Edge-Assisted Collaborative Perception in Autonomous Driving: A Reflection on Communication Design

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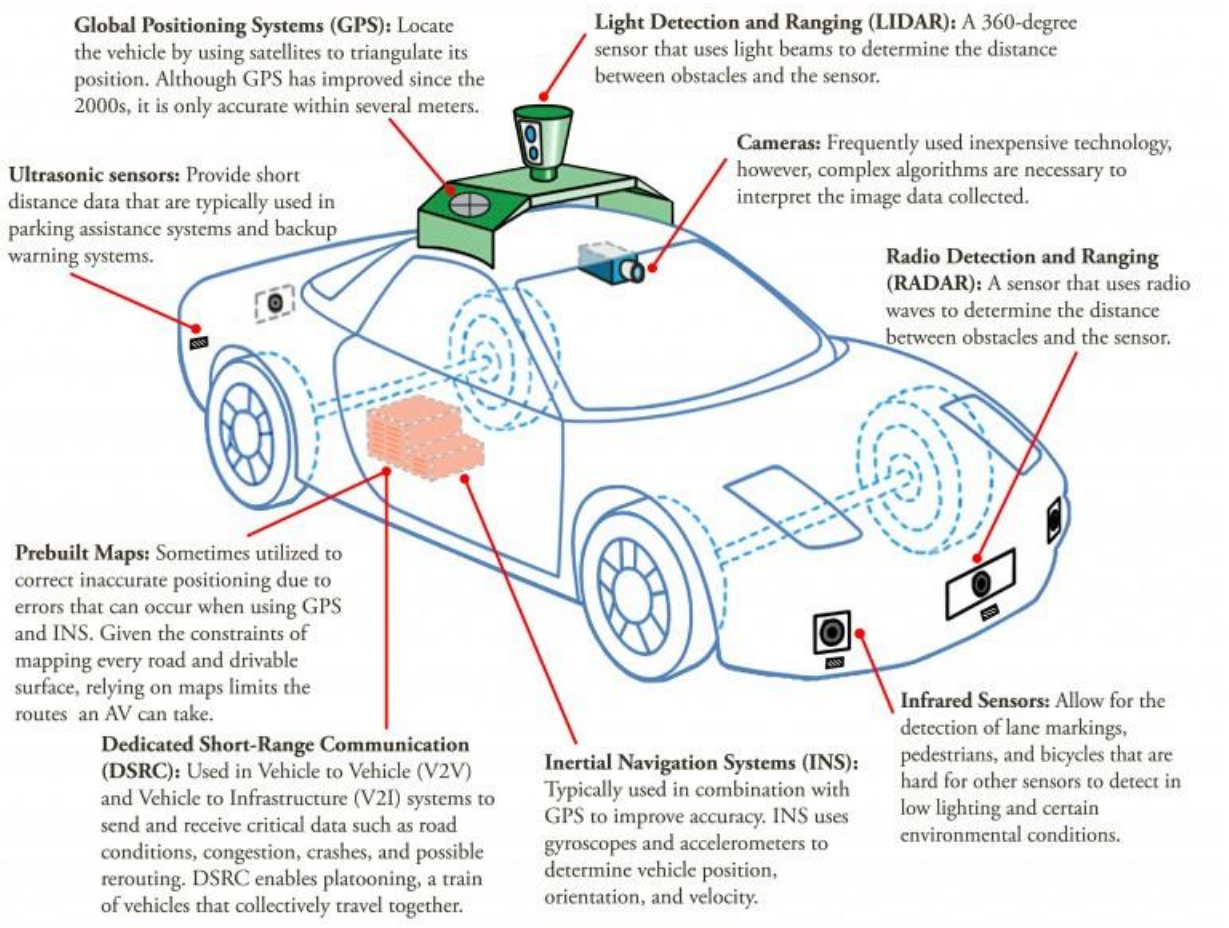
Outlines

- Autonomous Driving & Collaborative Perception
- V2X Communications
- Preliminary Simulation Study
- Edge-Assisted Collaborative Perception: Vision
- Conclusions

Physical Components of an Autonomous Driving Vehicle



Source: "Autonomous Vehicles Fact Sheet", University of Michigan

- **Sensors**
  - Video cameras
  - LiDAR
  - RADAR
  - GPS
  - Gyroscope, accelerometer, speed, …
- Central computer
- **Communication system**
  - V2V / V2I / V2X
  - DSRC / C-V2X / satellite / …

Collaborative/Cooperative Services in Autonomous Driving

❑ Collaborative Awareness

- ❖ **Goal:** make other vehicles aware of self vehicle
- ❖ **Share:** vehicle location, direction, velocity, …
- ❖ **Data size:** small, fixed length

Source: Islam, Md Ashraful, and Nasimul Hyder Maruf Bhuyan. "The effect of radio channel modelling on the network performance in VANET." (2015).

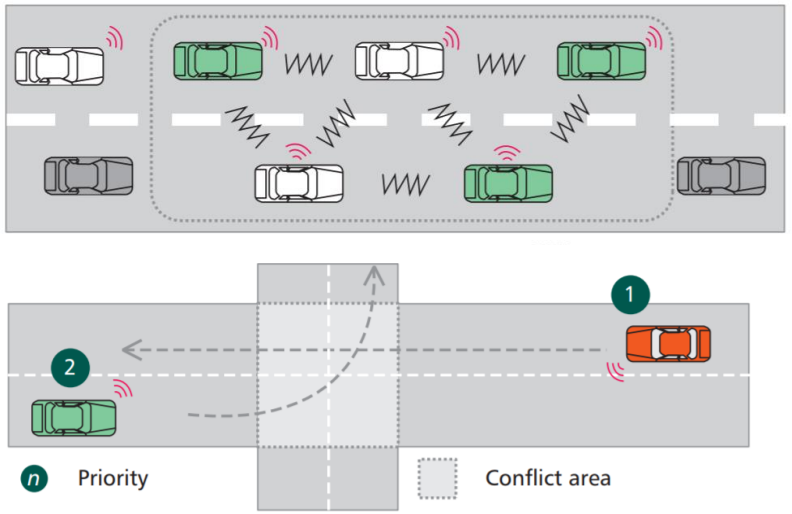
❑ Collaborative Perception

- ❖ **Goal:** remove blind spots, improve perception accuracy
- ❖ **Share:** sensor data or perception results
- ❖ **Data size:** large, variable size

Source: This paper.

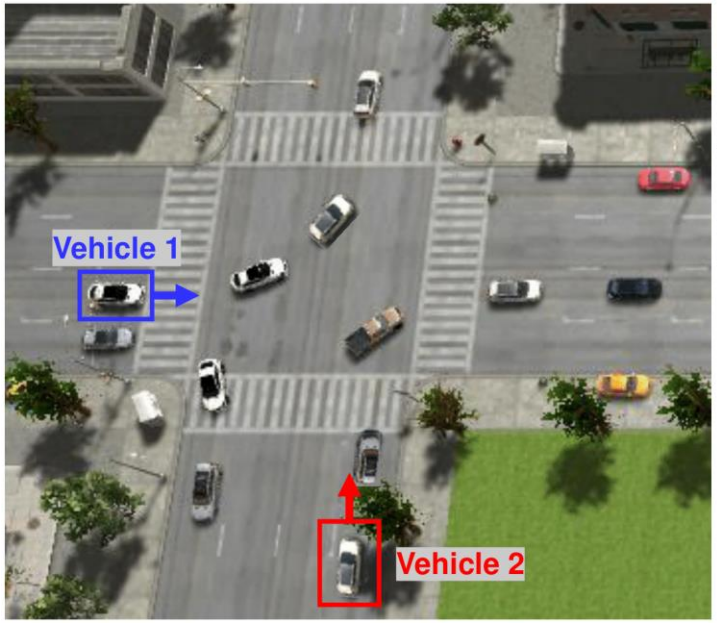
❑ Collaborative Maneuvering

- ❖ **Goal:** platooning, cooperative passing/turning, intersection
- ❖ **Share:** driving commands based on CA/CP
- ❖ **Data size:** pre-defined cmds

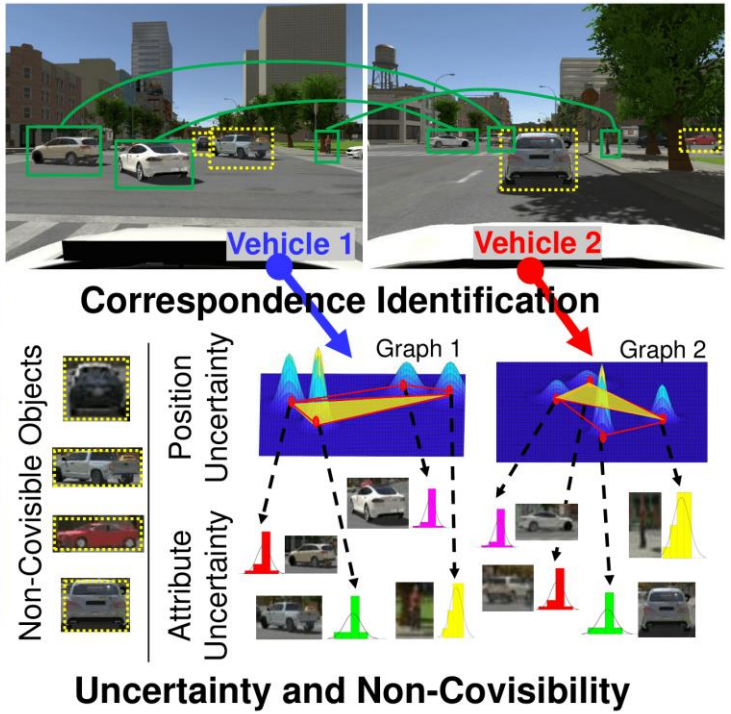


Source: Hobert, Laurens, Andreas Festag, Ignacio Llatser, Luciano Altomare, Filippo Visintainer, and Andras Kovacs. "Enhancements of V2X communication in support of cooperative autonomous driving." *IEEE communications magazine* 53, no. 12 (2015): 64-70.

Collaborative Perception in Autonomous Driving



Motivating Scenarios in Connected Autonomous Driving



Source: Gao, Peng, Rui Guo, Hongsheng Lu, and Hao Zhang. "Regularized graph matching for correspondence identification under uncertainty in collaborative perception." RSS (2020).

- **Goal:** share sensory data or results to improve other vehicles' perception accuracy and remove blind spots.

1. Broadcast local sensor data (e.g., images) or processed results (e.g. detected objects, features and spatial relations) to near-by vehicles.
2. Identify correspondence between local view and received view.
3. Aggregate two views to detect non-covisible objects, and accurately locate covisible objects.

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Vehicle-to-Everything (V2X) Communications

*Source: Jonathan M. Gitlin, "*Qualcomm covers all the bases with a cellular "vehicle-to-everything" chipset, *" Ars Technica.*

5.9 GHz — Official V2X bands in most countries

Multiple Use Cases — CA, CP, CM, Internet

Two Racing Stds. — DSRC, C-V2X

DSRC & C-V2X

Dedicated Short Range Communication (DSRC)

- US DOT project.
- FCC allocated 75 MHz in 5.9 GHz in 1999 …
- … but repurposed to unlicensed and C-V2X in 2020[1].
- Still majorly used in EU, Japan and other countries.

- **802.11p**, with IEEE 1609 (WAVE) or ETSI ITS-G5
  - ✓ WLAN-based, mature
  - ✓ Very low latency
  - ✓ Higher penetration
  - ✓ Range up to 300m
  - x No infrastructure mode
  - x No Internet access
  - x Lower speed and utilization
  - x CSMA/CA

Cellular Vehicle-to-Everything (C-V2X)

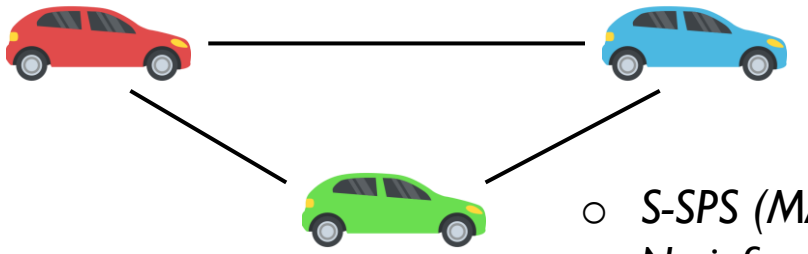
- 3GPP Release 14 (2017) and onward.
- Active industry involvement: Qualcomm, 5GAA, …
- Supported by FCC.
- LTE & NR-based, compatible with cellular network.

- Dual mode: **direct** (V2V/V2I) and **in-direct** (via BS).
  - ✓ Higher speed, better MAC
  - ✓ Reliability
  - ✓ Cellular, Internet access
  - ✓ Range up to >1000m
  - x New tech., low penetration
  - x More time to mature
  - x Higher latency (down in NR)
  - x Strict time synchronization

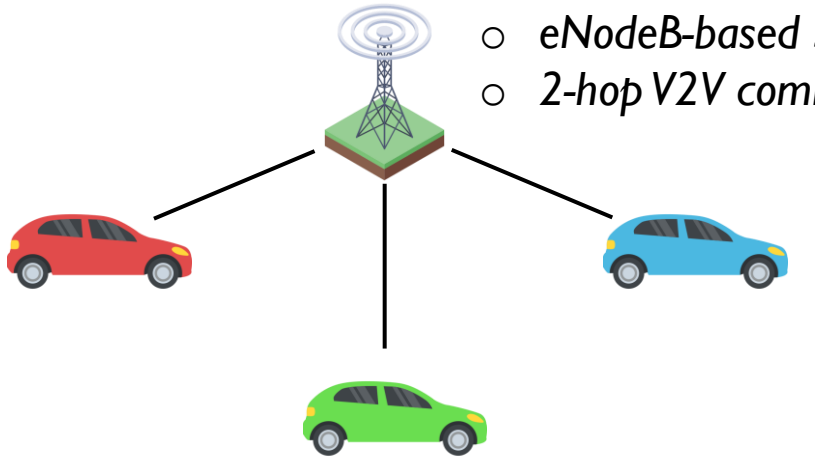
[1] Wiquist, W. "FCC Modernizes 5.9 GHz Band for Wi-Fi and Auto Safety." *FCC News* (2020).

C-V2X Direct and In-Direct Modes

Direct V2V communications (via PC5 interface)



- *S-SPS (MAC)*
- *No infrastructure support*



- *eNodeB-based scheduling*
- *2-hop V2V communications*

In-Direct V2V/V2I communications (via Uu interface)

Sensing-based Semi-Persistent Scheduling (S-SPS)

1. Define selection window W (1-1000ms).
2. Sense past N windows for reservation by other vehicles, and exclude CRs in W.
3. Sense past N windows for RSRP.
   Exclude in W those > th_{RSRP}.
   Increase th_{RSRP} until 20% CRs remaining.
4. Sese past N windows for RSSI.
   Exclude in W those > th_{RSSI}.
   Increase th_{RSSI} until 20% CRs remaining.
5. Pick one CR from W to reserve for R windows.

No scheduling policy specified in 3GPP Releases.

What's missing, and our proposal

- **Direct Mode:** no central scheduling | congestion | contention & collision | inefficiency
- **In-Direct Mode:** 2-hop | double prop delay | half channel efficiency

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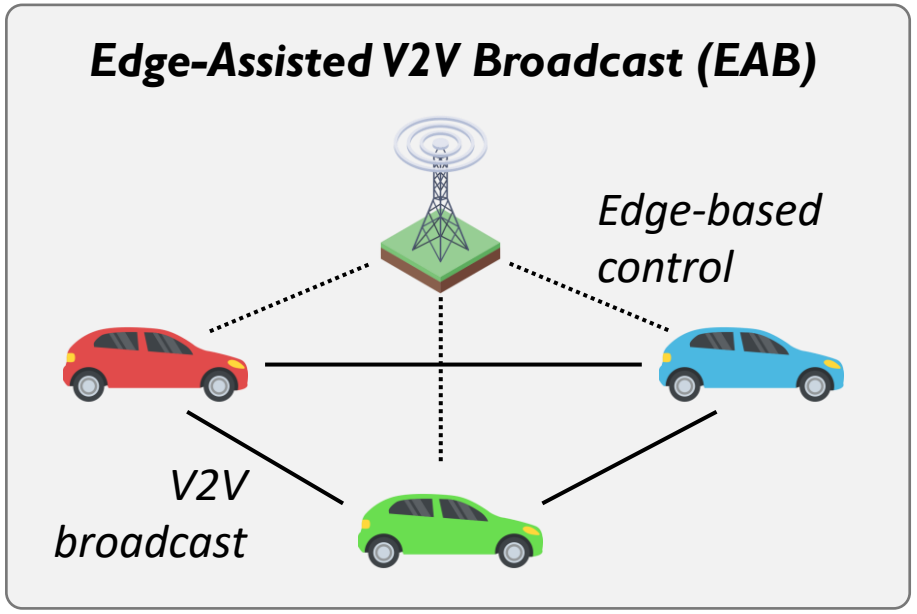
We propose …



- **Direct V2V** — No intermediary for additional overhead. Full channel usage.
- **Broadcast** — Reach all near-by vehicles & RSU at once. Max efficiency.
- **Edge scheduling** — Central scheduling for efficient MAC. Eliminate collision, max channel utilization.
- **Mobility mgnt.** — Hybrid mode for mobility management.

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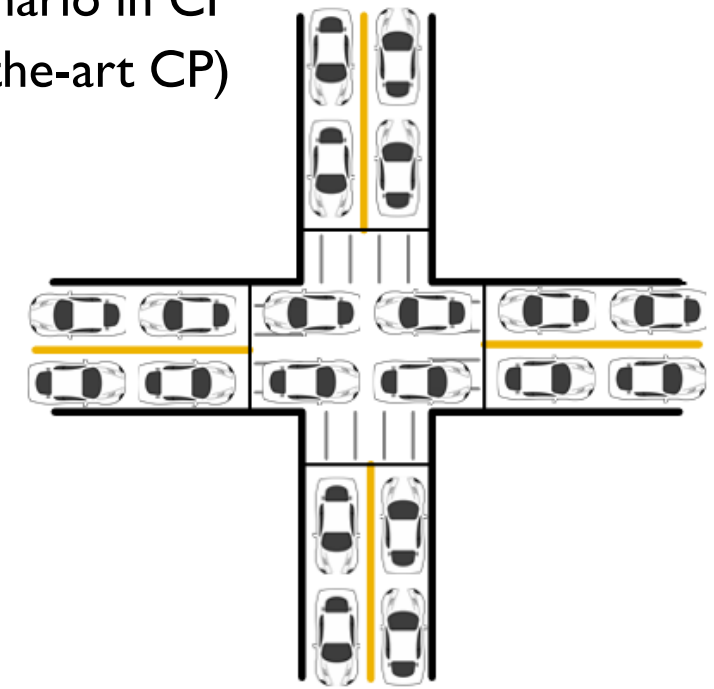
Preliminary Simulation: Goal and Settings

- **Goal:** Verify S-SPS and EAB performance for collaborative perception use cases.
  - EAB: simple round-robin scheduling
- **Settings:**
  - NS3 C-V2X simulator[2], modified for CP (large-sized messages per window) and EAB scheduling
  - Traffic scenario: **4-way congested traffic**, one of the hardest scenario in CP
  - Message sizes: **1.2KB to 50KB per 100ms** (in-range of state-of-the-art CP)
    - Comparison: CA message size is commonly ~200B / 100ms.

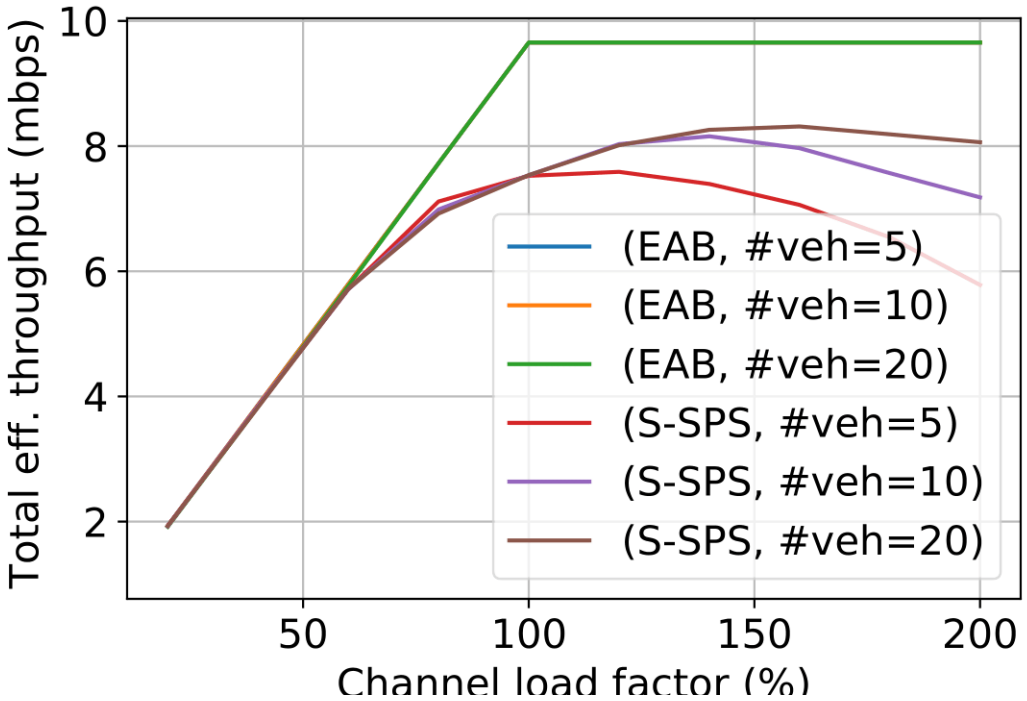
Table 1: Default Simulation Parameters

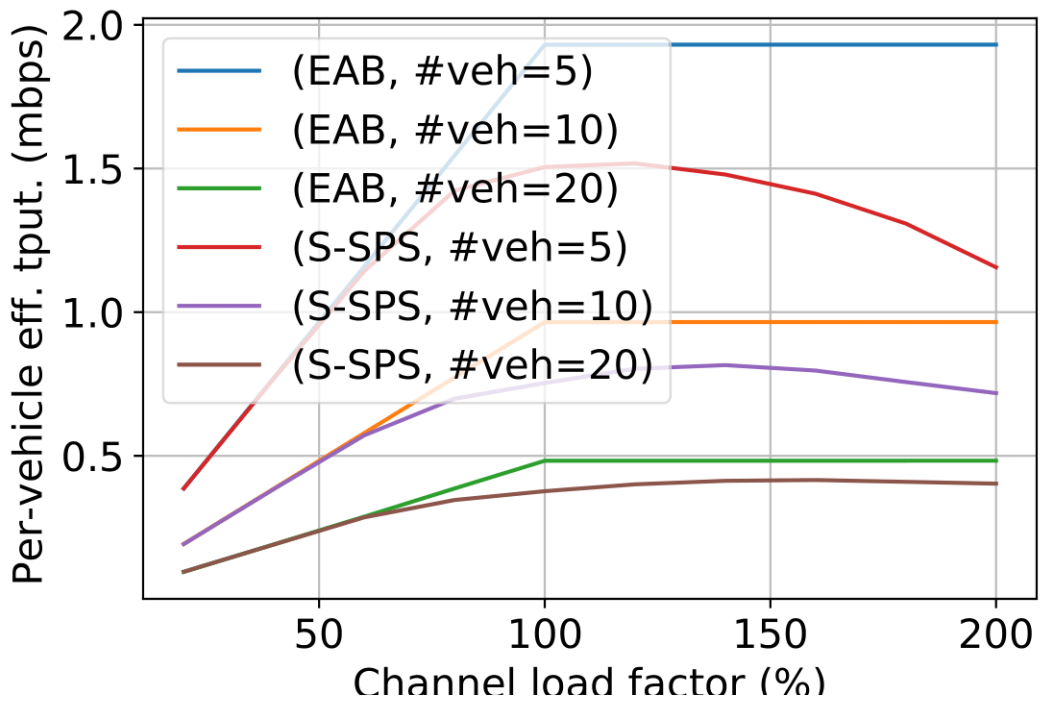
Vehicle Parameters	
Number of vehicles (n)	5-20
Update interval (u) / Selection Window	100ms / 96ms
CPM data size [12]	1, 207 to 48, 280 Bytes
Reselection probability (P)	0.8
Channel Parameters	
Channel bandwidth	10 MHz
PRBs per subchannel	25
Number of subchannels	1
Maximum theoretical bitrate (b)	9.656 Mbps
Channel load factor (ϕ)	20% to 200%



[2] F. Eckermann, M. Kahlert, C. Wietfeld, "Performance Analysis of C-V2X Mode 4 Communication Introducing an Open-Source C-V2X Simulator", In 2019 IEEE 90th Vehicular Technology Conference (VTC-Fall), Honolulu, Hawaii, USA, September 2019.

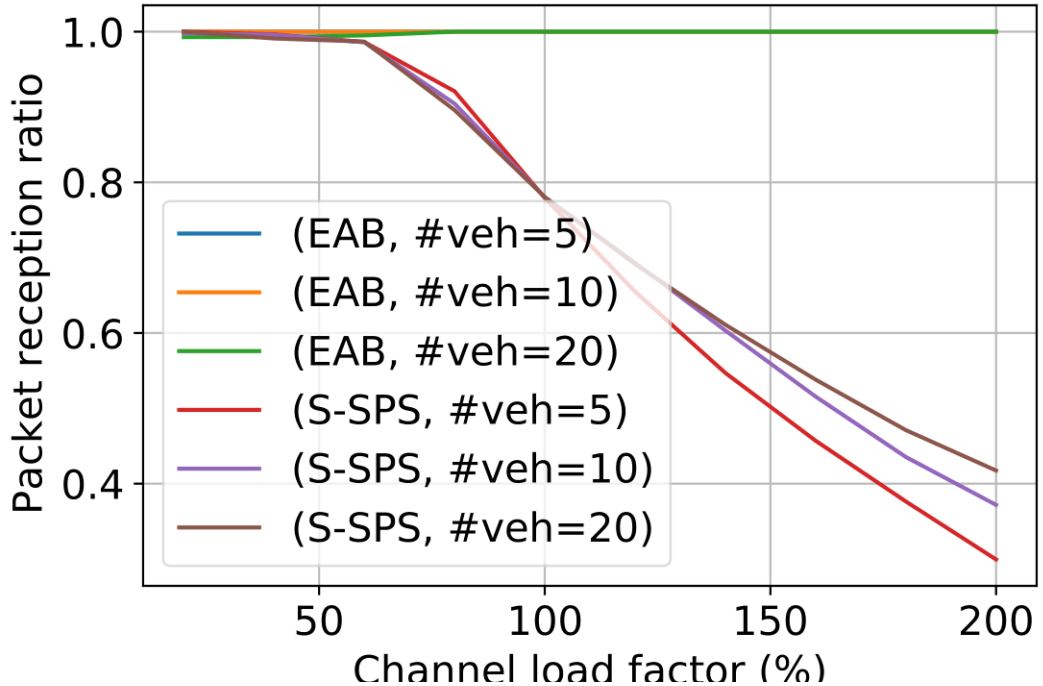
Preliminary Simulation: Results

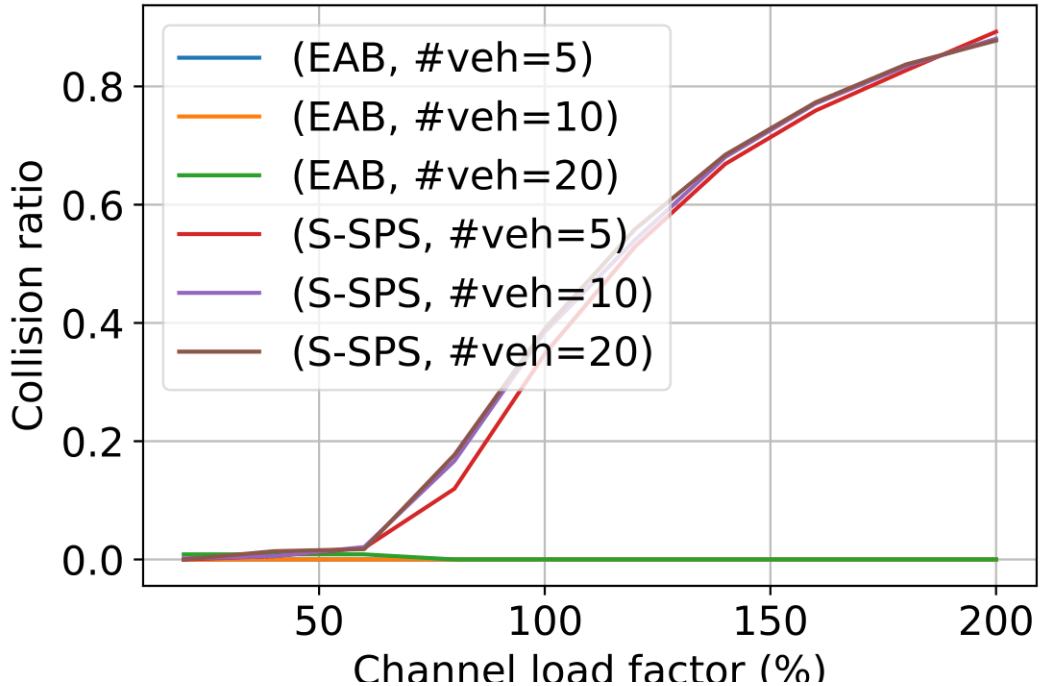




Total Throughput	**Per-Vehicle Throughput**
❑ EAB achieves higher throughput.	
❑ S-SPS throughput increases with #veh, increases then decreases with channel load (excessive collision)	❑ More vehicles decrease throughput of each vehicle.

Preliminary Simulation: Results





Packet Reception Ratio (PRR)	Collision Ratio
❑ EAB achieves no collision, and near-perfect packet reception (close-proximity scenario).	
❑ S-SPS results in congestion & collision when traffic exceeds 50%. #veh has some but not significant impact.	

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What (Challenges) We Face in Collaborative Perception

1

Insufficient data rate

- DSRC or C-V2X supporting up to 100Mbps.
- 5G NR bands pending licensing & requires research.
- Saturated by a few tens of vehicles.

2

Lack of global view & coordination

- No central scheduling leads to high congestion & collision.
- No global view leads to redundant data transmission.
- Prune to distributed malicious behaviors.

3

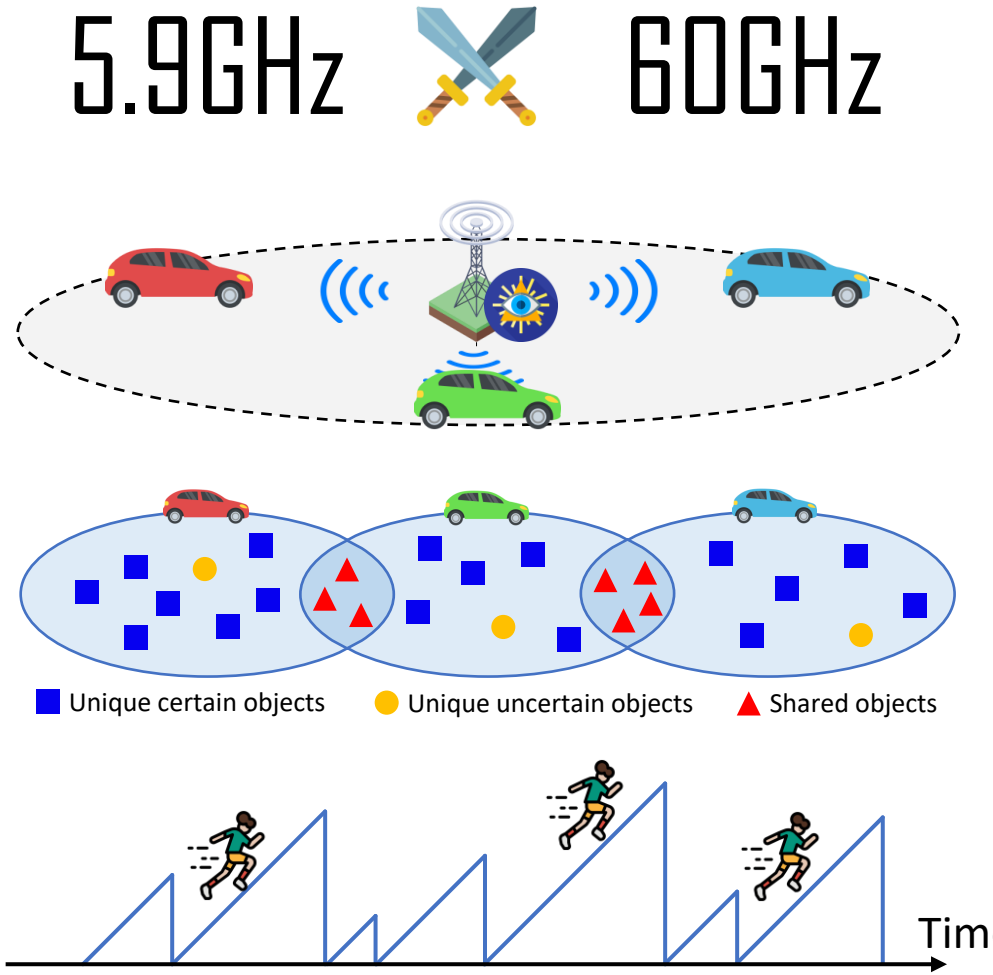
Data redundancy & uncertainty

- Vehicle views can overlap.
- Objects/areas differ in uncertainty.
- Data selection is important / required in some cases.

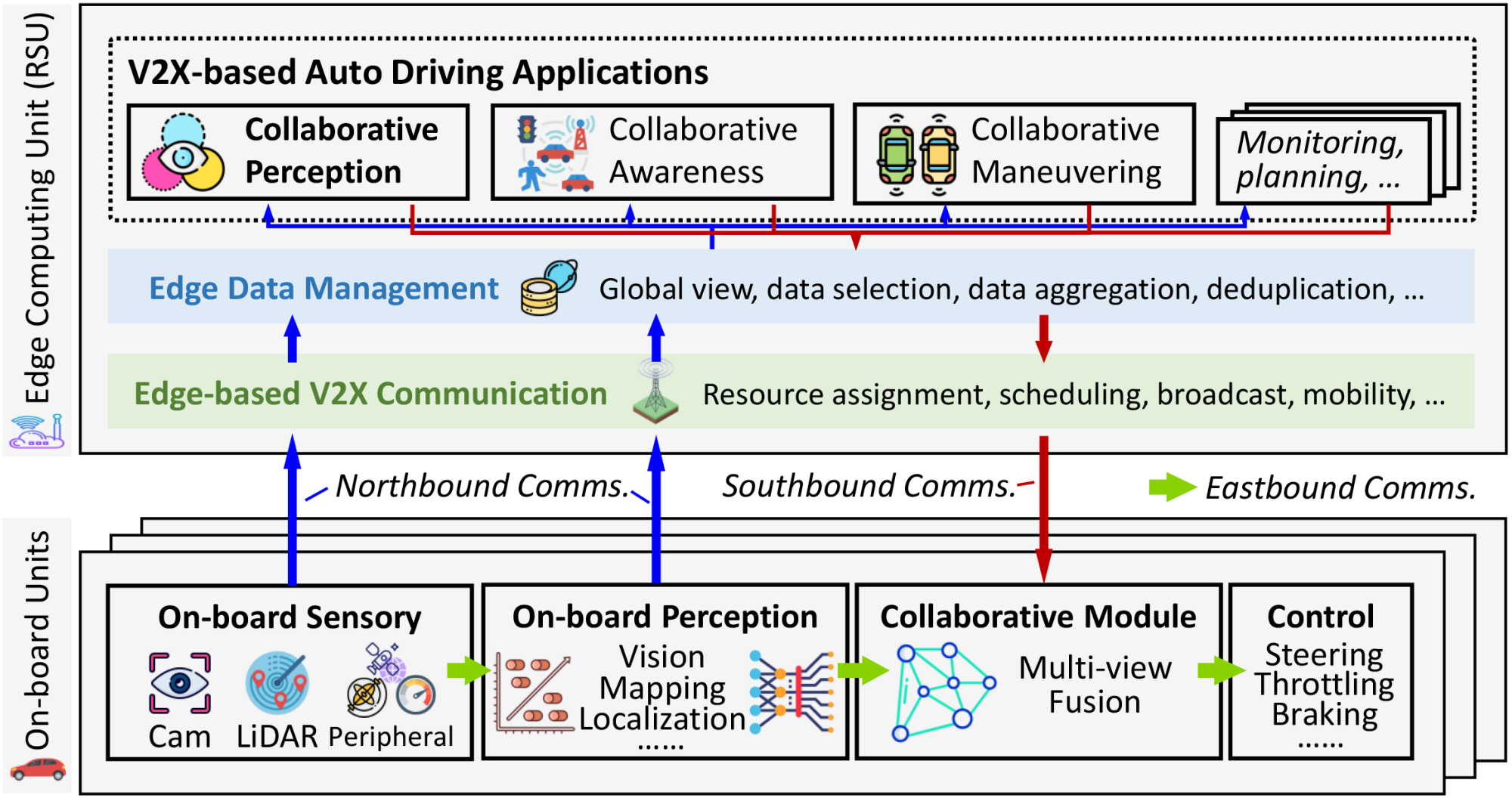
4

Real-time requirement

- Strict latency bounds.
- End-to-end Age-of-Information (AoI).



Our Vision: Edge-Assisted CP



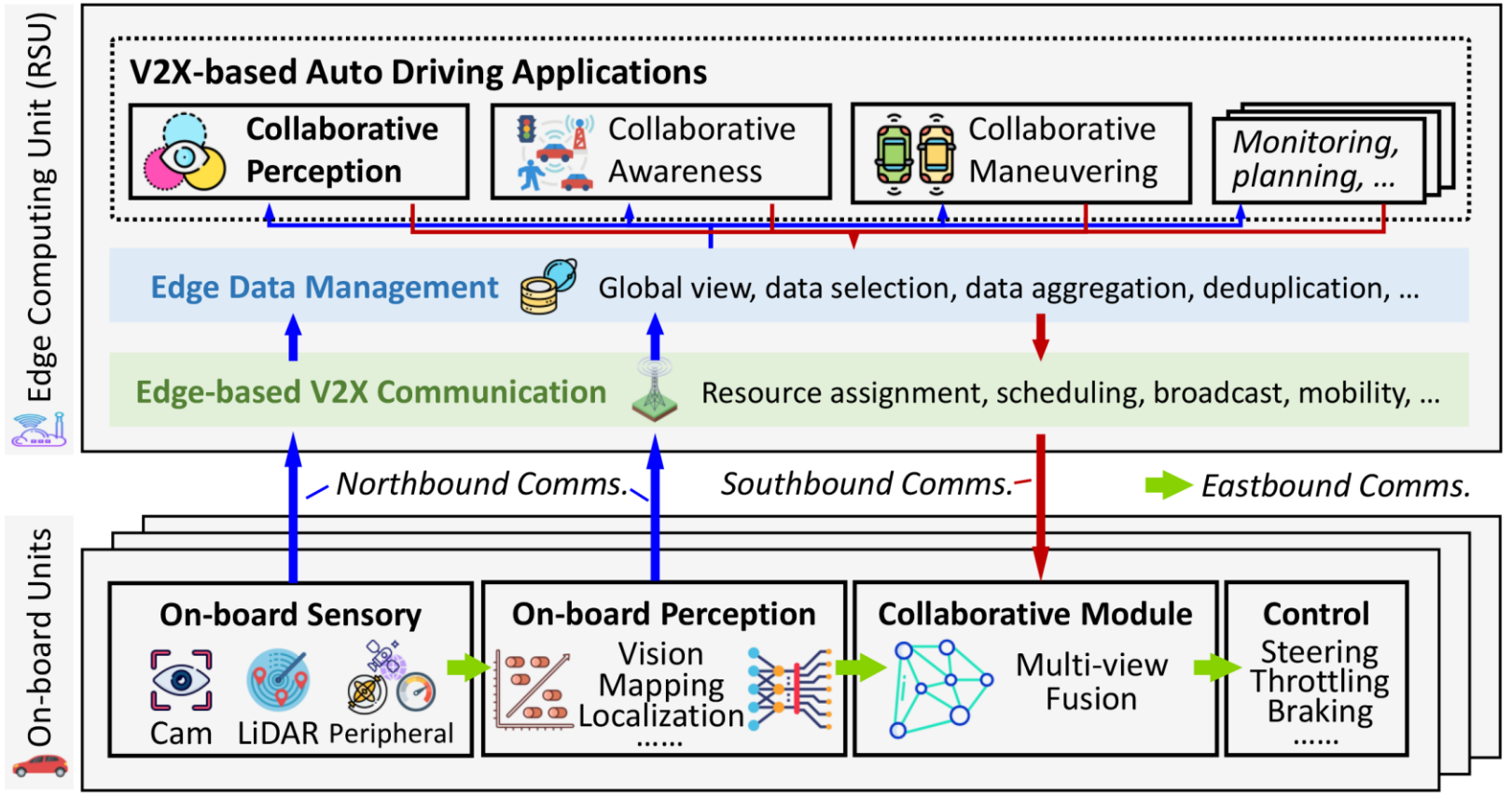
Looking Forward

Edge-based V2X

- PHY-MAC Design
- Mobility
- Real-time & freshness
- Data-/app-awareness

Edge-Assisted Communication-Efficient CP

- Data deduplication & selection
- Global view
- Edge-vehicle multi-fusion
- App-network co-design



CP/Other App Inter-play

- Cross-app data management
- Cross-app communication sharing

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- Collaborative perception + C-V2X
  - An important use case…
  - …yet many unsolved challenges.

- Preliminary simulation study
  - C-V2X direct mode versus Edge-Assisted Broadcast
  - NS-3 simulations based on urban scenario
  - Compared throughput, PRR and collision ratio
  - EAB outperforms C-V2X direct mode in congested scenario
  - More study needed for latency, different traffic scenarios, advanced scheduling, power control, etc.

- **Conclusions:** application-network co-design.
  - A huge design space with a lot of challenges and opportunities.

Thank you very much!

Q&A?