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Resources on the Move: How Vehicles Provide Service Support for Smart Cities

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In Collaboration with my former students and visitors: Xianhao Chen, Yiqin Deng, Haichuan Ding, Xiaoxia Huang, Pan Li, Yawei Pang, Jie Wang, Haixia Zhang

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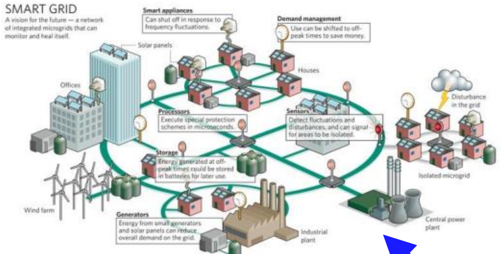
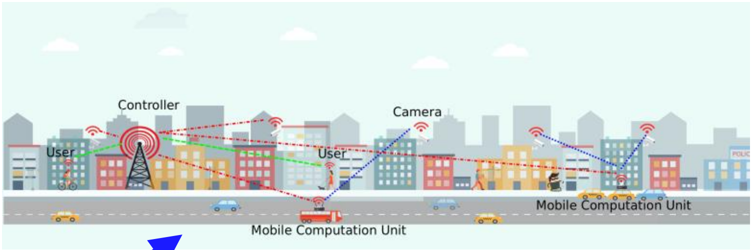
Wireless Intelligence & Networked Things Laboratory (WINET)

IoT+ICT+C(AI/ML)+C： Sensing + Communications + Computing + Control



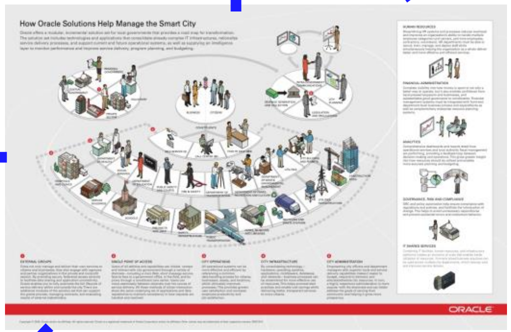
smart grid

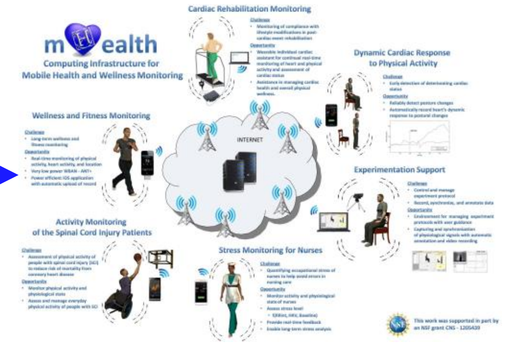
smart transportation



smart public safety

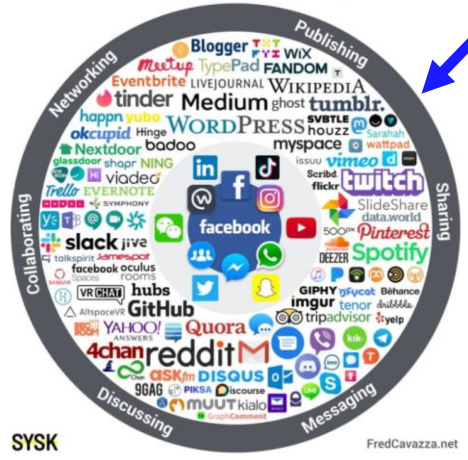
smart community

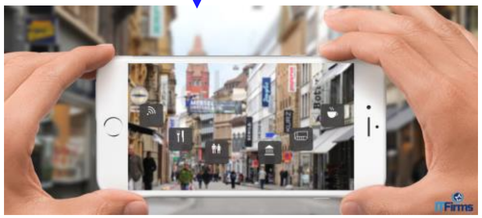




smart city

smart health



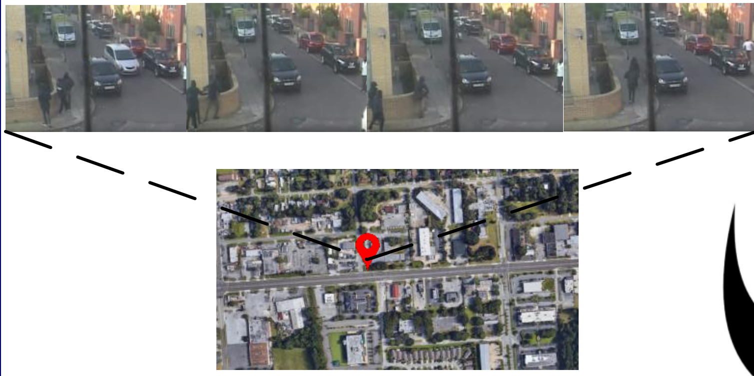


smart social

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

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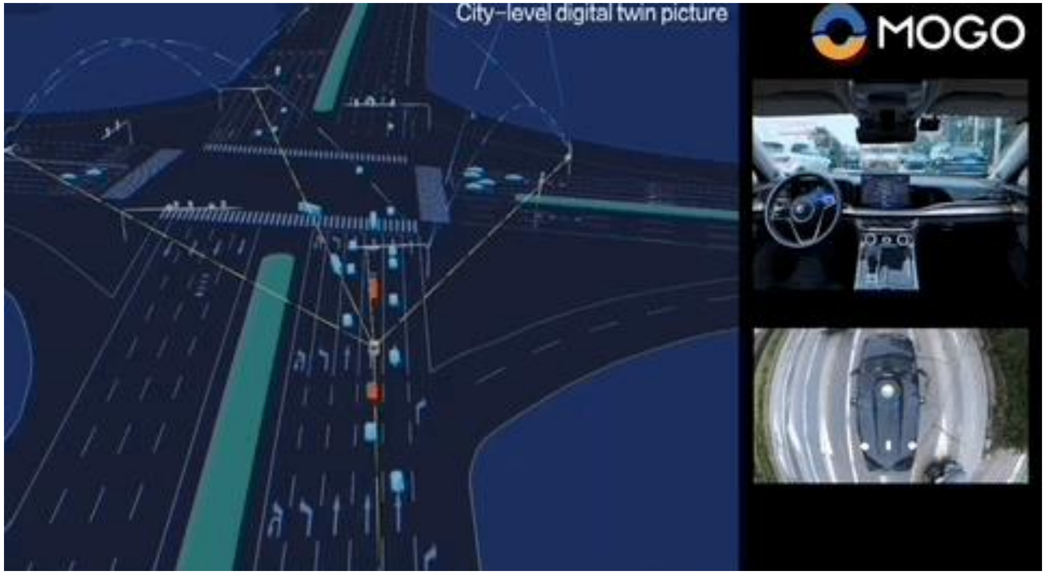
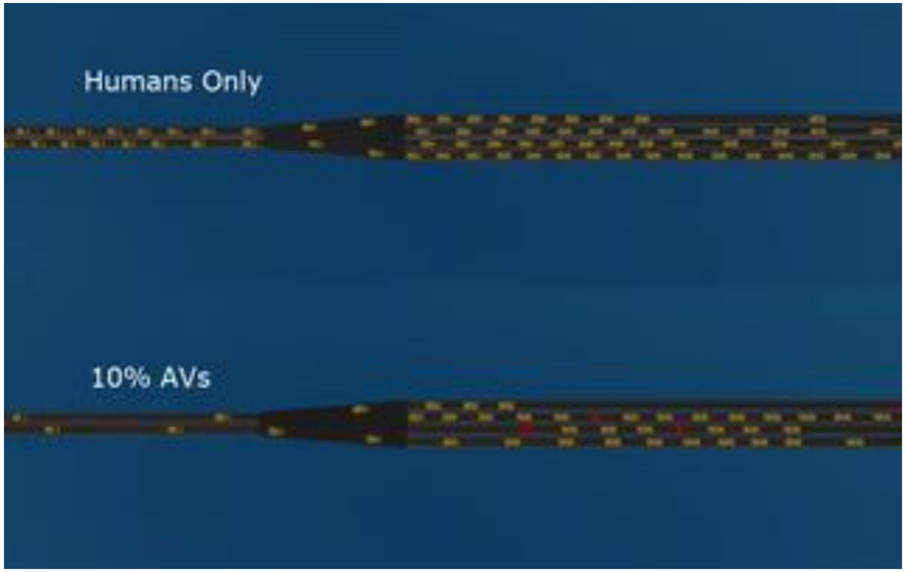
- AI digitized roads (Mogo AI)

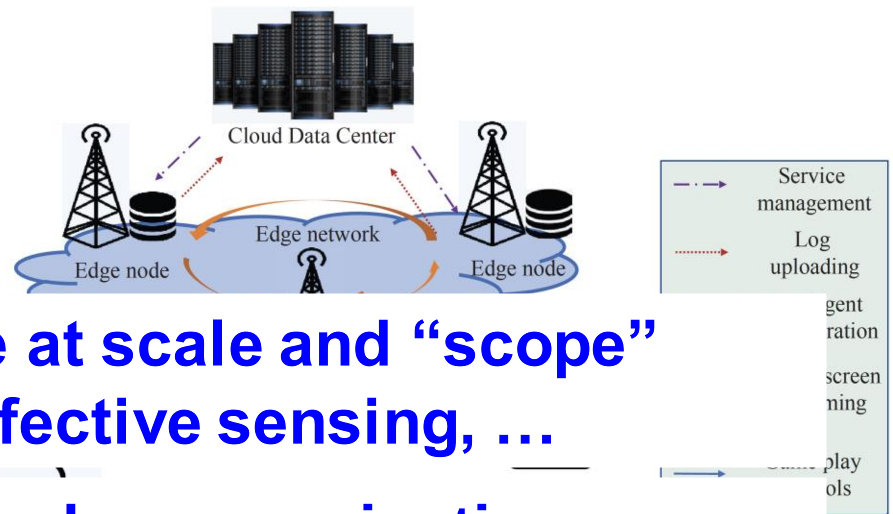


- Autonomous driving and traffic control



Newly emerging applications of smart cities

- Emerging applications
  - Augmented reality (AR)/Virtual reality (VR) Navigation/Metaverse/digital twins



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

Question: how can we effectively support all these wishful activities to manage a smart city?

Action items: 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)
  - Move data to the right place at the right time!: potentially large volume to be “computed”
- Need to have computing capability in situ and in tempore: perform data analytics for spot 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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Technically, 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 deployment)
  - Low latency guarantee for timely actions
  - Flexible distributed collaborative learning

Computing

- Storage/buffering for caching & 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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Holistic design to accomplish a mission!

video data collection

action: control

data analytics: ML

data transport

Anomaly detection (e.g., Amber

al

- **A single resource (1D) is not enough!**
- **Demand a good coordination of multiple resources (mD)!**

Further analysis at city police department

Inconclusive but suspicious?

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Where do we get resources?

- 5G/6G and beyond?
  - ➢ Yes, it is an option
  - ➢ But costly
    - ✓ CAPEX: Infrastructure investment cost (BSs, land permit, …)
    - ✓ OPEX: 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: the holy grail

- 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?
- Resources on the move
  - ✓ BS, AP, DAS,…
  - ✓ Computing servers
  - ✓ Storage
  - ✓ AI/ML toolboxes

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

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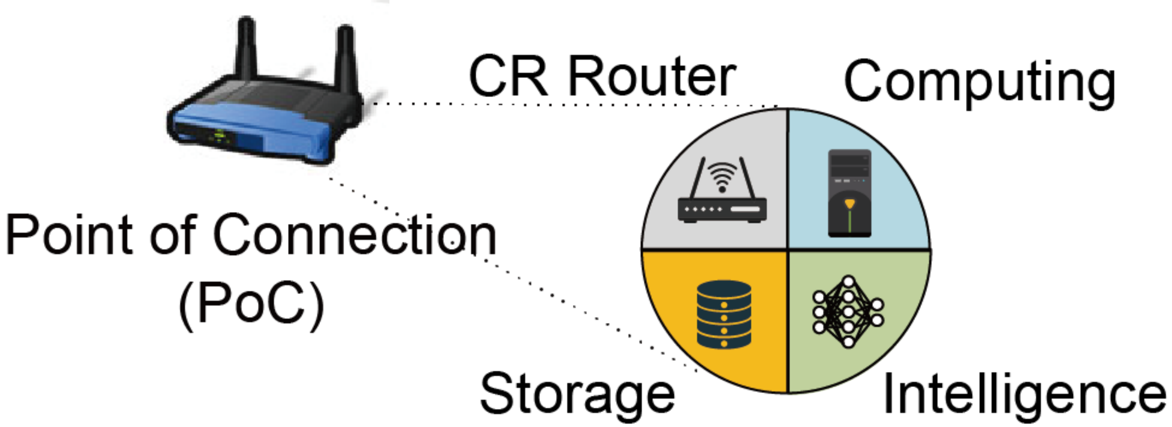
SCCSI enablers: Point of Connection (PoC)

- 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 (e.g., edge/fog)
- Storage/memory/caching: fast distributed **networked storage** for data storage, buffering, and prefetching/caching (e.g., information centric networking or ICN)
- Intelligence: **Customized AI/ML** toolboxes! (e.g., DNN/FL)



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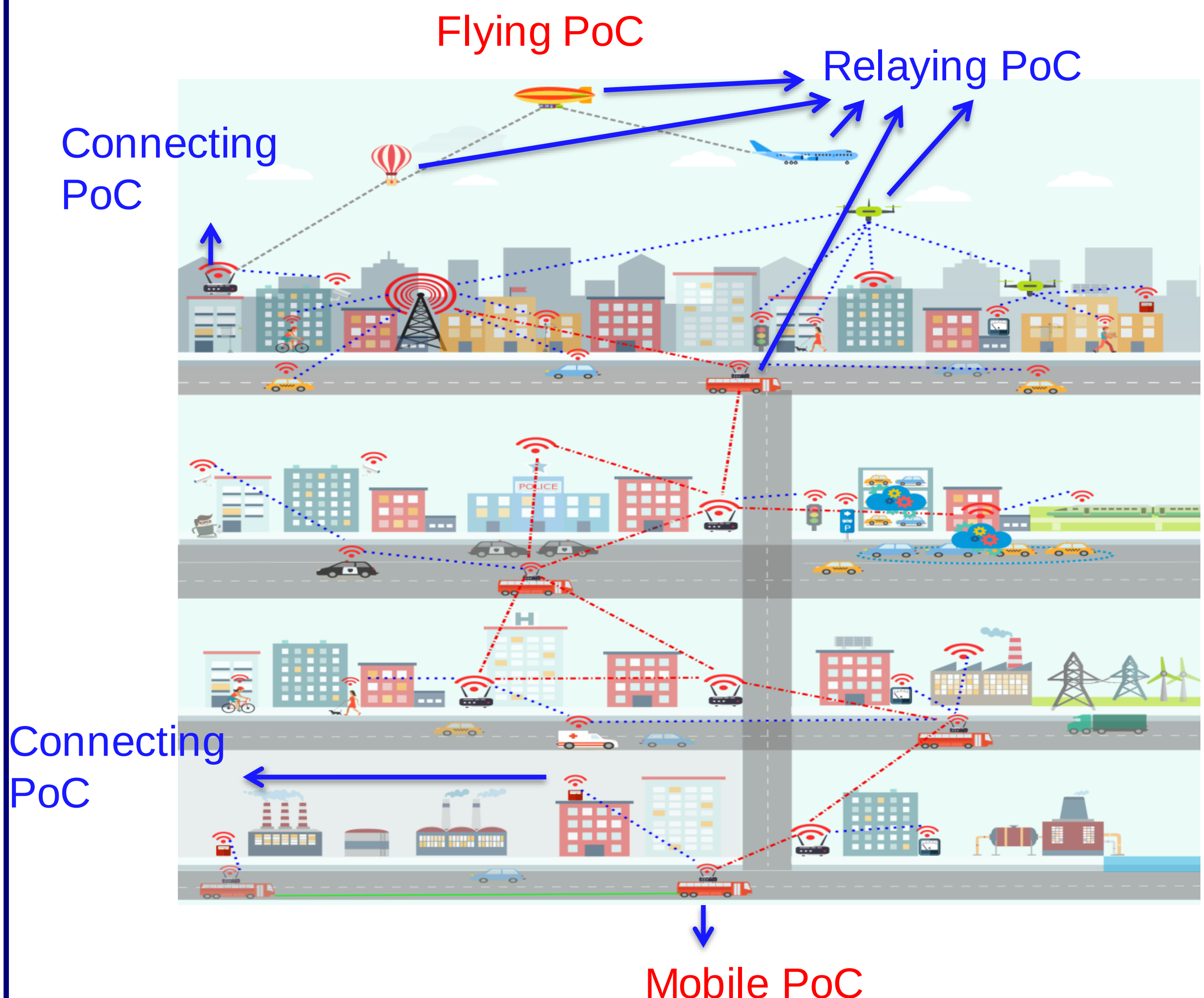
A SCCSI Service Network:
Beef up the network edge + Mobile infrastructure



PoC can be simplified intelligent reflecting surfaces (RISs)

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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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Intuitive Benefits

- The more the users (vehicles), the better the service quality
  - ➢ When more vehicles are available, more SCCSI resources can be made available, i.e., frequency reuse can be optimized
    - ✓ More "computing servers", more mobile base stations, …
  - ➢ "取之于民，用之于民！"
  - ➢ "众人拾柴火焰高！"
  - ➢ More powerful SCCSI in connected and autonomous vehicles can be leveraged
- Getting much "closer" to end users
  - ➢ Mobility helps push services to the edge

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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

- Leverage 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 incentivized 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," Accepted for publication in *IEEE Communications Surveys and Tutorials*. **DOI:** 10.1109/COMST.2024.3370169, 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.

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Resources on the Move: Vehicles as a Service (VaaS)

- Edge Communication resources (e.g., small cells)
  - Push communications services closer to end users
  - 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
  - Design flexible data transmission schemes (data blasting, store-carry-forward)
- 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
- Edge Intelligence (e.g., federated learning)
- Edge Security & Privacy (e.g., hardening the edge)

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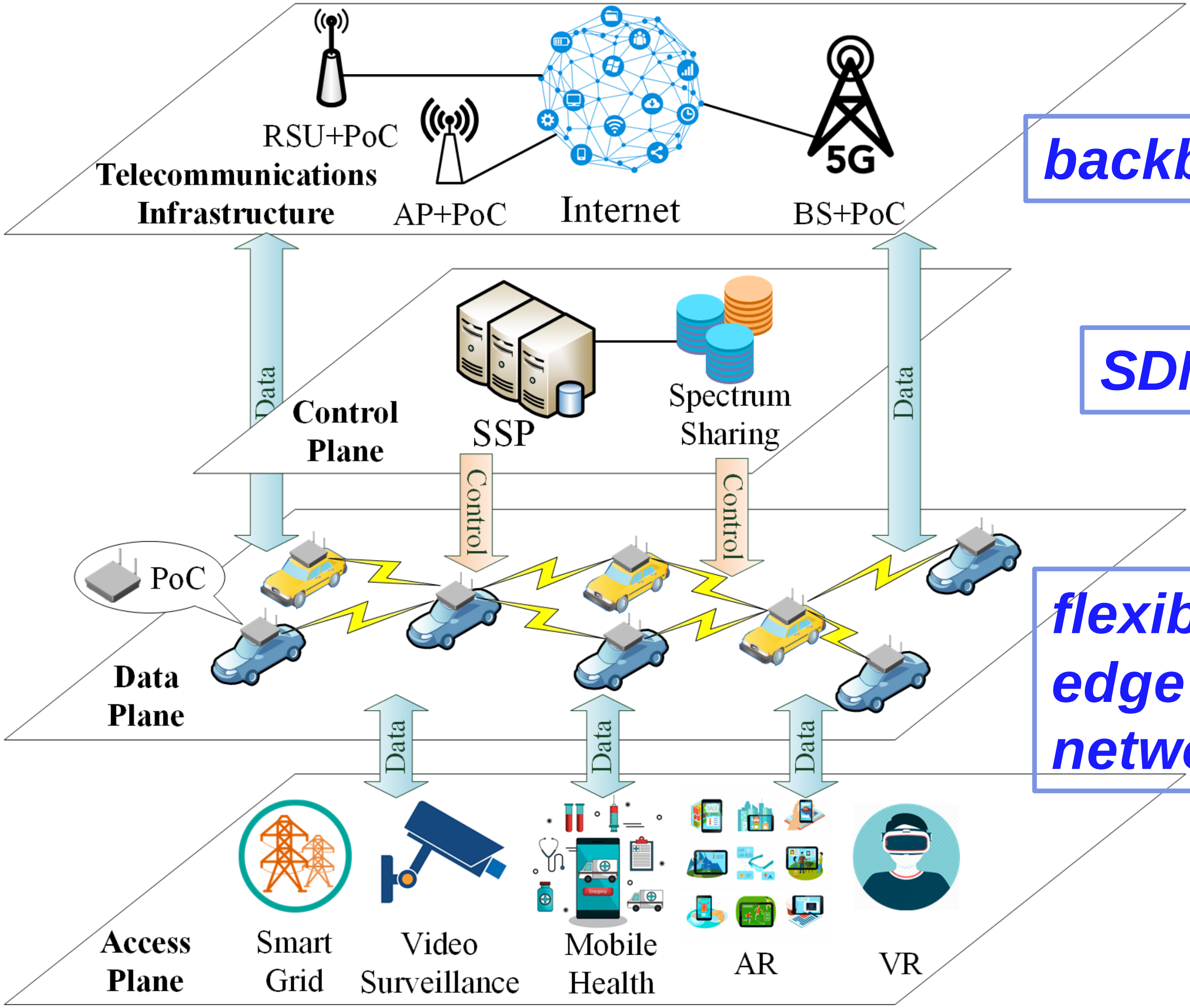
Design of A SCCSI Service Network



backbone

SDN

flexible edge networks

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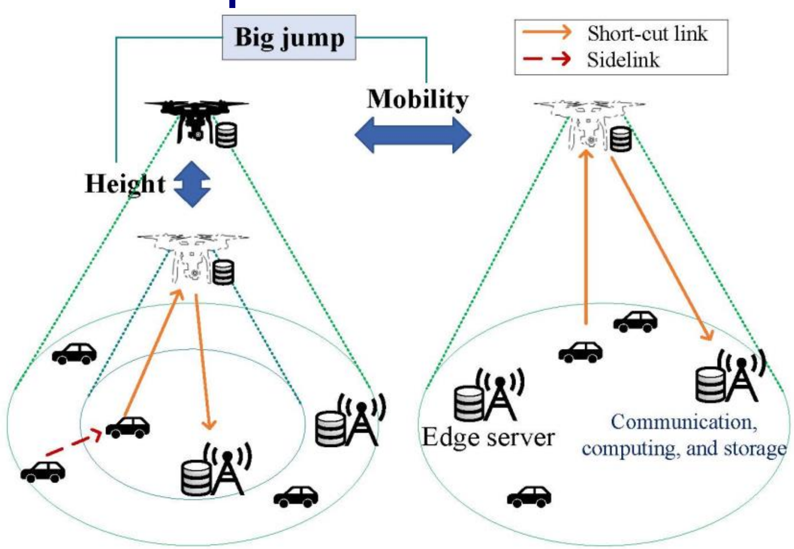
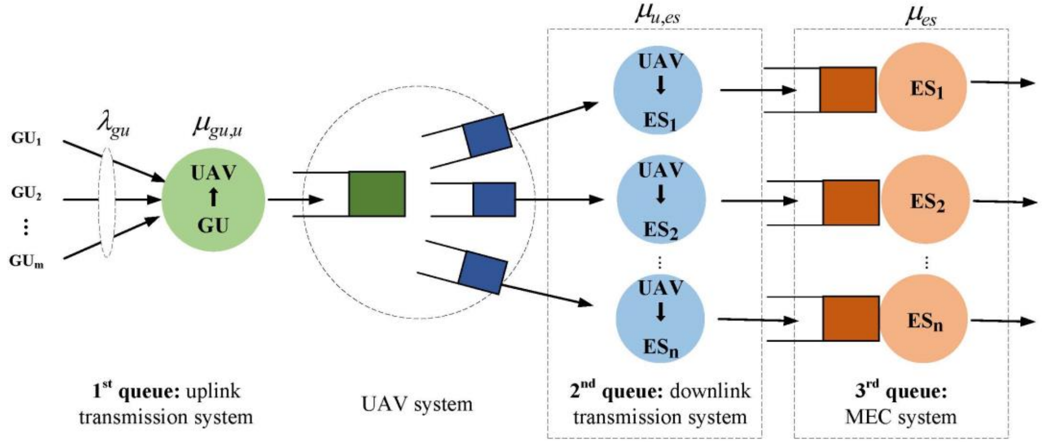
Leveraging Over-The-Air (OTA) Advantages

- UAVs/drones provide rapid deployability & agility





$$
\begin{aligned}
(\mathbf{P1}):\quad \max_{h,x}\quad & x\pi R_c^2 \lambda_{\text{gu}} \bar{P}_{\text{cov,gu}}(\beta, h) \\
\text{s.t.}\quad & \mathbb{1}[x>0] L^{bound}(h,x) \le D^{th}, \\
& h>0, \\
& x \in [0,1],
\end{aligned}
$$

- Y. Deng, H. Zhang, X. Chen, and Y. Fang, "UAV-assisted MEC with an expandable computing resource pool: Rethinking the UAV deployment," Accepted for publication in *IEEE Wireless Communications*.
- Y. Deng, H. Zhang, X. Chen, and Y. Fang, "UAV-assisted multi-access edge computing with altitude-dependent computing power," Accepted for publication in *IEEE Transactions on Wireless Communications*.

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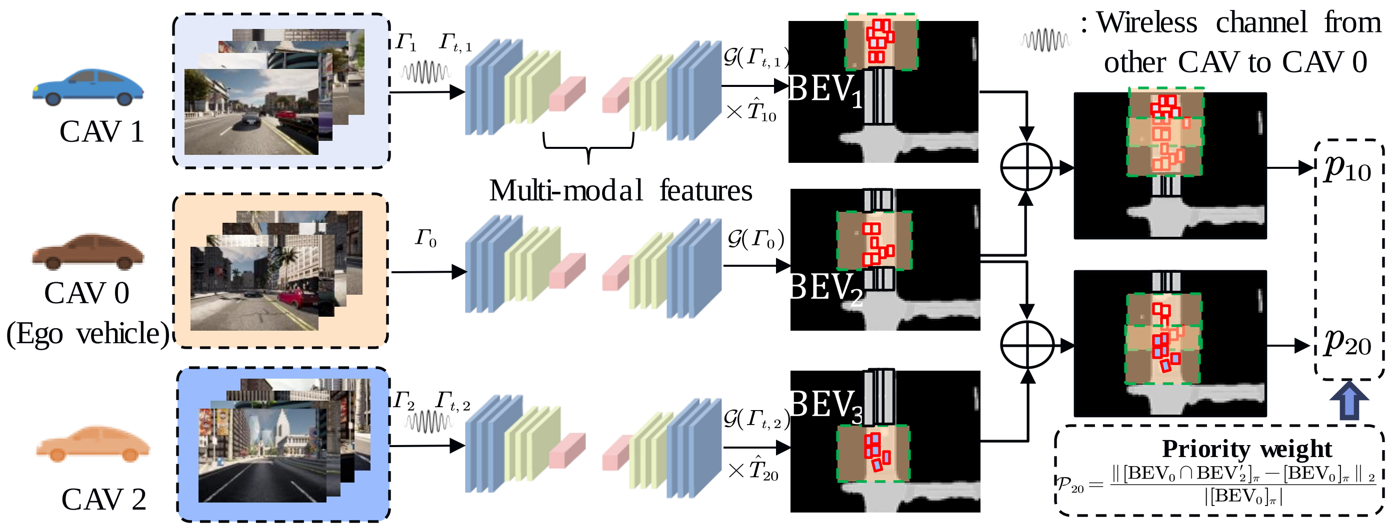
Prioritizing the Use of Constrained Resources

- Tradeoff between perception utility and spectrum constraints



(a) Camera sensing (b) Encoder & Decoder (c) BEV feature (d) Weight determination

- Zhengru Fang, Senkang Hu, Haonan An, Yuang Zhang, Jingjing Wang, Hangcheng Cao, Xianhao Chen, and Yugaung Fang, "PACP: Priority-Aware Collaborative Perception for Connected and Autonomous Vehicles," submitted for publication.
- Yuang Zhang, Haonan An, Zhengru Fang, Guowen Xu, Yuan Zhou, Xianhao Chen, and Yuguang Fang, "SmartCooper: Vehicle collaborative perception under adaptive fusion and judger mechanism," 2024 IEEE International Conference on Robotics and Automation (ICRA), Yokohama, Japan, May 13-17, 2024.

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Incentivizing Participations: Service Auction

Single-round and sealed-bid double auction

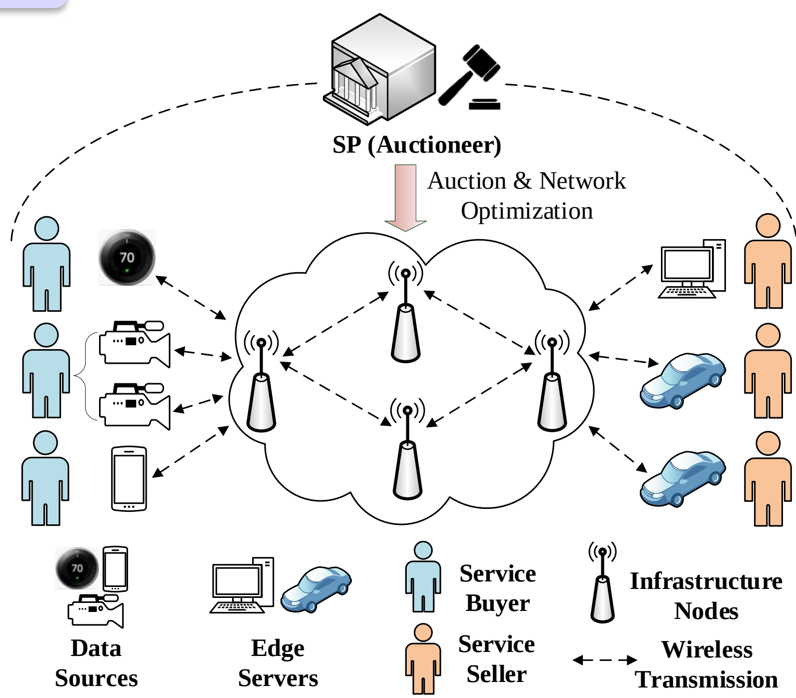
Incentive: monetary or redeemable points

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

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

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

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

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

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

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

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

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

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

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

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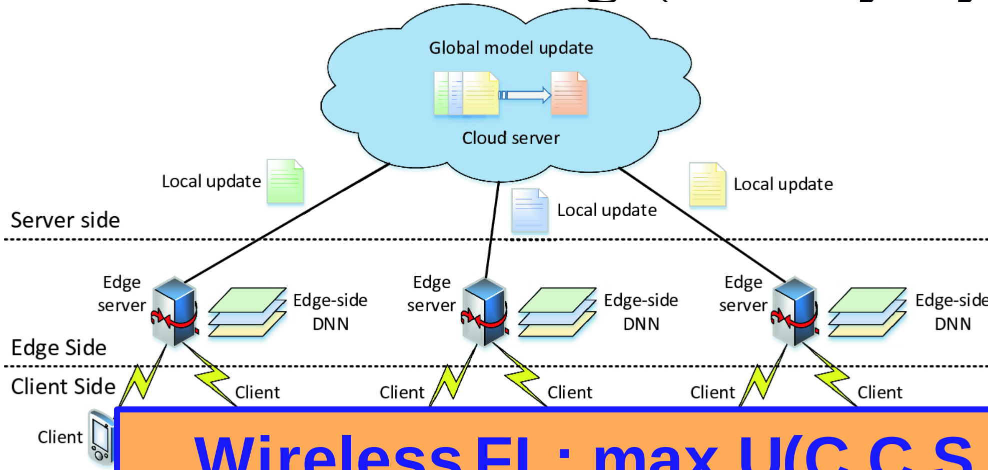
Federated Learning (Privacy by Design)

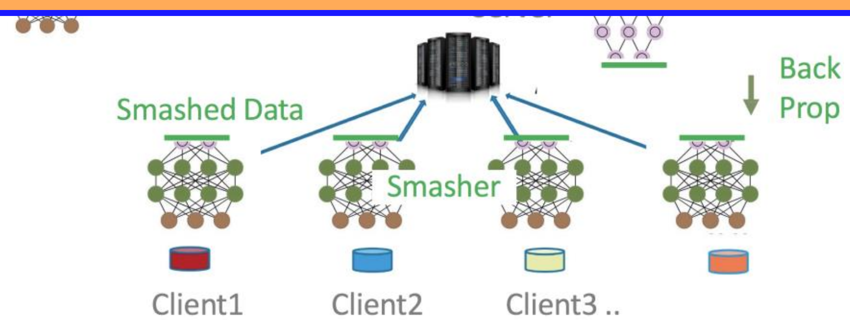


Hierarchical FL

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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Recap

- Offer a 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)
  - ➢ Mobile vehicles are leveraged to push sensing, communications, computing, storage, and intelligence to the EDGE!
  - ➢ A SCCSI service network is organized to manage and secure the ecosystem of a smart city
  - ➢ A viable solution to the digital divide problem is potentially provided

More 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.
2. **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.
3. **H. Ding**, Y. Ma, C. Zhang, X. Li, B. Lin, Y. Fang and S. Chen, "Probabilistic data prefetching for data transportation in smart cities," *IEEE Internet of Things Journal,* **9**(3): 1655-1666, 2022.
4. **H. Ding,** Y. Guo, X. Li and Y. Fang, "Beef up the edge: spectrum-aware placement of edge computing services for the Internet of Things," *IEEE Transactions on Mobile Computing,* **18**(12): 2783-2795, 2019.
5. **H. Ding,** X. Li, Y. Cai, B. Lorenzo and Y. Fang, "Intelligent data transportation in smart cities: a spectrum-aware approach," *IEEE/ACM Transactions on Networking*, **26**(6): 2598-2611, 2018.
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7. **H. Ding**, C. Zhang, B. Lorenzo, and Y. Fang, "Access point recruitment in a vehicular cognitive capability harvesting network: How much data can be uploaded?" *IEEE Trans. Veh. Technol.*, **67**(7): 6438-6445, 2018.
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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.