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

• 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

- E-payment
- Signal Phase and Timing
- Safety Messages
- Probe Data
- Instrumented Roadside

“The Network”

Opportunity for Innovation

➢ Real Time Network Data
➢ Situation Relevant Information

US Department of Transportation Vision
Wireless Connectivity Modes

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

Benefits
- Safety
- Traffic Efficiency
- Automated Driving

Challenges
- Deployment
- Spectrum
- Protocols
V2X is … Vehicle to Everything

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

V2I
V2T
V2B
V2P
V2V

Access Point
Base Station
Collision Avoidance: What if …?

Legend:

- **Message Transmission**: (range 100s meters)
- **Vehicle heading**: →

**1st Gen**: warn driver
**2nd Gen**: automated collision avoidance
We are doing this

• 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?”

- Contrast sensor and DSRC

Autonomous Radar

Packet header | intersection state

Frequent broadcasts
360 Degree dissemination

Packet header | My vehicle state

Packet header | My vehicle state
Communication Advantages

- 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

- 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 …
State DOTs are Enthusiastic
DSRC V2I Roadside Units: Operational and Planned

Total Deployed & Planned = 5,315 so far

26 States covering 79% of US population
Map of deployment sites and projects

Uses of the 5.9 GHz band: Connected Vehicle Deployment Locations – Planned and Operational

- WSDOT SPaT, Poulson
- WSDOT Seattle SR-522 SPaT
- Lake Forest Park/Kenmore
- King County, WA
- WSDOT SPaT, Spokane
- Ada County Highway District
- WSDOT SPaT, Vancouver
- San Francisco ATCMTD
- California CV Test Bed
- Provo BRT
- I-580/Washoe County, NV
- Las Vegas Freemont Street SPaT Corridor
- Los Angeles, CA
- LA ATCMTD
- San Jose, CA (2)
- Anthem Test Bed
- Denver ATCMTD Program
- Loop 101 Mobility Project
- College Station, TX
- Houston, TX
- Honolulu, HI
- Texas Connected Freight ATCMTD
- Lansing M-43 Project
- MDOT Wayne County Project
- Safety Pilot, Ann Arbor
- Road Commission for Oakland City
- Macomb County Dept. Roads Projects (3)
- MichDOT I-75 Connected Work Zone
- Southeast MI Ypsilanti Township, MI
- INDOT SPaT Merrillville
- NYC Pilot
- Long Island, NY
- NYS Thruway
- St. Clair and Lapeer Counties, MI
- Smart Belt Coalition, OH
- Niagara/Buffalo ATCMTD
- NH DOT SPaT, PHILA
- Smart Belt Coalition, PA
- DeIDOT SPaT
- SmartPGH
- PennDOT SPaT, Pittsburgh
- PennDOT SPaT, Ross Township
- PennDOT SPaT, Harrisburg
- Florida DOT SPaT, I-76
- Fairfax County, VA
- Howard County SPaT
- Virginia (VDOT)
- NCDOT SPaT, Cary
- GA DOT CV ATCMTD
- Tallahassee SPaT
- Miami Freight Project
- Orlando, FL (2)

Planned Projects
Operational Projects

Source: Volpe, the National Transportation Systems Center (USDOT). May 2019.

The project information and data contained on this map was gathered from publicly available materials and is subject to change.

<table>
<thead>
<tr>
<th>Planned Projects</th>
<th>Operational Projects</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>#Projects</td>
<td>#Devices*</td>
<td>#Infrastructure</td>
</tr>
<tr>
<td>35</td>
<td>3,266</td>
<td>802</td>
</tr>
<tr>
<td>52</td>
<td>15,435</td>
<td>6,086</td>
</tr>
<tr>
<td>87</td>
<td>18,701</td>
<td>6,888</td>
</tr>
</tbody>
</table>

*Includes aftermarket devices
**Includes devices in phased deployments
Why do we care?

- **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?

Example of DSRC Prototype System
Many suppliers are in this space
DSRC Standards: mature, expanding

Standards are necessary for interoperability

- New application standards
  - Message Dictionary (SAE J2735)
  - Application Reqs. (SAE J2945/x)
  - DSRC WAVE Short Message Protocol (WSMP) and WAVE Service Advertisement (WSA) (IEEE 1609.3)
  - DSRC Multi-Channel MAC (IEEE 1609.4)
  - DSRC PHY+MAC (IEEE 802.11p)
  - Other DSRC applications
  - TCP/UDP
  - IPv6

V2V Safety Concept
(US terminology and spectrum)

- 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**

<table>
<thead>
<tr>
<th>Part I</th>
<th>Part II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basic Vehicle State</td>
<td>Other optional safety-related data</td>
</tr>
<tr>
<td>(Temp ID, Seq. #, Time, Position Motion, Control, Vehicle Size)</td>
<td>Required for V2V Safety Applications</td>
</tr>
<tr>
<td>Mandatory in Basic Safety Message</td>
<td></td>
</tr>
<tr>
<td>Vehicle Safety Extension</td>
<td></td>
</tr>
<tr>
<td>Event Flags</td>
<td></td>
</tr>
<tr>
<td>Path History</td>
<td></td>
</tr>
<tr>
<td>Path Prediction</td>
<td></td>
</tr>
</tbody>
</table>

**5.9GHz DSRC Spectrum Allocation**

- Accident Avoidance, Safety of Life
- Control Channel
- Hi-Power, Long Range
- Dedicated Vehicle Crash Avoidance Channel
Example collision applications

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

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

HV = Host Vehicle (driver gets a warning)
RV = Remote Vehicle (its BSM triggers warning)
Cooperative Automated Driving has emerged as an important application.
Cooperative Automated Driving with DSRC

V2X becomes additional sensor
Highly improved mapping & localization, perception, and path planning

Local Sensors (Day 1 approach)

- Perception
- Mapping
- Localization

Local Sensors + V2X data

- Cooperative Perception
- Cooperative Mapping
- Cooperative Localization

Controller

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

## US DSRC Spectrum

### Seven 10-MHz Channels

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

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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BSM</td>
<td>Basic Safety Message</td>
</tr>
<tr>
<td>VRU</td>
<td>Vulnerable Road User</td>
</tr>
<tr>
<td>PSM</td>
<td>Personal Safety Message</td>
</tr>
<tr>
<td>WSA</td>
<td>WAVE Service Advertisement</td>
</tr>
<tr>
<td>C-ACC</td>
<td>Cooperative Adaptive Cruise Control</td>
</tr>
<tr>
<td>SCMS</td>
<td>Security Confidential Management System</td>
</tr>
</tbody>
</table>

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*FCC and SAE J2945/0
Challenges: Technical

- Scalability
- Security/Privacy
- Certification
- Evolution
Basic V2V Safety Model

hello

Message received
What about this?
LIMERIC:
Linear Message Rate Integrated Control

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”
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

OMNIAIR TESTING AND CERTIFICATION OVERVIEW

Device Maker
- Application Submission
  - Test Plan Generation
    - Authorized Test Laboratory Selection

OmniAir Consortium
- Conformance Testing
  - Interoperability Testing
    - Field Verification (2018)

Authorized Test Lab
- Test Report Generation
- Test Report Review & Certification Grant Decision
- Trademark Rules Certificate/Mark Issued & Listing
FCC **REQUIRES** use of DSRC. Why?

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

-Source: FCC 03-32
Alternative V2X Technologies?

• 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?

- 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 two non-interoperable technologies, crash benefit cut in half to ~40%

If US fleet split between three non-interoperable technologies, crash benefit cut in half to ~26%
Traditional wireless evolution vs. V2X

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

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

But, V2X is this …

Not this …
Is “better” always better?

**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

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?

• 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

IEEE

DSRC
IEEE 802.11p

Interoperable, Coexistent
Backward compatible

NGV
IEEE 802.11bd

LTE V2X
Rel. 14/15

No coexistence
or interoperability

NR V2X
Rel. 16

No coexistence
or interoperability

3GPP

DSRC
IEEE 802.11p

+ LTE V2X
Rel. 14/15

+ NR V2X
Rel. 16

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

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

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

### DSRC band: Seven 10-MHz Channels

<table>
<thead>
<tr>
<th>Channel</th>
<th>Service Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH 172</td>
<td>Reserved (safety only)</td>
</tr>
<tr>
<td>CH 174</td>
<td>Safety &amp; Service</td>
</tr>
<tr>
<td>CH 176</td>
<td>Safety &amp; Service</td>
</tr>
<tr>
<td>CH 178</td>
<td>Control</td>
</tr>
<tr>
<td>CH 180</td>
<td>Safety &amp; Service</td>
</tr>
<tr>
<td>CH 182</td>
<td>Safety &amp; Service</td>
</tr>
<tr>
<td>CH 184</td>
<td>Service (safety only)</td>
</tr>
</tbody>
</table>

### DSRC + NGV band: No change

<table>
<thead>
<tr>
<th>Channel</th>
<th>Service Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>CH 172</td>
<td>Reserved (safety only)</td>
</tr>
<tr>
<td>CH 174</td>
<td>Safety &amp; Service</td>
</tr>
<tr>
<td>CH 176</td>
<td>Safety &amp; Service</td>
</tr>
<tr>
<td>CH 178</td>
<td>Control</td>
</tr>
<tr>
<td>CH 180</td>
<td>Safety &amp; Service</td>
</tr>
<tr>
<td>CH 182</td>
<td>Safety &amp; Service</td>
</tr>
<tr>
<td>CH 184</td>
<td>Service (safety only)</td>
</tr>
</tbody>
</table>

### 5GAA C-V2X Request

<table>
<thead>
<tr>
<th>Channel</th>
<th>Service Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>DSRC CH 172</td>
<td>Service</td>
</tr>
<tr>
<td>New Radio V2X (No DSRC) 40 MHz</td>
<td></td>
</tr>
<tr>
<td>4G LTE V2X (No DSRC) 20 MHz</td>
<td></td>
</tr>
</tbody>
</table>

### Notes

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

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No Coexistence (C-V2X) means band fragmentation:
“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
# Evolution Attributes and NGV

<table>
<thead>
<tr>
<th>Key Attributes</th>
<th>IEEE NGV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maintain band integrity (no fragmentation)?</td>
<td>Yes</td>
</tr>
<tr>
<td>Lower equipment cost for vehicle (no extra technologies)?</td>
<td>Yes</td>
</tr>
<tr>
<td>Consistent with DSRC deployments and standards?</td>
<td>Yes</td>
</tr>
<tr>
<td>Spectrally efficient (no duplication of applications)?</td>
<td>Yes</td>
</tr>
<tr>
<td>Accommodate future generations in same channels?</td>
<td>Yes</td>
</tr>
<tr>
<td>Seamless evolution for DSRC?</td>
<td>Yes</td>
</tr>
<tr>
<td>Protect current DSRC investments?</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Toyota message to USDOT

Relationship of non-DSRC technologies to DSRC

<table>
<thead>
<tr>
<th>Non-DSRC Technology</th>
<th>LTE V2X</th>
<th>NR V2X (plan)</th>
<th>IEEE NGV (plan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interoperable with DSRC?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Coexistent with DSRC?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Backward compatible with DSRC?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Best V2X scenario

- DSRC + NGV
- DSRC alone

Worst V2X scenario

- DSRC + NGV + LTE V2X + NR V2X

Toyota reply to “Notice of Request for Comments: V2X Communications”
Challenges: Business

Cost = fixed per vehicle
Benefits = f(incorporation)

• 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

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

• 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?

Let’s All Row Together

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