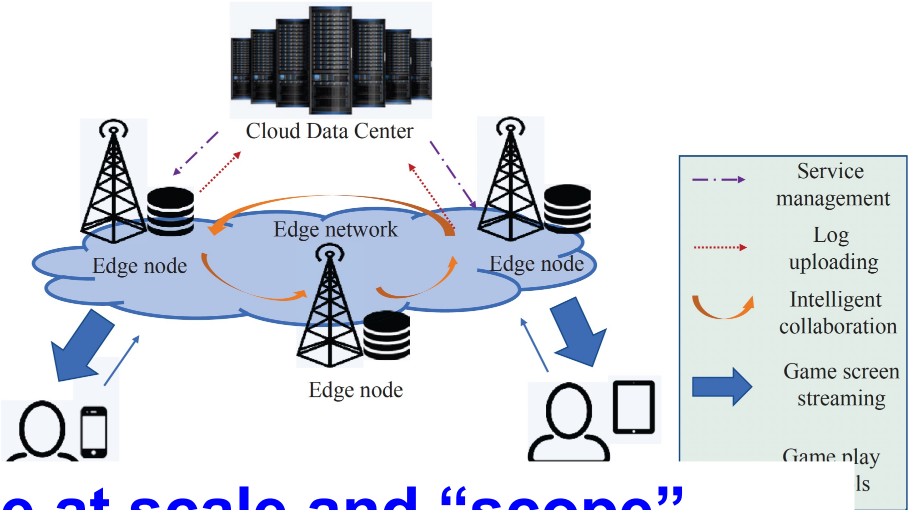
CES 2023: AI, Smart Health, EVs Dominate This Year's Tech Show



Newly emerging applications of smart cities

- Emerging applications
  - Augmented reality (AR)/Virtual reality (VR) Navigation/Metaverse
  - Autonomous driving
  - 360°/stereoscopic/6DoF video streaming
  - Online gaming



- **Big sensing → sense at scale and "scope"**
  - ✓ **Crowdsensing, affective sensing, …**
- **Big data → storage and communications**
- **Big computing → processing, AI/ML**

Question: how can we effectively support all these in a smart city?

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What do we need to do?

- Need to know information about the city (sensing)
  - "pulse of a city!"
  - Eventful and informational data
  - Personal activities & behaviors (e.g., emotional/community sensing)
  - Consumer data for city operations
- Need to have network support to transport data/information around (networking or ICT)
  - Transport data of potentially large volume from sources to premises where actions can be taken: to be processed or consumed
- Need to have computing capability in situ and in tempore to process/extract useful information at the spots of actions (computing and/or AI/ML)
- Need to store/buffer/cache data for optimization (storage)
- Need to secure the living ecosystem in both physical space and cyberspace (security and privacy)

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In other words? We do need "resources"!

- Sensing and communications
  - Sensing efficiency
  - Spectrum efficiency
  - Energy efficiency

IoT/ICT

- Computing & machine learning
  - In situ and in tempore computing (computing service placement)
  - Low latency guarantee for timely actions
  - Flexible distributed collaborative learning

Computing

- Storage/buffering for scheduling
  - In situ and in tempore storage (buffering and caching)
  - Effective fragmented/distributed queue management for optimal communications and computing (queueing)

Storage

- Security and privacy
  - Secure and/privacy mechanisms (hardening of the weakest links)

Security

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Where do we get resources?

- 5G/6G and beyond?
  - ➢ Yes, it is an option
  - ➢ But costly
    - ✓ Infrastructure investment cost (BSs, land permit, …)
    - ✓ Operational, administrative & maintenance (OAM) sustainable cost
- Crowdsourcing? yes, but
  - ➢ A lot of research, but not much action
  - ➢ Passive mode operations (relying on what has been given)
  - ➢ Lack of viable incentives (there is no free lunch!)
  - ➢ Not systematically investigated for big effort like smart city
  - ➢ Mostly focused on resource of a single dimension!
- But, we do need multi-dimensional resources! Particularly "resources" without excessive cost? Where to find such "jewels"?

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Searching for the alternatives

- What are the most popular things on the streets?
  - Vehicles!!!
  - Omnipresent vehicles
  - Mobile vehicles: space/air/ground/sea/under-surface…
- What do we use them for?
  - Transport people or goods!
  - Can we do anything else? …Yes!
- What if vehicles are equipped/carried with powerful SCCSI* capability: powerful set-top devices with SCCSI capability?
  - ✓ BS, AP, DAS,…
  - ✓ Computing servers
  - ✓ Storage
  - ✓ AI/ML toolboxes

* SCCSI: Sensing, Communications, Computing, Storage & Intelligence

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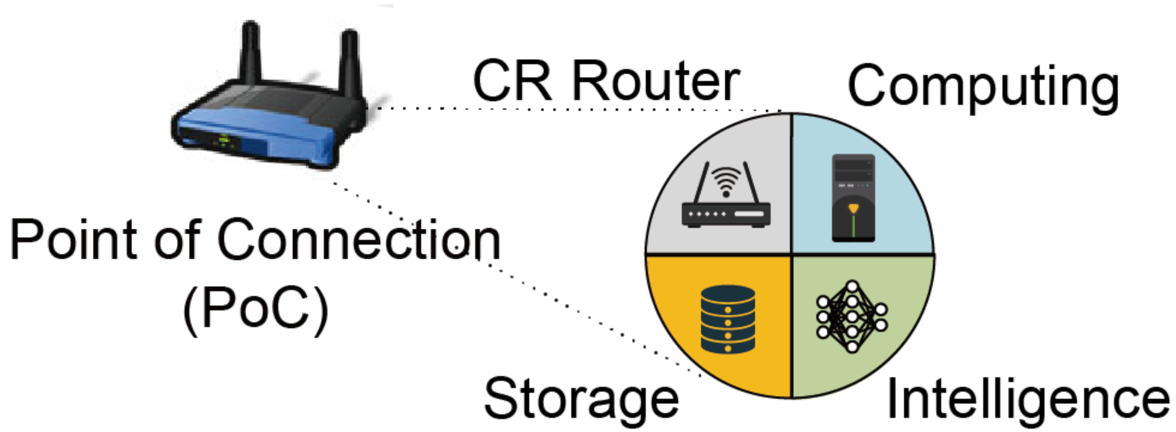
SCCSI enablers: Point of Connection (PoC)

- Sensing: **multi-modal** sensors or a collection of sensors
- Communications: **cognitive router** with cognitive/agile radios with fast transmission (data blasting) capability
- Computing: customized **AI-nized** (AI-aware) computers with high computing capability
- Storage/memory/caching: fast distributed **networked storage** for data storage, buffering, and prefetching/caching
- Intelligence: **Customized AI/ML** toolboxes!



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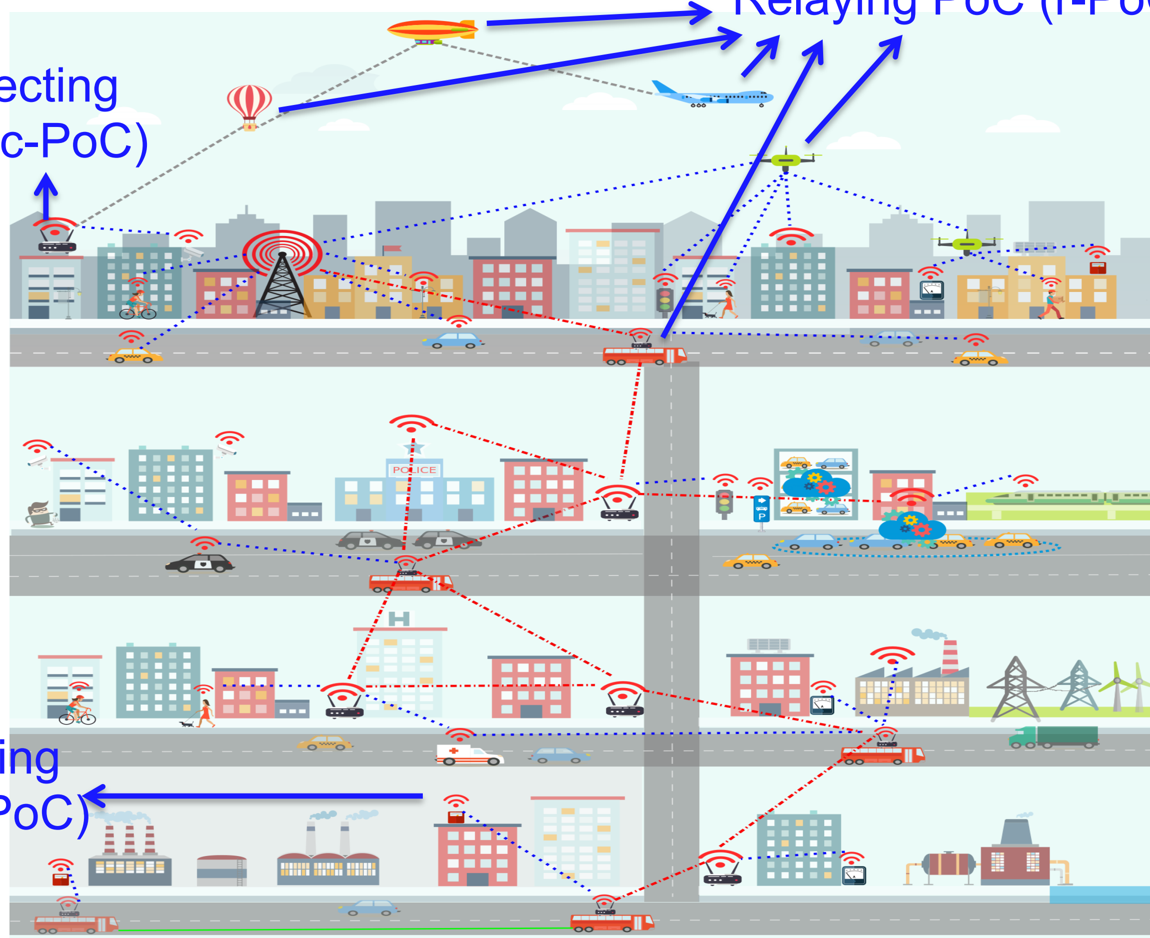
a SCCSI Service Network:
Beef up the network edge + Mobile infrastructure

Relaying PoC (r-PoC)

Connecting PoC (c-PoC)



r-PoC can be simplified intelligent reflecting surfaces (RISs)

Connecting PoC (c-PoC)

Mobile PoC (m-PoC)

Our proposed approach

- Leverage vast and omnipresent vehicles (space/air/ground/sea/under-surface): a dynamic web of sensors/monitors/watchdogs, a network of data carriers, a distributed system of storage and buffers, a grid of computing servers, and a

- **A naturally formed web of dynamic resources for sensing, communications, computing, storage & intelligence (SCCSI)!!!**
- **A SCCSI Service Network!**

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Leverage resource opportunities

- Leverage the powerful capability of vehicles in situ and in tempore
  - Tremendous sensing (e.g., lidar, radar, cameras, …)
  - Cognitive vehicular mesh (e.g., OBUs/CR routers/mobile BS/APs)
  - Dynamic vehicular cloud/edge computing (e.g., mobile computers)
  - Large distributed storage network (e.g., self-organized distributed storage)
  - AI/ML toolboxes
- Leverage (controlled) vehicular mobility opportunity
  - Take advantage of shared mobility to opportunistically transport data to the proximity of data consumers (end users/computing sites)
  - Proactively recruit/deploy vehicles to link networked things
    - ✓ Satellites/airships/airplanes/balloons/helicopters/drones/…
  - Relieve the burden of existing legacy systems (5G/WiFi/DSRC…)
- Leverage spectrum opportunity
  - Collaborative spectrum sensing (let PoC do the sensing)
  - Temporal and spatial spectrum availability (spectrum map)

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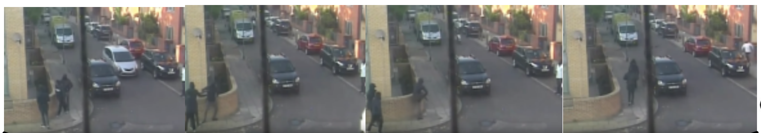
Leverage resource opportunities

- Harness opportunistic capability in situ and in tempore in a smart city
  - Use roadside parked vehicles and/or platooning vehicles to form SCCSI facility (roadside fogs or platooning cloudlets)
  - Utilize AI-nized vehicles in parking lots to form cloud/edge computing facilities (e.g., parking lot clouds)
  - Design incentivize mechanisms to make vehicles flock
- Demand a holistic design approach! (the Chinese medicine approach)

1. X. Chen, Y. Fang, etc., "Vehicles as a Services (VaaS): leverage vehicles to beef up the edge," https://doi.org/10.48550/arXiv.2304.11397.
2. H. Ding, C. Zhang, Y. Cai, and Y. Fang, "Smart cities on wheels: a newly emerging vehicular cognitive capability harvesting network for data transportation," *IEEE Wireless Commun. Mag.*, **25**(2): 160-169, 2018.
3. H. Ding, Y. Fang, X. Huang, M. Pan, P. Li, and S. Glisic, "Cognitive capacity harvesting networks: Architectural evolution toward future cognitive radio networks," *IEEE Commun. Surveys Tuts.*, **19**(3): 1902–1923, 2017.

Use case: interactive video surveillance

video data collection



action: control

data transport

data analytics: ML

Anomaly detection (e.g., Amber alerting/criminal tracking)

Analysis at local police station

Inconclusive but suspicious?

Further analysis at city police department

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Vehicle as a Service (VaaS)

- Edge Communication resources (e.g., small cells)
  - Push communications services closer to end users
- Edge Computing resources (e.g., edge servers)
  - Conduct pre-processing: eliminate redundancy at the edge (e.g., semantic communications)
  - Harness edge/fog computing: reduce latency or backbone traffic
- Edge Storage/Caching (e.g., edge servers)
  - Boost resource utilization (spectrum & mobility): use opportunistic scheduling at the edge to smooth out variations
  - Design flexible data transmission schemes (data blasting, store-carry-forward)
  - Take advantage of the nature of delay-tolerant traffic (e.g., video traffic forms over 70% of Internet traffic!): shift delay-tolerant traffic to the "harvested" resources to save licensed bands
- Edge Intelligence (e.g., federated learning)
- Edge Security & Privacy (e.g., hardening the edge)

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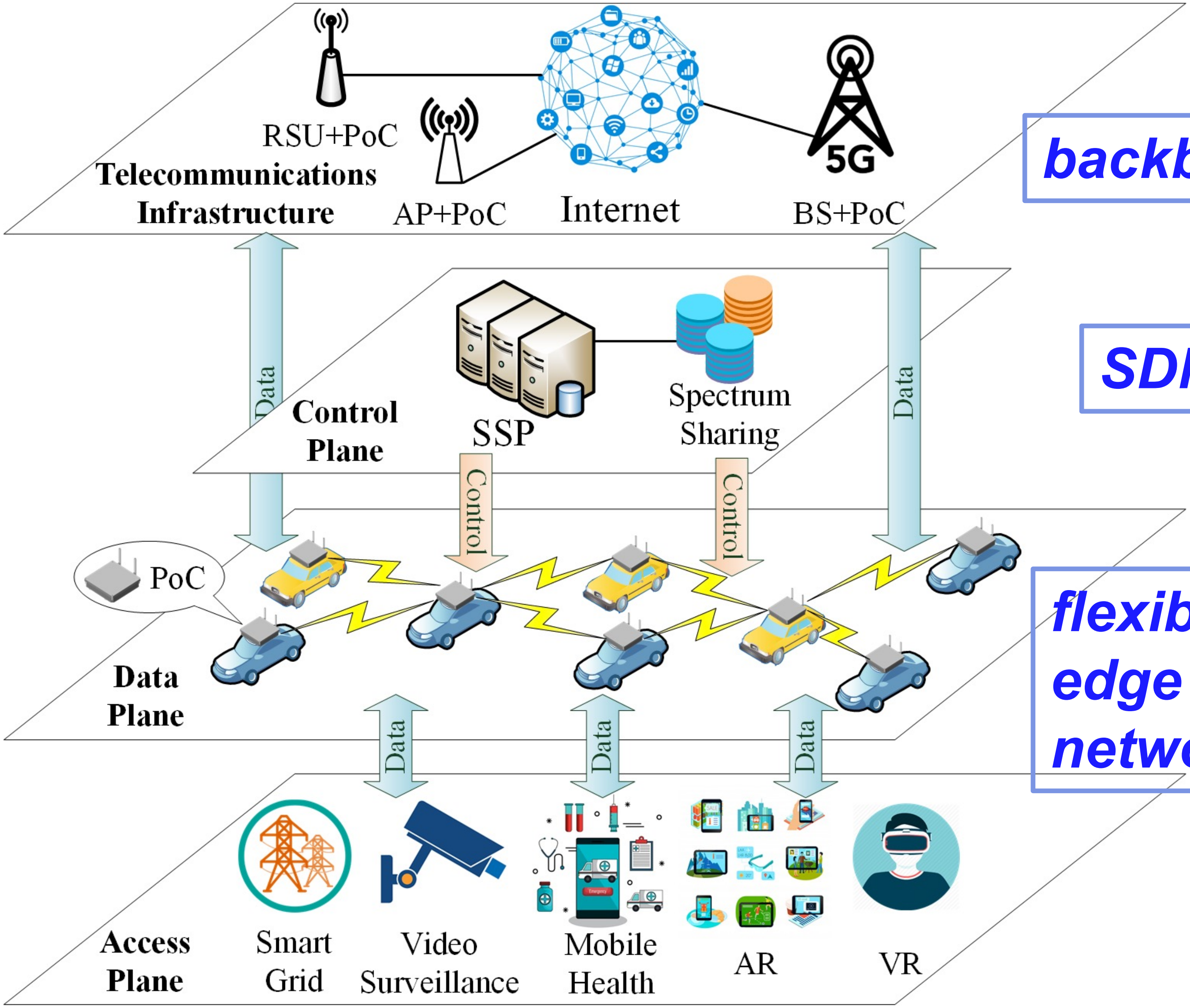
A SCCSI Service Network



backbone

SDN

flexible edge networks

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Incentive Mechanism Design: Service Auction

Single-round and sealed-bid double auction

Incentive: monetary or redeemable points

Buyer i's profile: QoS

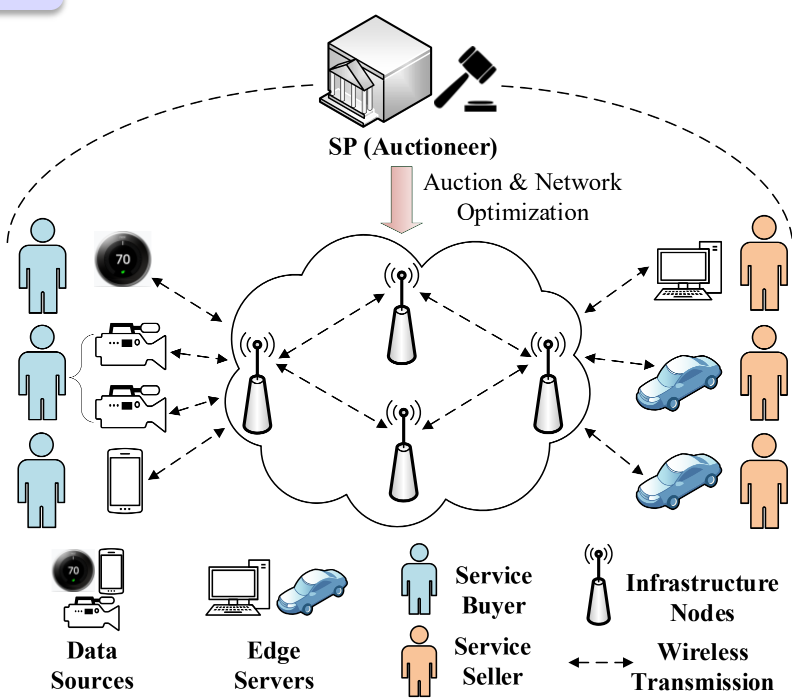
e2e service requirement: $s_{i,k} = \{r_{i,k}, \theta_{i,k}, \delta_{i,k}\}$

- e2e data rate: $r_{i,k}$
- Computing requirement: $\theta_{i,k}$
- Storage requirement: $\delta_{i,k}$

Bid price: $b_{i,k}$

Seller j's profile:

- Computing capability: Θ_j
- Storage space: Δ_j
- Ask price: $a_{i,j,k}$



- **X. Chen**, G. Zhu, H. Ding, L. Zhang, H. Zhang, and Y. Fang, "End-to-End Service Auction: A General Double Auction Mechanism for Edge Computing Services," *IEEE/ACM Transactions on Networking,* 30(6): 2616-2629, 2022.
- **X. Chen**, Y. Deng, G. Zhu, D. Wang, and Y. Fang, "From Resource Auction to Service Auction: An Auction Paradigm Shift in Wireless Networks," *IEEE Wireless Communications,* 29(2):185-191, 2022.

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Service Network Optimization

Construct a network flow optimization problem for MEC systems.

Decision variables
d: service assignment, **x**: network resource allocation, **f**: data flow

Data flow conservation

$$\max_{\boldsymbol{d},\boldsymbol{x},\boldsymbol{f}} \sum_{i\in\mathcal{I}} \sum_{1\le k\le K_i} \sum_{j\in\mathcal{J}} M_{i,k} d^j_{i,k},$$ Throughput maximization

$$s.t. \sum_{j\in\mathcal{J}} d^j_{i,k} \le 1, \quad \forall i\in\mathcal{I}, 1\le k\le K_i, \tag{1}$$ One request is assigned to at most one server

$$\boldsymbol{A}\boldsymbol{f}^{\intercal}_{i,k} = \sum_{j\in\mathcal{J}} d^j_{i,k} r_{i,k}(\boldsymbol{s}_{i,k} - \boldsymbol{h}_j)^{\intercal}, \quad \forall i\in\mathcal{I}, 1\le k\le K_i, \tag{2}$$

Link capacity

$$\sum_{i\in\mathcal{I}} \sum_{1\le k\le K_i} f^{i,k}_l \le C_l(\boldsymbol{x}), \quad \forall l\in\mathcal{L}, \tag{3}$$

$$\text{Constraints on } \boldsymbol{x}, \tag{4}$$

Networking constraints: Configure network resource allocation and routing path. (3) and (4) are application specific

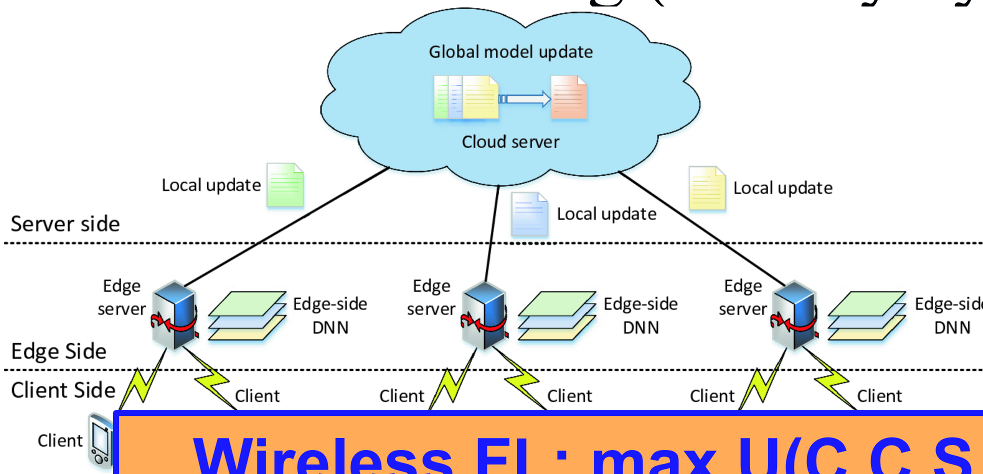
$$\sum_{i\in\mathcal{I}} \sum_{1\le k\le K_i} d^j_{i,k} \theta_{i,k} \le \Theta_j, \quad \forall j\in\mathcal{J}, \tag{5}$$ Computing constraints

$$\sum_{i\in\mathcal{I}} \sum_{1\le k\le K_i} d^j_{i,k} \delta_{i,k} \le \Delta_j, \quad \forall j\in\mathcal{J}, \tag{6}$$ Storage constraints

$$f^{i,k}_l \ge 0, \quad \forall i\in\mathcal{I}, 1\le k\le K_i, l\in\mathcal{L}, \tag{7}$$

$$d^j_{i,k} \in \{0,1\}, \quad \forall i\in\mathcal{I}, 1\le k\le K_i, j\in\mathcal{J}. \tag{8}$$

Federated Learning (Privacy by Design)

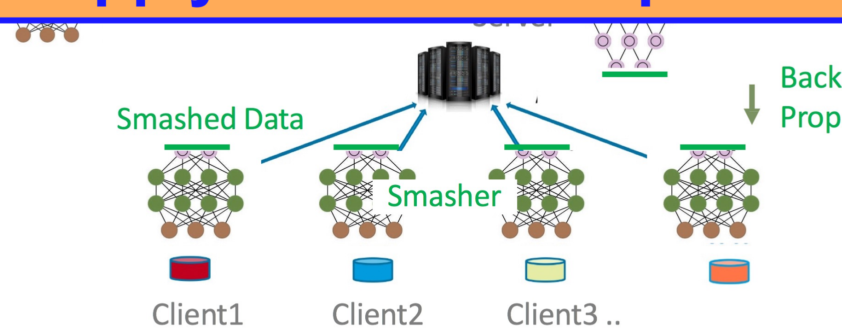


Hierarchical FL

Wireless FL: max U(C,C,S,I)

(J. Zhang, J ... rential privacy
in mobile ed...

Must handle uncertainty on service demands and resource supply: stochastic optimization



Split FL

(http://splitlearning.github.io)

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Managing Security at Edge

- IoT devices/edge devices/VaaS vehicles, belonging to the same organization, typically join together to manage the community for the same mission
  - Powerful devices can join together to manage the ecosystem and harden the edge for resource-constrained devices
- Blockchain can be leveraged to establish trusted ecosystem in an untrusted environments
- Location-based cryptographic schemes can be utilized to localize the impact of attacks
  - Info data can only be accessed with location-based keys
- Design for Resilience is the norm rather than after-thought
  - Self-defense, adaptation, and self-healing capability: manageable security configuration adaptation (human immune systems)

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Recap

- Offer an envisioned design of a multi-dimensional resource network of SCCSI: via VaaS
- Provide city authority with a cost-effective and sustainable solution to building a smart city
  - ➢ City authority acts as an SSP, building the partial infrastructure
    - ✓ Customized PoCs are deployed at strategic locations in the city
  - ➢ Mobile SCCSI-empowered vehicles over the space/air/ground/sea are deployed/outsourced/leveraged in situ and in tempore
    - ✓ e.g., UAVs or drones, CAVs, cars, trucks, buses, dispatchable vehicles
  - ➢ Networked vehicles serve as sensing fabrics, a communication network, a distributed computing system, a distributed storage network, and an Internet of Intelligence (IoI) or AI-based IoT (AIoT)
  - ➢ leverages vehicles to push sensing, communications, computing, storage, and intelligence to the EDGE!
  - ➢ Utilizes a SCCSI network to manage and secure the ecosystem of a smart city
  - ➢ Potentially provides a viable solution to the digital divide problem

Related publications

1. **X. Chen**, G. Zhu, H. Ding, L. Zhang, H. Zhang, and Y. Fang, "End-to-end service auction: A general double auction mechanism for edge computing services," *IEEE/ACM Transactions on Networking,* 30(6): 2616-2629, 2022.
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10. **H. Ding**, C. Zhang, X. Li, J. Liu, M. Pan, Y. Fang, and S. Chen, "Session-based cooperation in cognitive radio networks: a network-level approach," *IEEE/ACM Trans. Networking*, 26(2): 685-698, 2018.