V2X Communication:
Getting our cars talking

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Toyota InfoTech Labs

Toyota Motor North America

Base: Mountain View Research Park (US Headquarters)

Location: Mountain View, CA

Established: April, 2001

Previously called Toyota InfoTechnology Center

Outline

TOYOTA InfoTech
Envisioning Mobility

- V2X: what is it and why should I care?
- DSRC: how does it work?
- What's hard about this? Part 1: technology
- What's hard about this? Part 2: other stuff
  - Business considerations
  - Regulatory considerations

The Connected Vehicle

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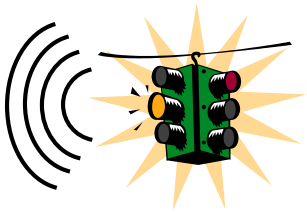
E-payment

"The Network"

Opportunity for Innovation



Signal Phase and Timing

Safety Messages

- Real Time Network Data
- Situation Relevant Information

Probe Data

Instrumented Roadside

US Department of Transportation Vision

Wireless Connectivity Modes

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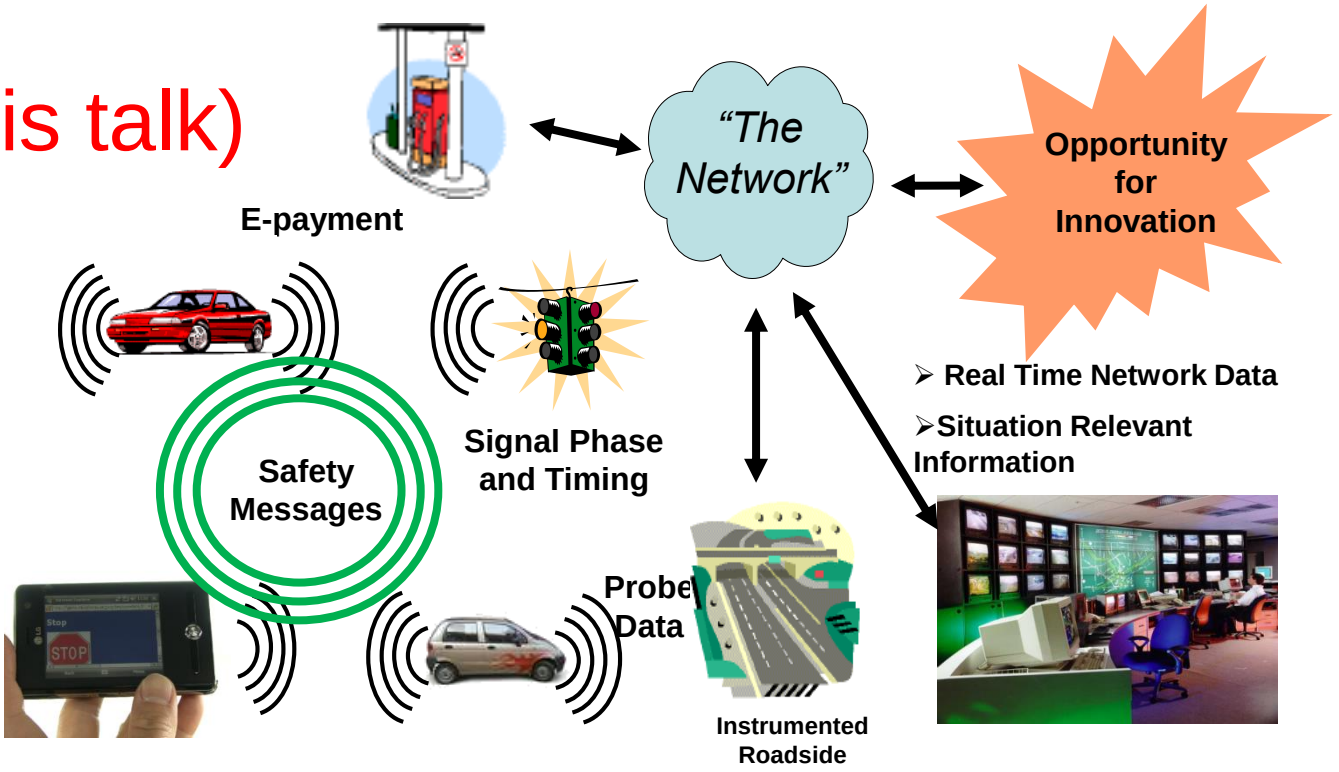
- Radio (AM, FM, XM)
- Cellular WAN (3G, 4G, 5G)
- Bluetooth
- Wi-Fi
- V2X (this talk)



Vehicular Network Hierarchy

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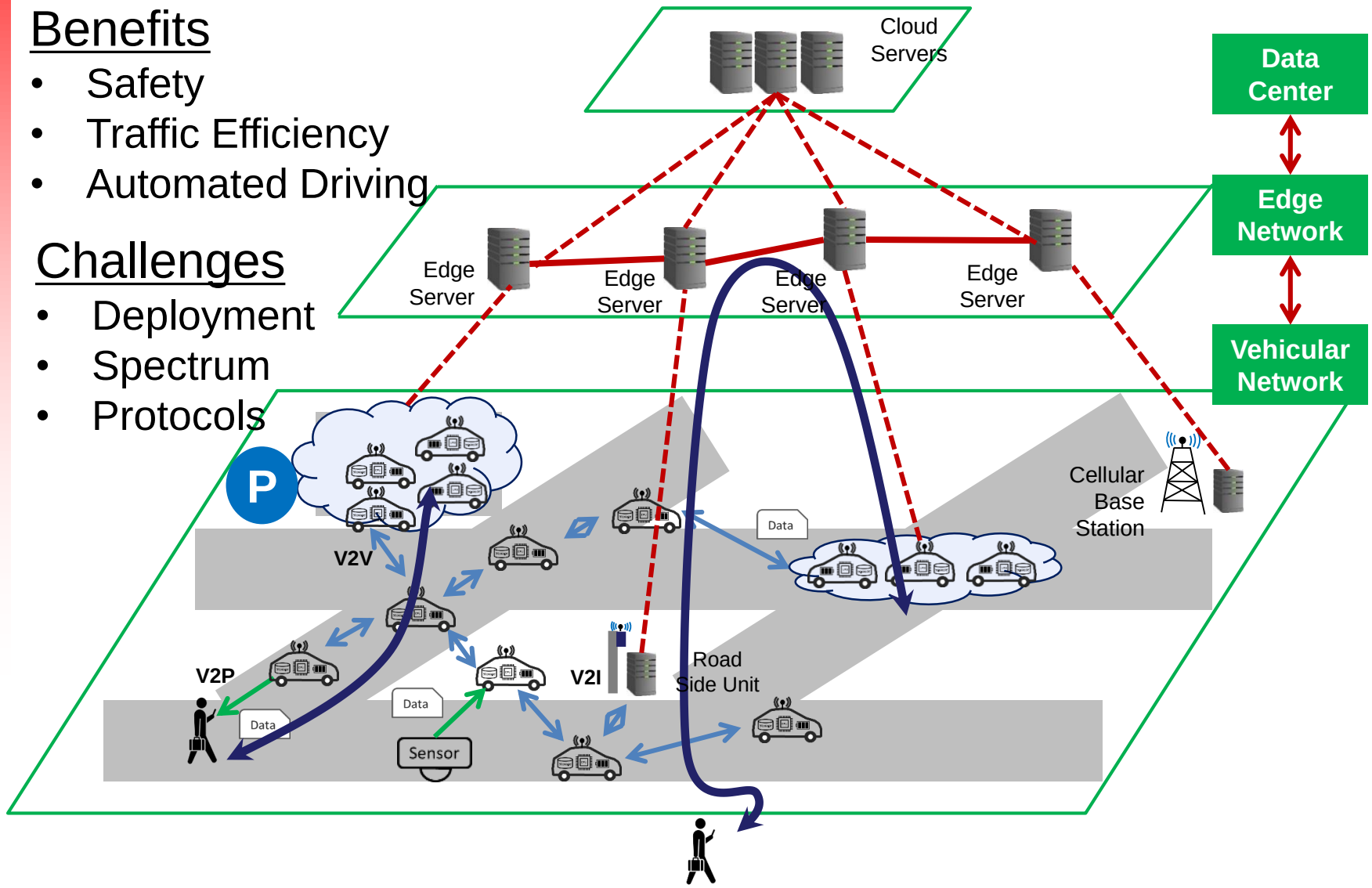
Benefits

- Safety
- Traffic Efficiency
- Automated Driving

Challenges

- Deployment
- Spectrum
- Protocols



V2X is … Vehicle to Everything

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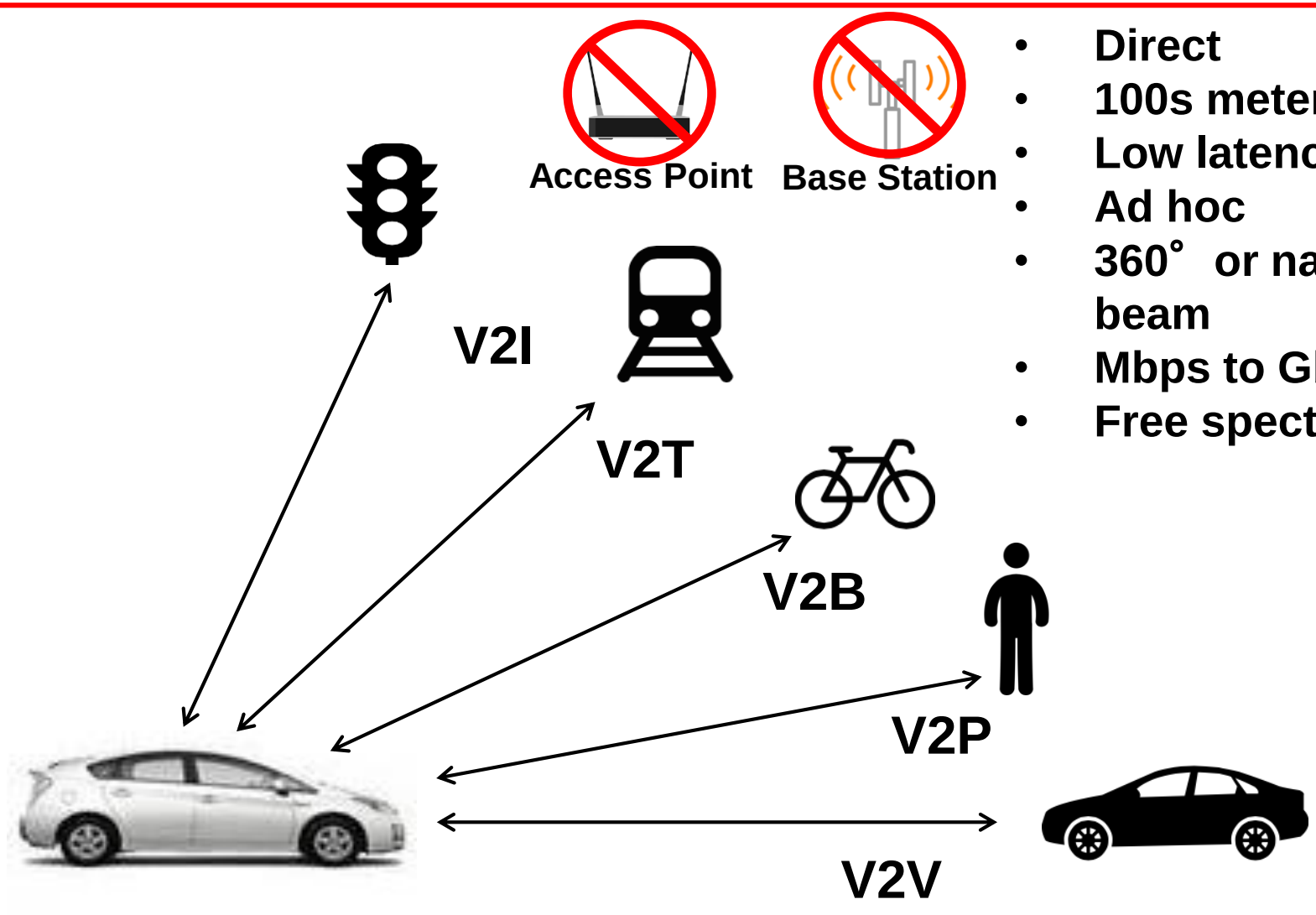

- Direct
- 100s meters
- Low latency
- Ad hoc
- 360° or narrow beam
- Mbps to Gbps
- Free spectrum

Collision Avoidance: What if …?

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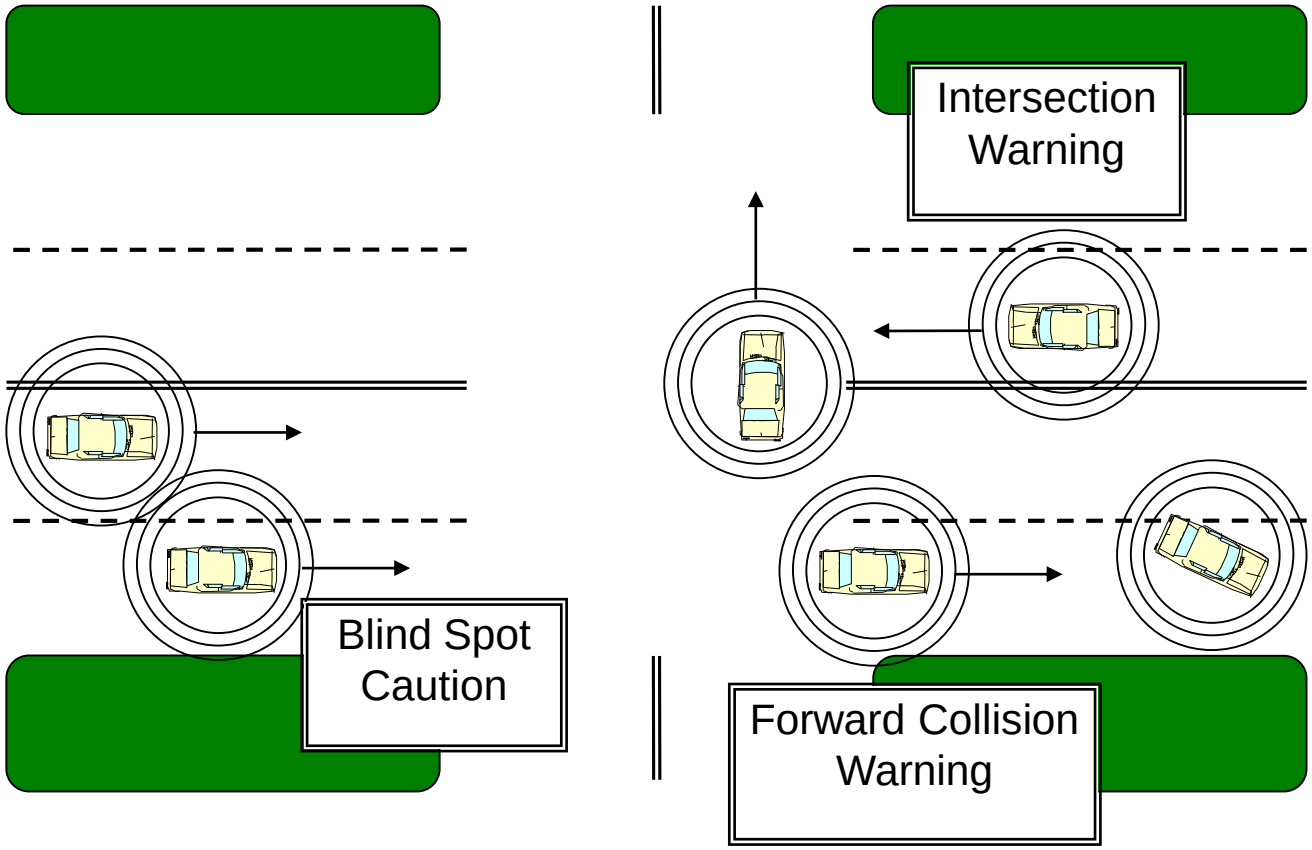

1st Gen: warn driver
2nd Gen: automated collision avoidance

Legend:

In-Vehicle Warning

Message Transmission (range 100s meters)

Vehicle heading

We are doing this

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- DSRC: Dedicated Short-Range Communication
  - IEEE portions also called: WAVE
    - (Wireless Access in Vehicular Environments)
- Many stakeholders in US, EU, JP, …
  - Terminology differs by region: ITS G5 in Europe, ITS Connect in Japan
- Later we will consider non-DSRC V2X technology

“Does my car have this already?”

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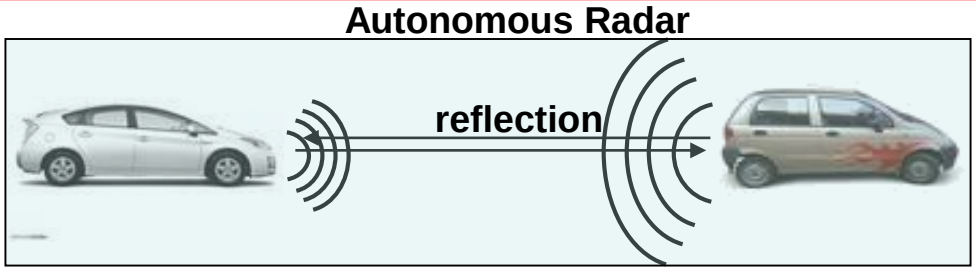
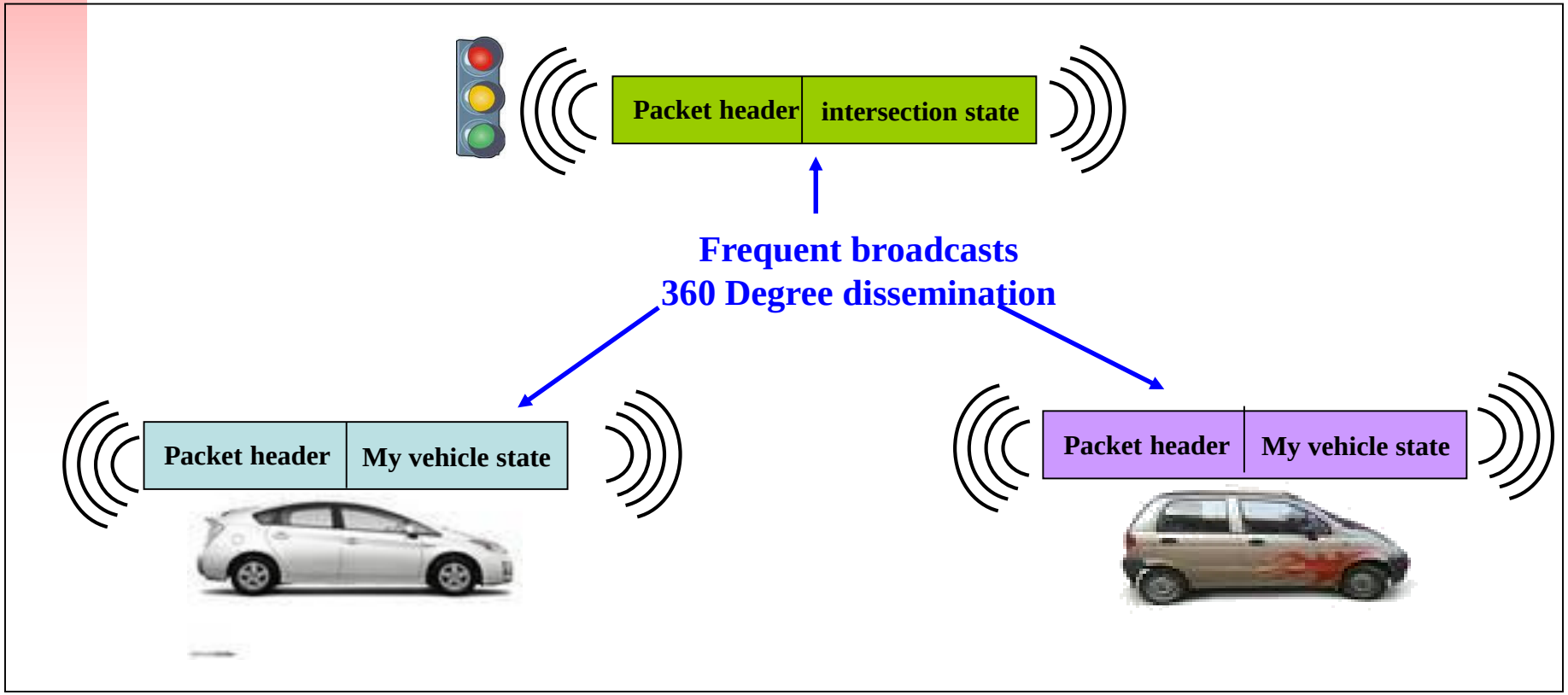
- Contrast sensor and DSRC





Communication Advantages

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- Much more precise data exchanged
- Longer range = 100s meters
- Communicate with non-nearest neighbors
- Non-line-of-sight capability (NLOS)
- 360 degrees with one device

- Disadvantage: dependent on another equipped device (vehicle, infrastructure, …)

→ DSRC and Sensors are complementary

Can I get this today? Yes

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- US: Automaker deployment since March 2017
- US: Most US states have DSRC infrastructure

- EU: Automaker deployment starting 2019
- EU: C-ROADS infrastructure: 17 countries

- Japan: > 150,000 DSRC-equipped cars
- Other regions are following …

GM

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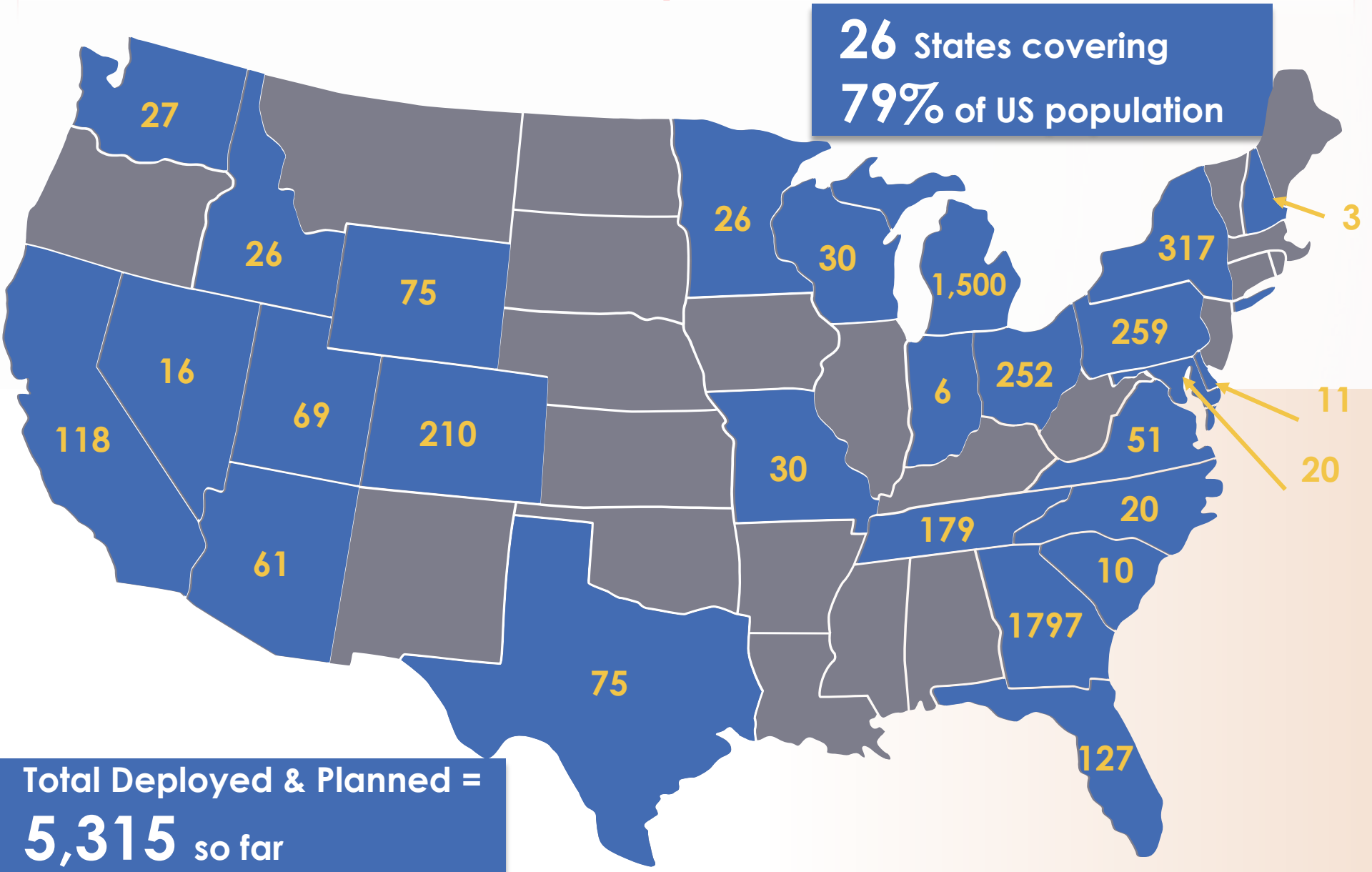
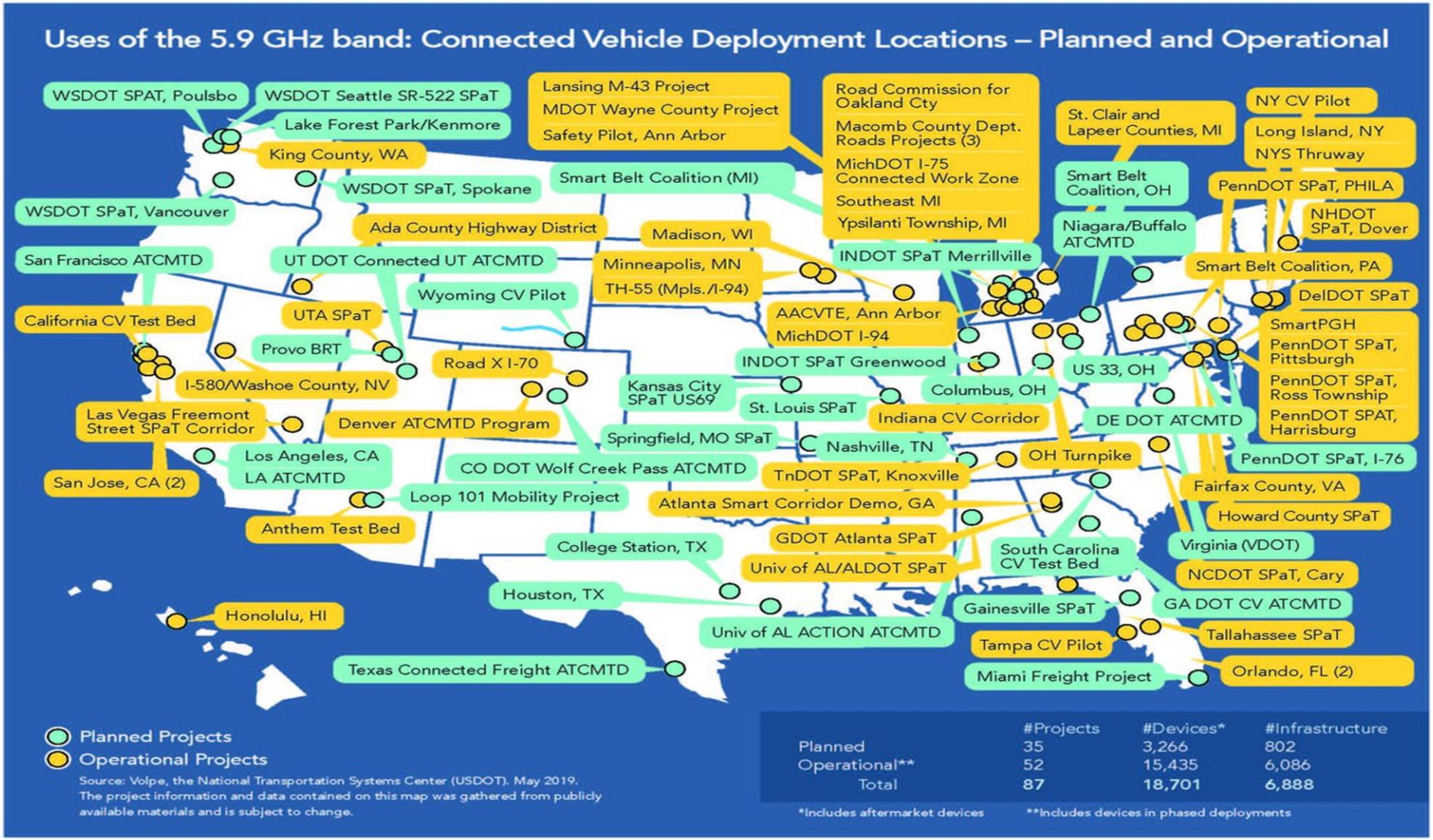
State DOTs are Enthusiastic

DSRC V2I Roadside Units: Operational and Planned



Map of deployment sites and projects



Why do we care?

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- **37,133** US road fatalities in 2017
- One every 14 minutes, 24 x 7
- DSRC can address 80% of crashes involving non-impaired drivers
- DSRC also:
  - makes traffic flow more efficiently,
  - reduces pollution and emissions
  - and improves automated driving

How does it work?

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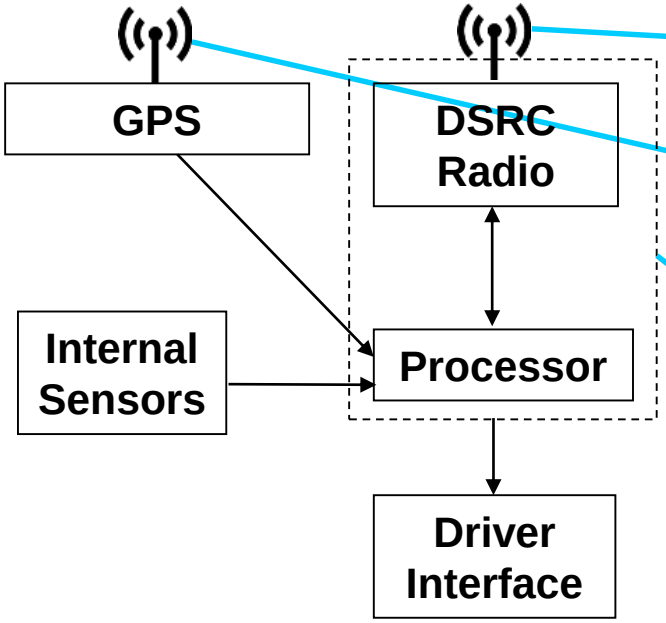
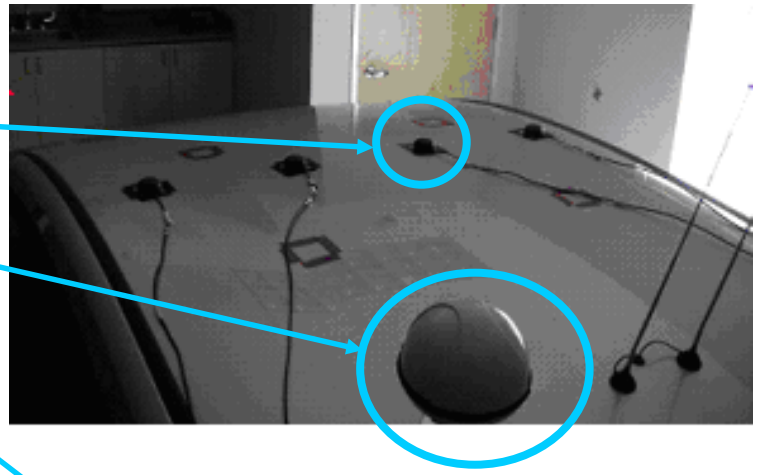


Prototypes



Example of DSRC Prototype System
Many suppliers are in this space

DSRC Standards: mature, expanding

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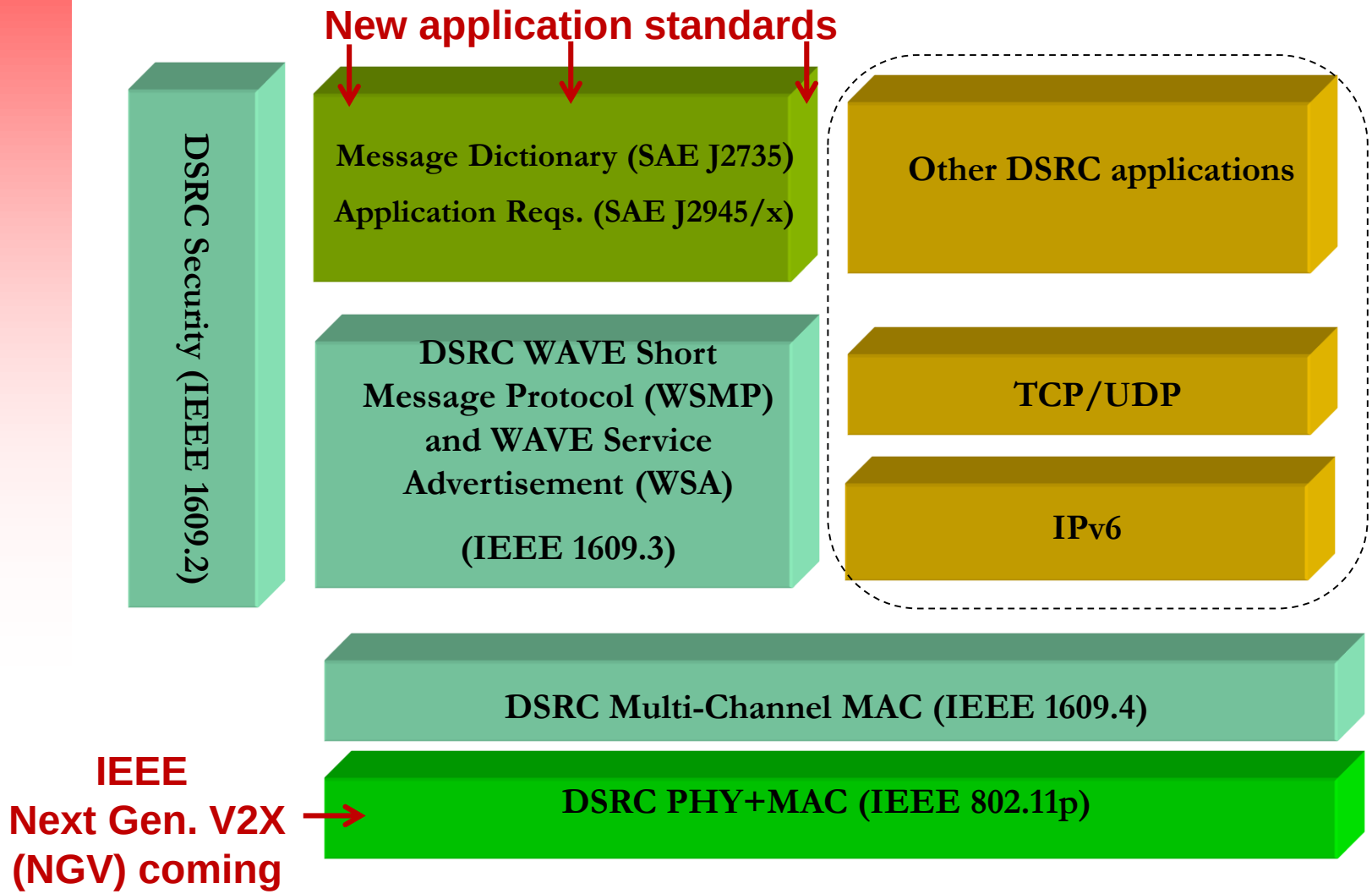
Standards are necessary for interoperability



See: J. Kenney, "DSRC Standards in the United States", Proc. IEEE, July 2011, Vol. 99, No. 7, pp. 1162-1182

V2V Safety Concept

(US terminology and spectrum)

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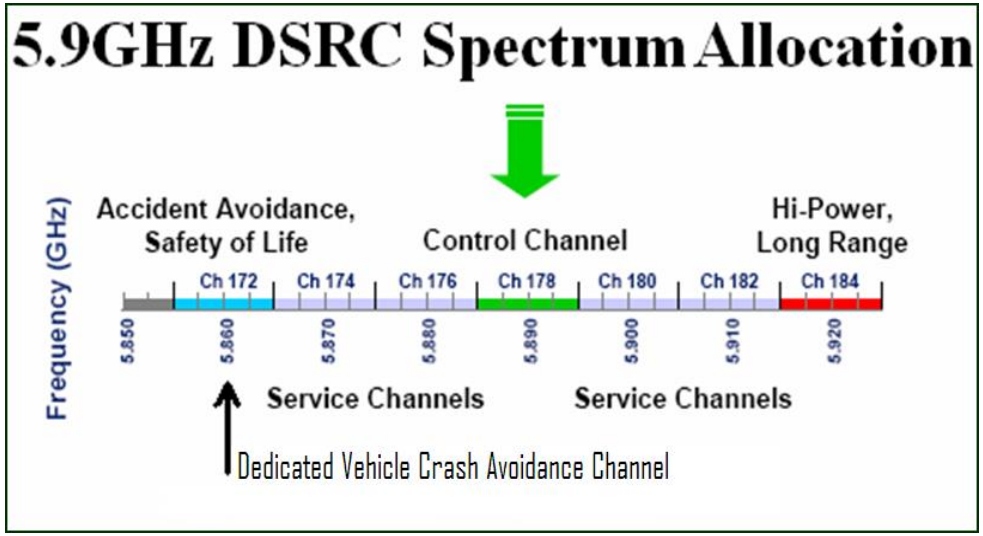
- Concept: each vehicle sends Basic Safety Messages frequently in all directions.
- Receiving vehicles assess collision threats
- Threat: Warn driver or take control of car

SAE J2735 Basic Safety Message	
Part I	**Basic Vehicle State** (Temp ID, Seq. #, Time, Position Motion, Control, Vehicle Size) ***Mandatory in Basic Safety Message***
Part II	**Vehicle Safety Extension** Event Flags Path History Path Prediction ***Required for V2V Safety Applications***
	Other optional safety-related data



Example collision applications

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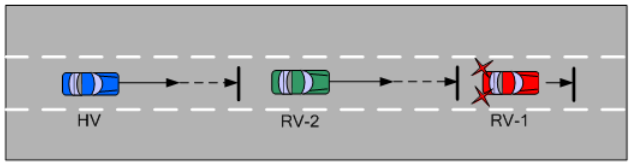
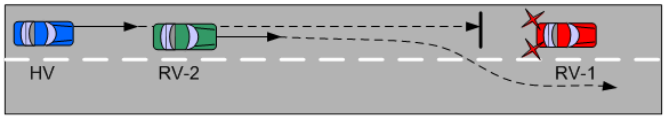
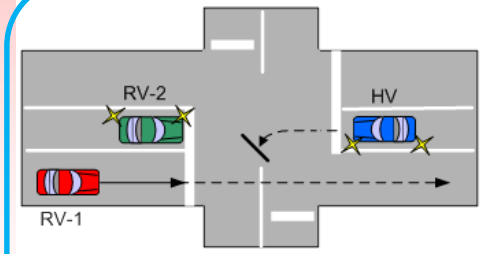


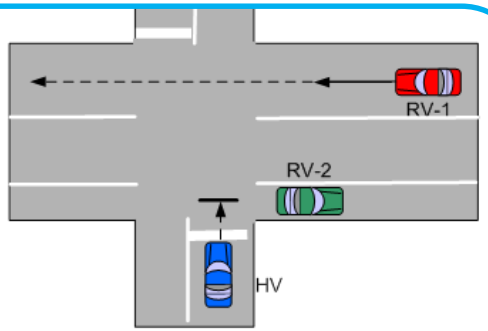
Emergency Electronic Brake Lights (EEBL)



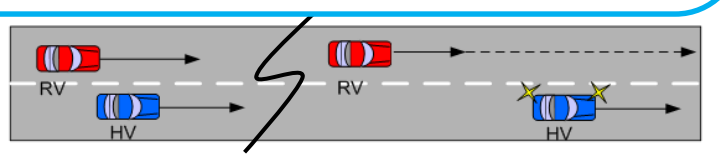
Forward Collision Warning (FCW)



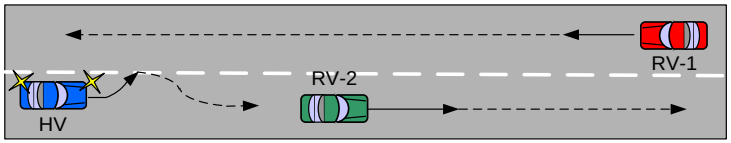
Left Turn Assist (LTA)



Intersection Movement Assist (IMA)



Blind Spot / Lane Change Warning (BSW / LCW)



Do Not Pass Warning (DNPW)

NHTSA estimates these two alone will save > 1000 lives/year

- All enabled by exchange of V2V BSMs
- Receiver applications are competitive, not standardized
- Innovative uses of BSM encouraged

HV = Host Vehicle (driver gets a warning)
RV = Remote Vehicle (its BSM triggers warning)

Connected Vehicle Applications

V2I Safety

- Red Light Violation Warning
- Curve Speed Warning
- Stop Sign Gap Assist
- Spot Weather Impact Warning
- Reduced Speed/Work Zone Warning
- Pedestrian in Signalized Crosswalk Warning (Transit)

V2V Safety

- Emergency Electronic Brake Lights (EEBL)
- Forward Collision Warning (FCW)
- Intersection Movement Assist (IMA)
- Left Turn Assist (LTA)
- Blind Spot/Lane Change Warning (BSW/LCW)
- Do Not Pass Warning (DNPW)
- Vehicle Turning Right in Front of Bus Warning (Transit)

Agency Data

- Probe-based Pavement Maintenance
- Probe-enabled Traffic Monitoring
- Vehicle Classification-based Traffic Studies
- CV-enabled Turning Movement & Intersection Analysis
- CV-enabled Origin-Destination Studies
- Work Zone Traveler Information

Environment

- Eco-Approach and Departure at Signalized Intersections
- Eco-Traffic Signal Timing
- Eco-Traffic Signal Priority
- Connected Eco-Driving
- Wireless Inductive/Resonance Charging
- Eco-Lanes Management
- Eco-Speed Harmonization
- Eco-Cooperative Adaptive Cruise Control
- Eco-Traveler Information
- Eco-Ramp Metering
- Low Emissions Zone Management
- AFV Charging / Fueling Information
- Eco-Smart Parking
- Dynamic Eco-Routing (light vehicle, transit, freight)
- Eco-ICM Decision Support System

Road Weather

- Motorist Advisories and Warnings (MAW)
- Enhanced MDSS
- Vehicle Data Translator (VDT)
- Weather Response Traffic Information (WxTINFO)

Mobility

- Advanced Traveler Information System
- Intelligent Traffic Signal System (I-SIG)
- Signal Priority (transit, freight)
- Mobile Accessible Pedestrian Signal System (PED-SIG)
- Emergency Vehicle Preemption (PREEMPT)
- Dynamic Speed Harmonization (SPD-HARM)
- Queue Warning (Q-WARN)
- Cooperative Adaptive Cruise Control (CACC)
- Incident Scene Pre-Arrival Staging Guidance for Emergency Responders (RESP-STG)
- Incident Scene Work Zone Alerts for Drivers and Workers (INC-ZONE)
- Emergency Communications and Evacuation (EVAC)
- Connection Protection (T-CONNECT)
- Dynamic Transit Operations (T-DISP)
- Dynamic Ridesharing (D-RIDE)
- Freight-Specific Dynamic Travel Planning and Performance
- Drayage Optimization

Smart Roadside

- Wireless Inspection
- Smart Truck Parking

Source US DOT

Cooperative Automated Driving has emerged as an important application

Cooperative Automated Driving with DSRC

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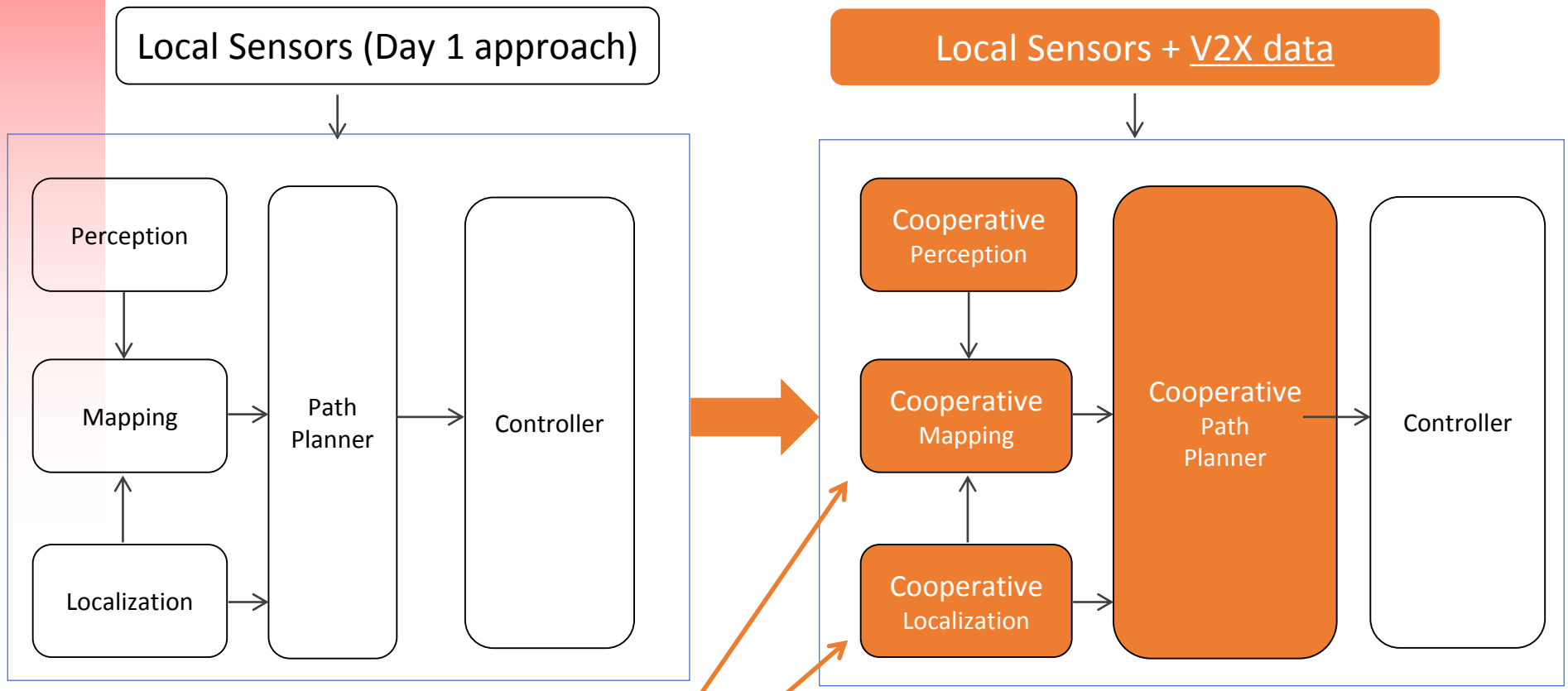
V2X becomes additional sensor

Highly improved mapping & localization, perception, and path planning



Toyota research: DSRC reduces Road Estimation Error from 3.59m to 0.55m @ 200m compared to camera + radar only

Toyota research: DSRC reduces Localization error by 21% even with only one additional DSRC vehicle's data

Channel Usage Plan

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US DSRC Spectrum

Seven 10-MHz Channels

5.850 GHz → 5.925 GHz

Reserved 5MHz	CH 172 Service (safety only)	CH 174 Safety & Service	CH 176 Safety & Service	CH 178 Control	CH 180 Safety & Service	CH 182 Safety & Service	CH 184 Service (safety only)

Every channel used for safety apps

Ch. 172	BSM safety and small set of V2I safety apps
Ch. 174	I→V safety and mobility, to avoid cross-channel interference to Ch. 172
Ch. 176	VRU safety (PSM) D→V, and download from SCMS (I→V)
Ch. 178	Control channel: WSAs, and low-bandwidth safety (I→V)
Ch. 180	Non-BSM V2V safety (e.g. C-ACC, sensor sharing), and mobility (I→V)
Ch. 182	I→V safety and mobility
Ch. 184	FCC designation for public safety. Ex: Preemption, Emergency Alert

Interleaved V2V and V2I limits interference

BSM = Basic Safety Message VRU = Vulnerable Road User PSM = Personal Safety Message
WSA = WAVE Service Advertisement C-ACC = Cooperative Adaptive Cruise Control
SCMS: Security Confidential Management System

***FCC and SAE J2945/0**

Challenges: Technical

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- Scalability
- Security/Privacy
- Certification
- Evolution

Basic V2V Safety Model

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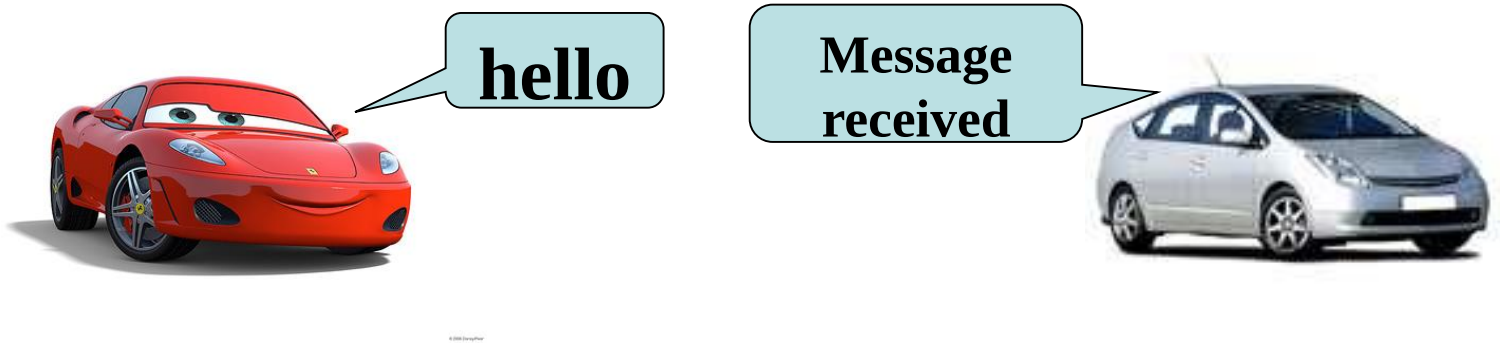

What about this?

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LIMERIC:
Linear Message Rate Integrated Control

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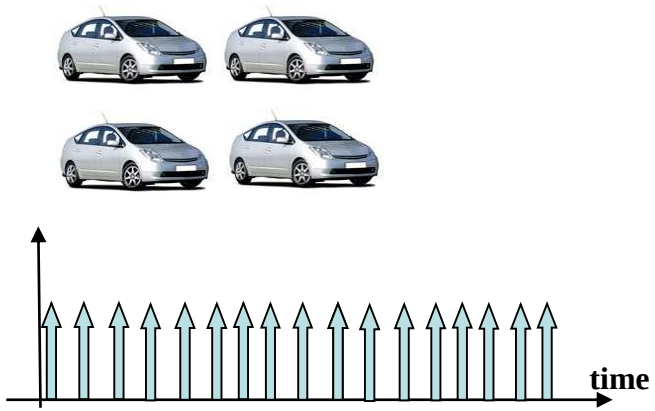
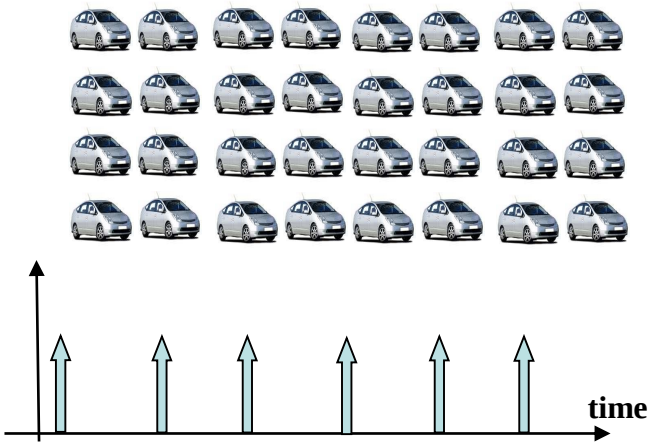


Safety message transmissions from each car



Safety message transmissions from each car

Goal:
Optimize aggregate throughput by controlling channel load

Main Idea:
If (traffic density = Low)
Then (car message rate = High)

Else if (traffic density = High)
Then (car message rate = Low)

Standardized in ETSI TS 102 687 v1.2.1 as the "adaptive approach"

Security/Privacy From Day 1

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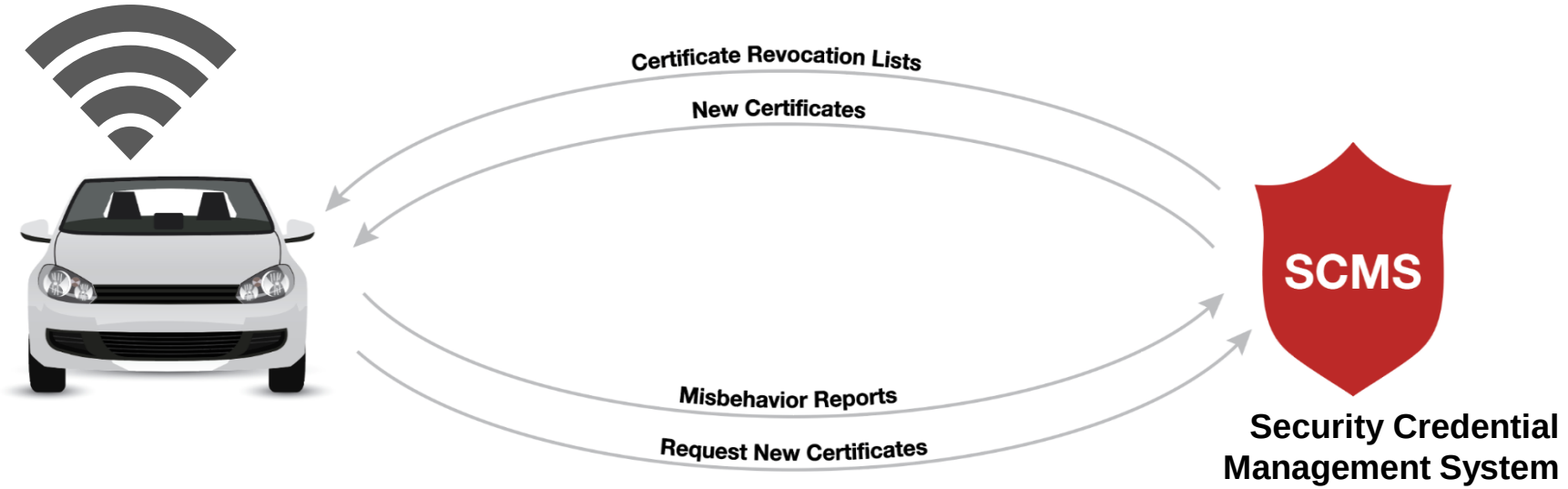
We emphasize privacy and security

- ✓ No personal identifiable information sent
- ✓ Authentication protects data integrity, validates transmission authority
- ✓ Encryption keeps data secret (selective applications)
- ✓ Frequent identity changes to prevent long-term tracking



Certification:
Conformance and Interoperability

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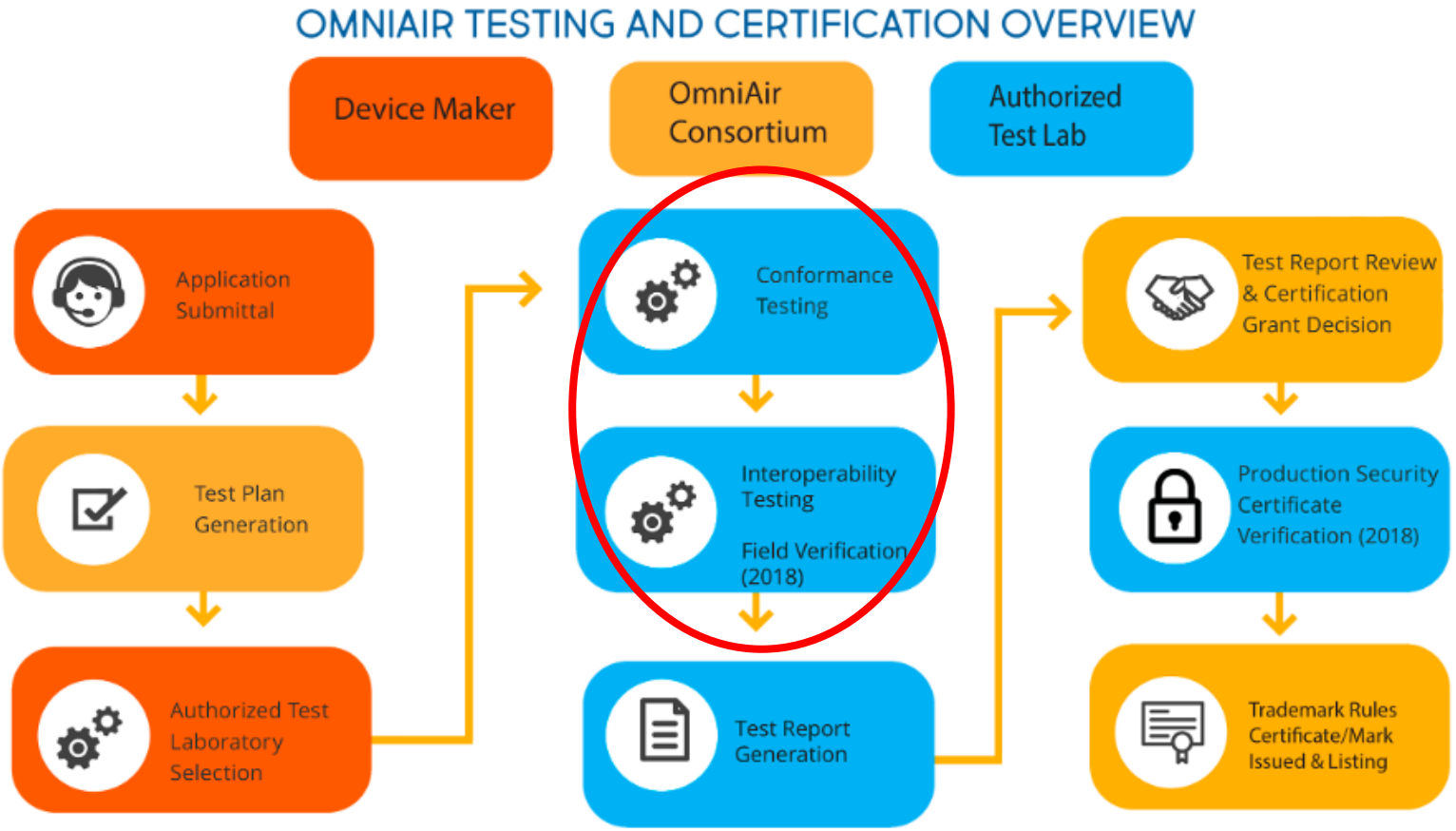

Evolution, Interoperability, and Innovation

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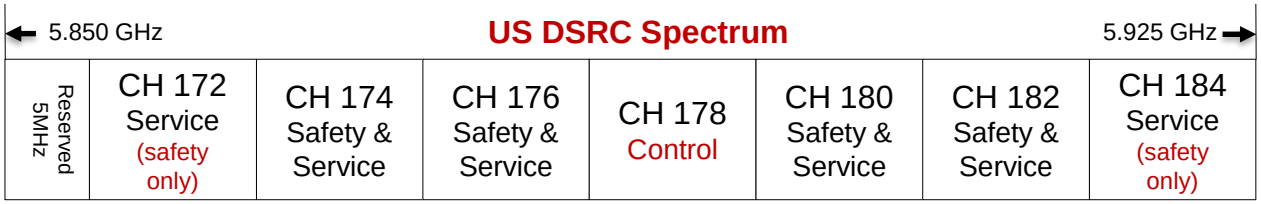

FCC REQUIRES use of DSRC. Why?

1. **Technology Interoperability** ← Most Important Reason
2. Robust safety communication
3. Promote deployment/Reduce cost
4. Consistent with Industry/Congressional/USDOT intent

-Source: FCC 03-32

Alternative V2X Technologies?

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- DSRC is incumbent. So, any discussion about alternatives in the US is a discussion about DSRC evolution
- Evolution is desirable way to introduce innovation
- But, evolution that sacrifices interoperability may do more harm than good

Why is interoperability important?

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- 37,133 US road fatalities in 2017
  - Increase of 14% in 3 years
- DSRC can address ~80% of crashes involving non-impaired drivers – source USDOT
- But only if all cars "speak" DSRC interoperably

If US fleet split between <u>two</u> non-interoperable technologies, crash benefit cut in half to ~40%

If US fleet split between <u>three</u> non-interoperable technologies, crash benefit cut in half to ~26%

Traditional wireless evolution vs. V2X

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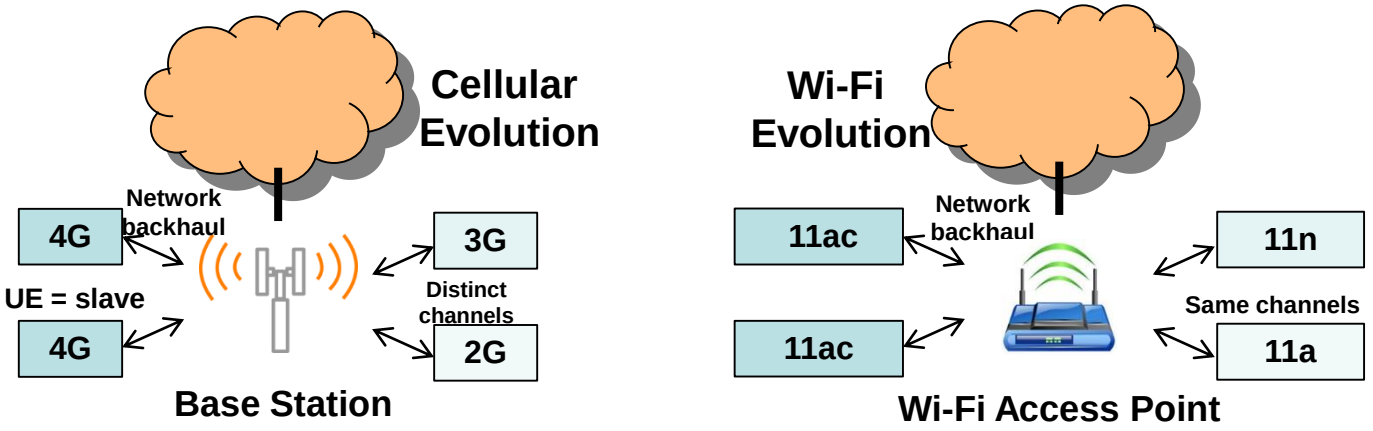
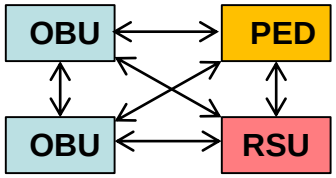


Mixing generations of end equipment is no problem for cellular/Wi-Fi

But, V2X is this …



Not this …

- ***Non-interoperable generations/technologies can disrupt V2X communication***
- ***V2X equipment lifetime typically much longer than consumer electronics***

Is “better” always better?

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English

This is example text to illustrate the relative efficiency of English vs Chinese as written language. We can see that Chinese can represent the same concept in a smaller space. It is more efficient than English. Why do so many people use English, for example at this conference?

Chinese

这段话用来例证英语和中文的书写表达效率。我们看出中文更加简洁，更有效率。但为何这里的很多人使用英文呢？

Interoperability is more important than marginal performance

C-V2X image of US V2X evolution

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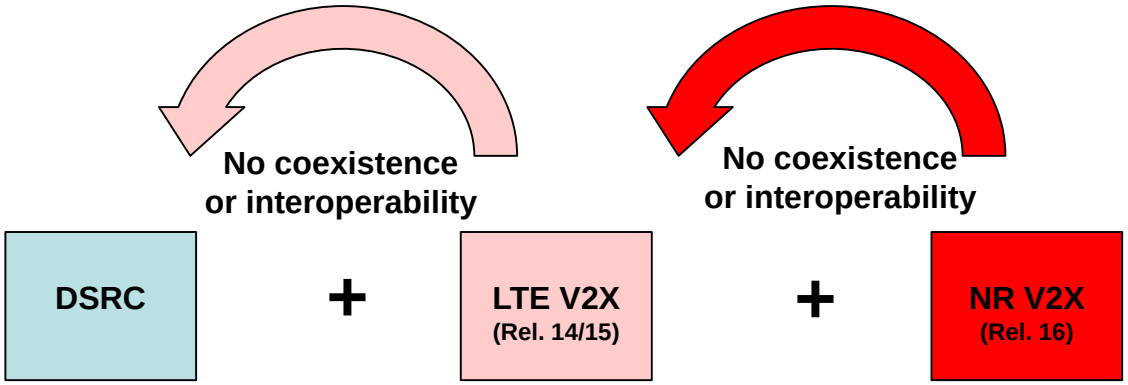

Coexistence means "same channel"
Interoperability means packet can be decoded at receiver

C-V2X image seems to be:
"Innovation requires sacrificing interoperability"

Can we innovate without sacrificing interoperability?

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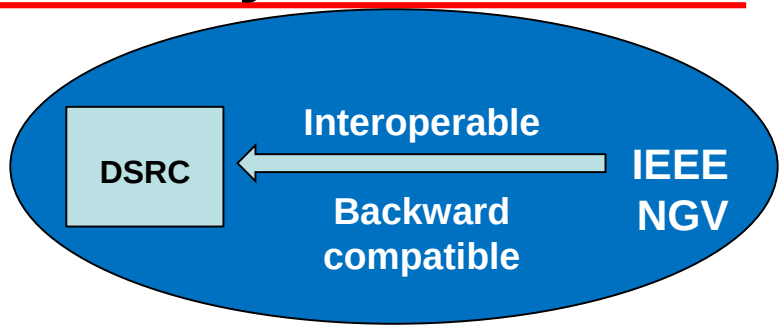

- Yes!
- New standard in IEEE called Next Generation V2X (NGV)
- Charter of NGV:

  "This amendment shall provide interoperability, coexistence, backward compatibility, and fairness with deployed" DSRC devices.
  [Source: IEEE 802 11-18-0861/r9]

- Seamless evolution from DSRC to NGV

Note: DSRC was specified in IEEE 802.11p amendment

NGV will be specified in IEEE 802.11bd amendment

Contrasting visions of evolution

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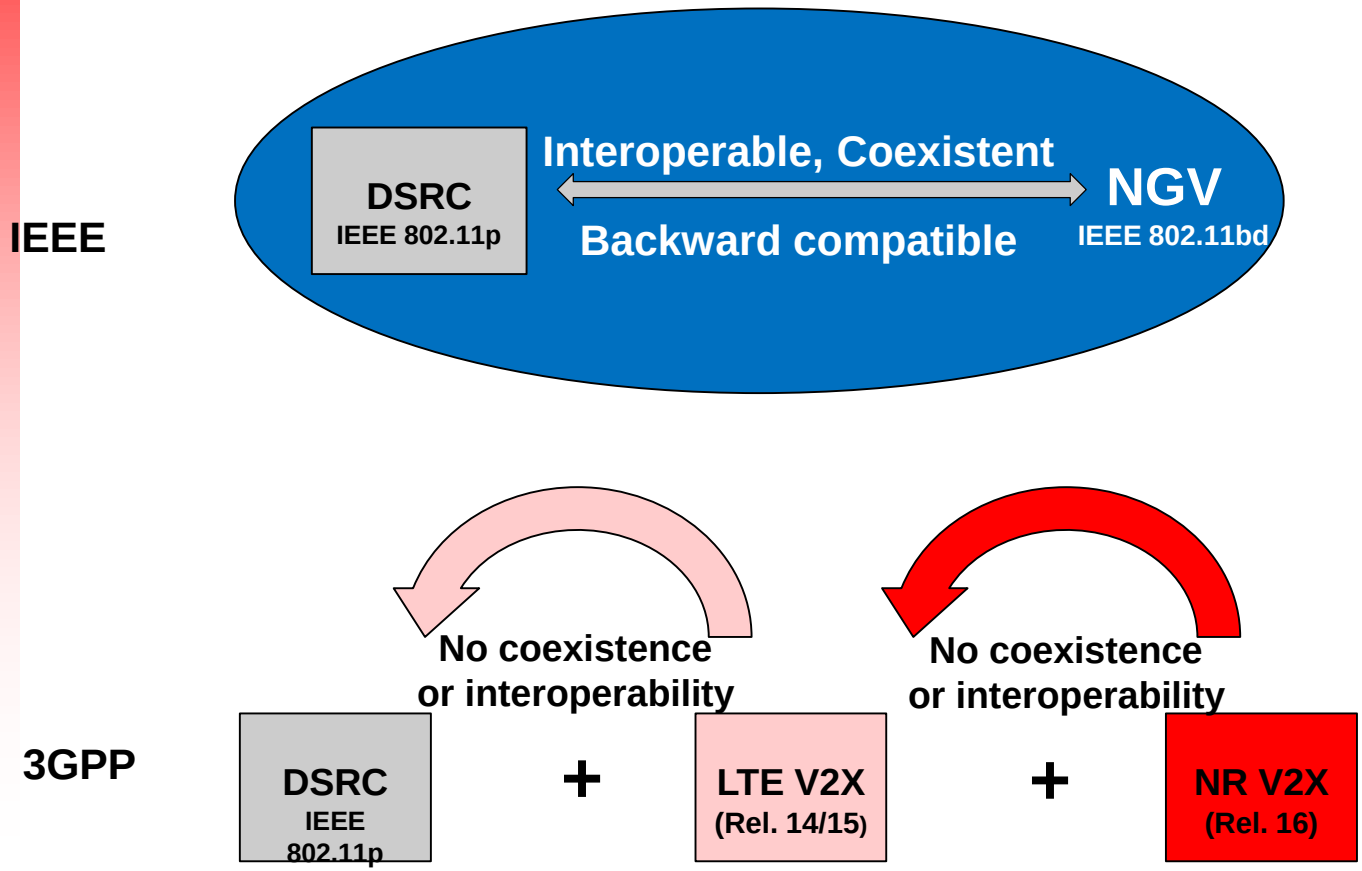

Coexistence means "same channel"
Interoperability means packet can be decoded at receiver

3GPP NR = New Radio (2020),
IEEE NGV = Next Generation V2X (2021)

Contrasting visions: Language analogy

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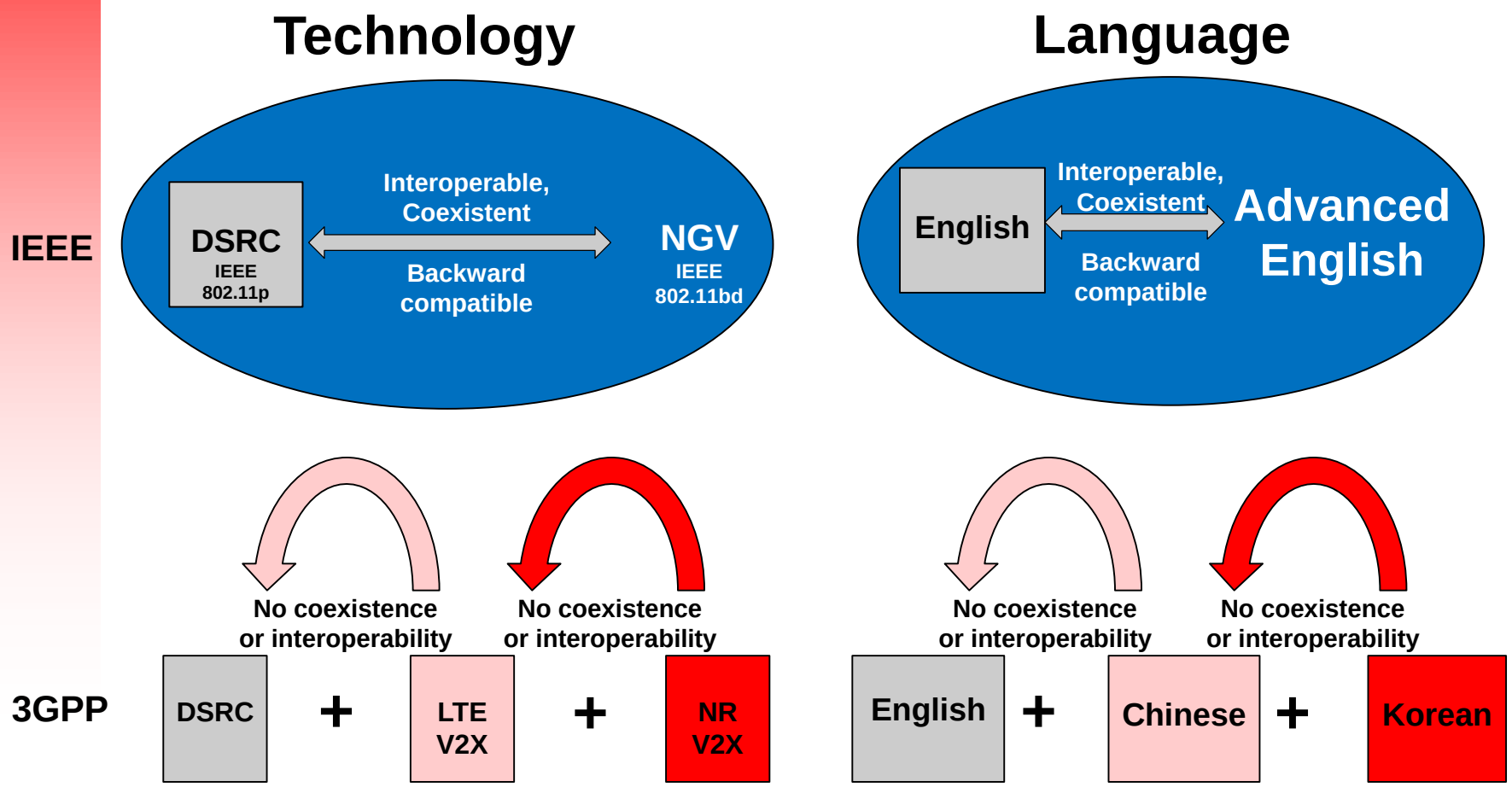
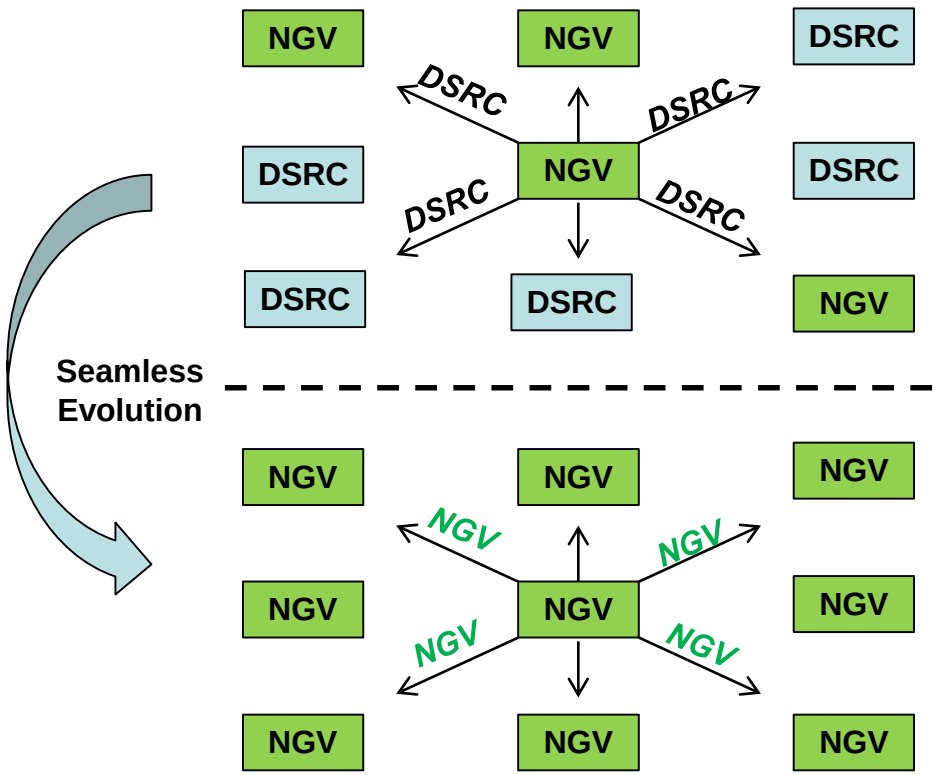


Coexistence means "same channel"
Interoperability means packet can be decoded at receiver

Interoperability: DSRC and NGV



- With DSRC neighbors, broadcast using DSRC
- Depending on situation, may also send additional NGV information
  - NGV appendix or
  - NGV duplicated message
- Conditions may include channel load (congestion)

- With only NGV neighbors,
- or if unicast to NGV device,
- or if industry consensus to use only NGV for a given use case:

➔ Transmit using NGV.

Packet-by-packet decision

Automotive Stakeholders Support NGV vision of evolution

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A consistent message from automotive stakeholders:

- **SAE DSRC TC**
  - "IEEE 802.11p (DSRC) is capable of meeting the requirements of planned safety, mobility, environmental sustainability, and automation use cases
  - "form the basis for a seamless evolution strategy"
- **IEEE 1609 WG**
  - "a WAVE device, based on [DSRC], is capable of meeting the requirements of planned safety, mobility, environmental sustainability, and automation use cases.
  - "form the basis for a seamless evolution strategy"
- **Car2Car Communications Consortium**
  - "IEEE 802.11p meets all use case requirements for Day 1 and Day 2 deployment"
  - "NGV amendment can provide a seamless evolution path"

Implications for 5.9 GHz

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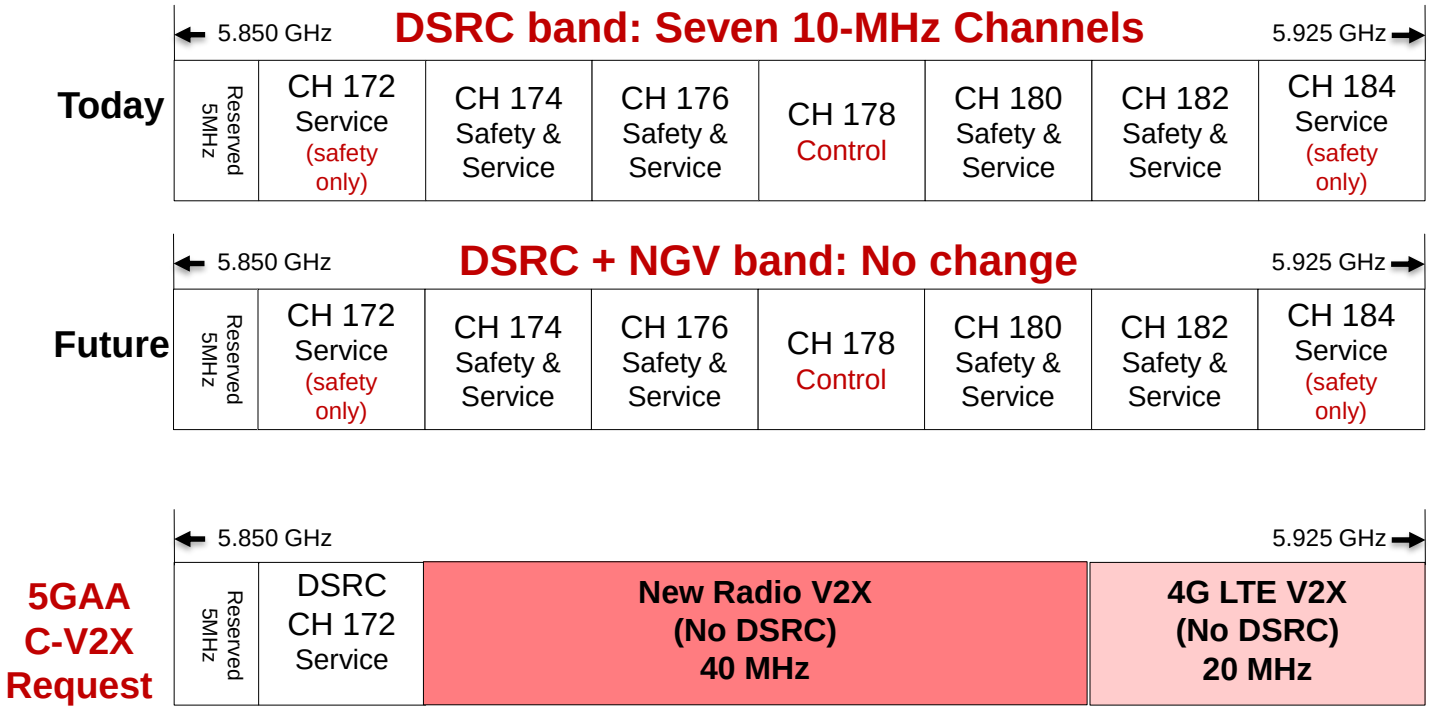

No Coexistence (C-V2X) means band fragmentation:

- Loss of interoperability reduces benefits
- Duplication of equipment drives up cost
- Duplication of services in sub-bands is inefficient use of key spectrum

Toyota to FCC

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"There are significant concerns that granting the 5GAA Waiver Request will stall or even derail vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) deployment in the United States. The potential safety benefits of this cooperative technology will undoubtedly diminish if the V2V and V2I market becomes fragmented into non-interoperable technologies. In addition, entities wishing to participate fully in a fragmented V2X ecosystem will be forced to invest in multiple technologies. Finally, duplicating identical services on different channels without additional benefit to consumers is spectrally inefficient." (emphasis added)

- Comments of TOYOTA MOTOR CORPORATION, FCC GN Docket No. 18-357

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Evolution Attributes and NGV

Key Attributes	IEEE NGV
Maintain band integrity (no fragmentation)?	Yes
Lower equipment cost for vehicle (no extra technologies)?	Yes
Consistent with DSRC deployments and standards?	Yes
Spectrally efficient (no duplication of applications)?	Yes
Accommodate future generations in same channels?	Yes
Seamless evolution for DSRC?	Yes
Protect current DSRC investments?	Yes

Toyota message to USDOT

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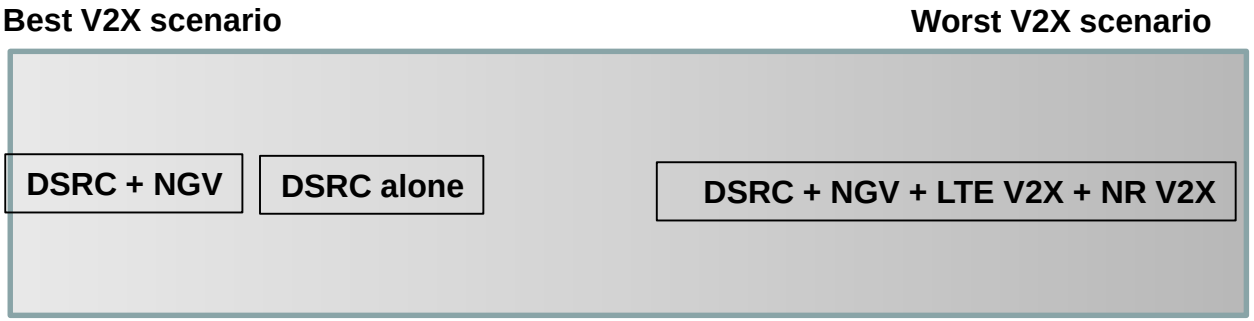
Relationship of non-DSRC technologies to DSRC

Non-DSRC Technology ⇒	LTE V2X	NR V2X (plan)	IEEE NGV (plan)
Interoperable with DSRC?	No	No	Yes
Coexistent with DSRC?	No	No	Yes
Backward compatible with DSRC?	No	No	Yes



Toyota reply to "Notice of Request for Comments: V2X Communications"

Docket No. DOT–OST–2018–0210

Challenges: Business

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Cost = fixed per vehicle

Benefits = f(penetration)

- OEM/Road Authority must take long view
  - Overcome natural conservative nature
- Initial deployment is an investment that will grow
  - Each equipped car provides benefits to owner and to others
- V2X is a “cooperative” technology
  - Benefits depend on decisions of others (OEMs, Road authorities, individuals)
- Is there a “critical mass” for V2X?
  - Not from a technical point of view: each new equipped car or roadside unit makes the road safer and more efficient
  - But, yes from a business point of view: when penetration exceeds a threshold, benefits are sufficient to motivate purchase, positive feedback

Challenges: Business

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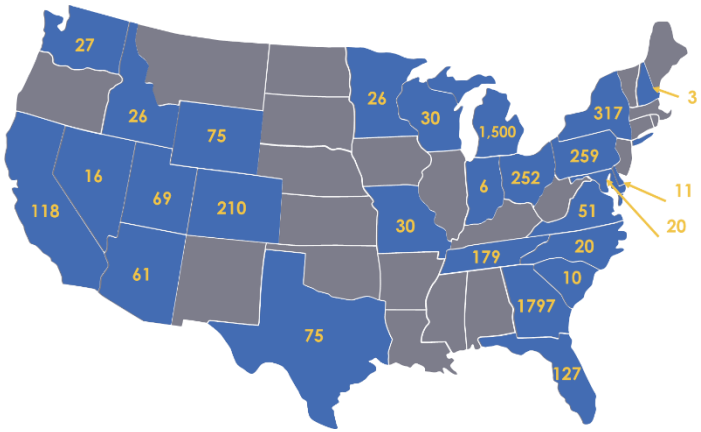
- NHTSA considered V2V mandate, but no progress → Voluntary deployment
- Best chance for success:
  - Unified, consensus action among stakeholders
  - Regulatory assurance of interoperability

Automakers

State & Local DOTs



Summary

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- DSRC: Mature, deployed, dedicated spectrum
  - Improves safety
  - Improves traffic efficiency
  - Improves automated driving
- Uncertainties about regulatory/business climate impacting deployment in US
- IEEE NGV will provide seamless evolution
- How does auto industry get over the hump on voluntary deployment?

Questions?

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Let's All Row Together

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