Introduction to Connected Vehicles (CVs)

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1941—Portable 2-Way Pack Radio!

591098 2ND ARMY MANEUVERS, ARKANSAS, SEPTEMBER 1941. 107TH CAVALRY REGIMENT OF OHIO, CONSISTING OF HORSES, MOTORCYCLES AND SCOUT CARS GO INTO SPEEDY ACTION AGAINST THE ENEMY. SOLDIERS OF TROOP B SENDING AND RECEIVING MESSAGES ON PORTABLE PACK RADIO, WHICH CAN BE USED ON GROUND AS WELL AS ON THE PACK. IT HAS A RANGE FROM 25 TO 50 MILES AND WEIGHS APPROX 175 POUNDS.

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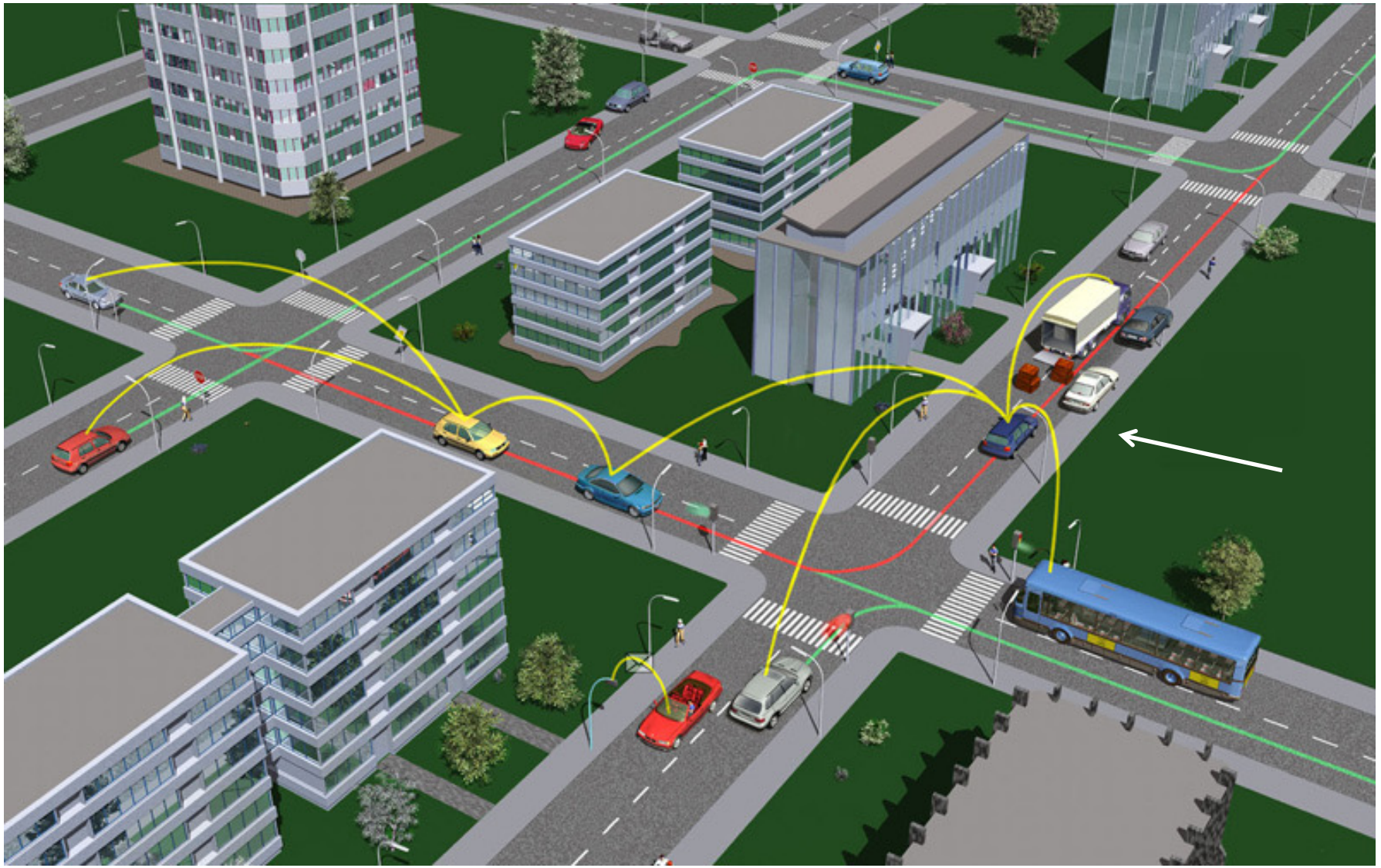
[ge.com–Image credit: Chris Hunter, Museum of Innovation and Science, Schenectady.]

Roadways of the Future



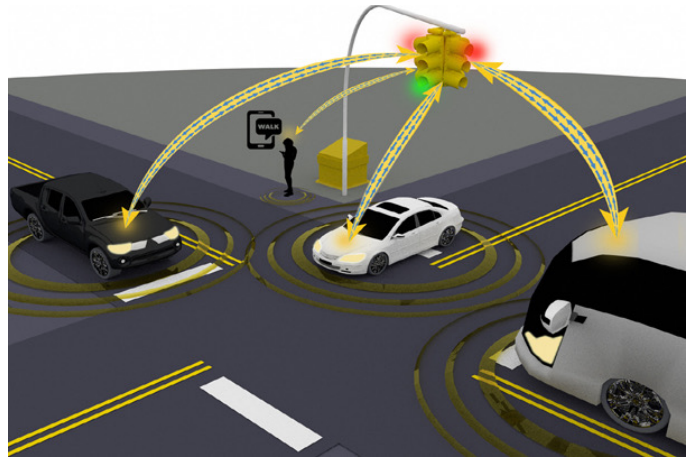
Connected Vehicles (CVs)

- Let vehicles "talk" to enhance proximity awareness
  - Reduce up to 80% of non-impaired crashes (~600,000 annually)
    - 98% of accidents today are due to human errors ☹
  - Increase transportation system efficiency
    - Reduced travel time, less traffic, and less pollution (save $70 billion/yr)
  - Comfort while driving, social inclusion (mobility for all), …
    - All vehicle types (legacy to fully autonomous)
- Emerging technology with rapid growth
  - Projected 2035 market value: $112 billion – with auto manufacturers such as Toyota, GM, and Jaguar

Vehicular Communication

Types of CV Communication

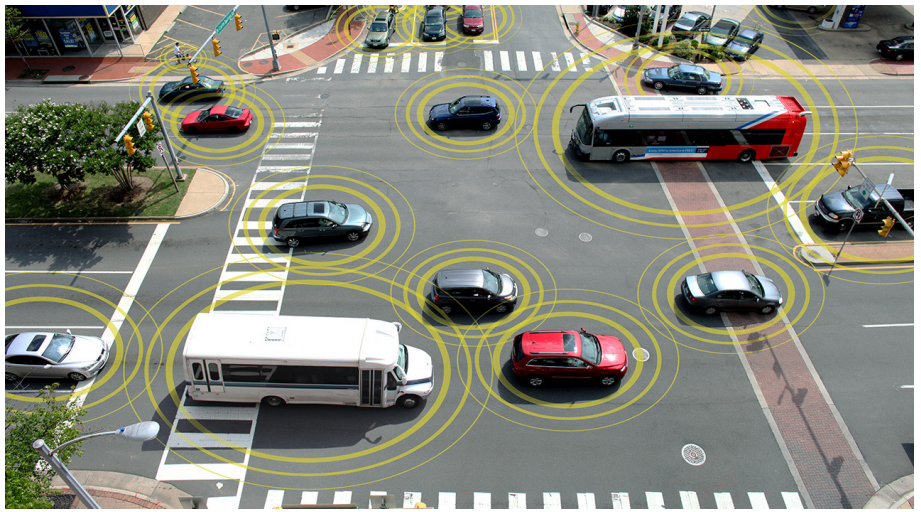
- Exploit wireless waves for *proactive* communication
- Depending on whom a vehicle communicates with
  - Vehicle-to-Cloud (V2C)
  - Vehicle-to-Vehicle (V2V)
  - Vehicle-to-Network (V2N)
  - Vehicle-to-Pedestrian (V2P)
  - Vehicle-to-Infrastructure (V2I)
  - Vehicle-to-[*insert your choice*] —> V2X
    - Cellular V2X—Vehicles as new citizens of the 5G ecosystem



[Courtesy: Department of Transportation]

Vehicle-to-Vehicle (V2V)

- Vehicles directly talk to each other
  - Frequently broadcast safety messages
- Coordinate with nearby vehicles
  - Events, movement, speed, location, …



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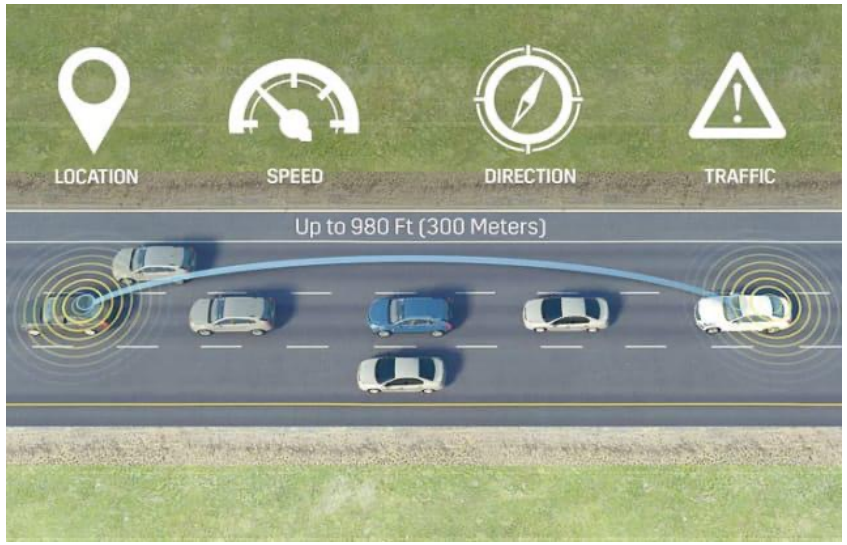

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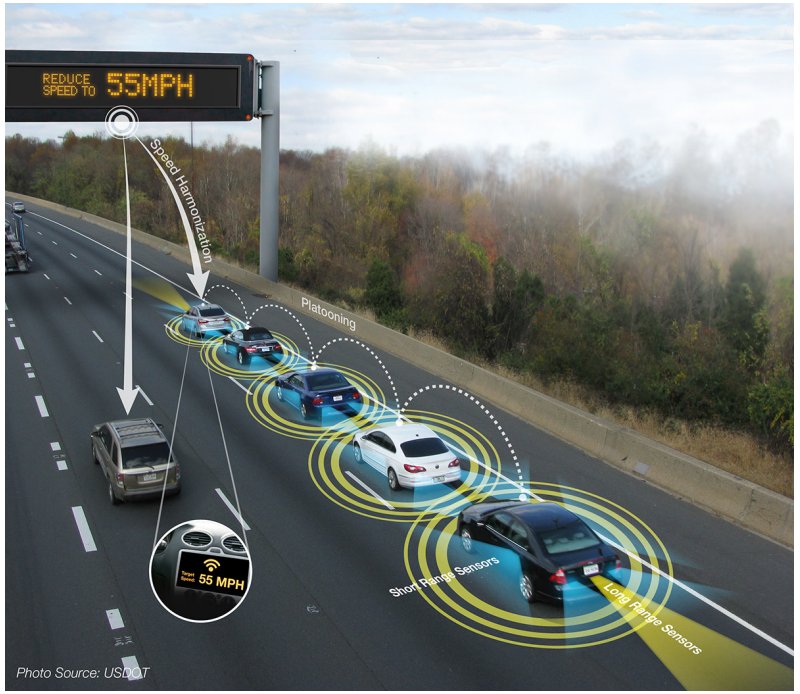
- Support non-line-of-sight (NLOS)
- Allow 360° coordination

V2V in Action: Notable Use Cases

- Primary goal: enhance safety
  - 360° awareness and coordination → collision avoidance
- Vehicle platooning (convoy)
  - Increase speed and harmonization
  - Reduce carbon emissions
- Real-time navigation assistance
  - Advanced Driver-Assistance Systems (ADAS)
  - Millisecond hazard/closure alerts
  - Cooperative perception

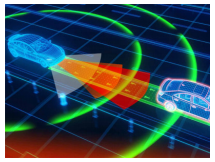


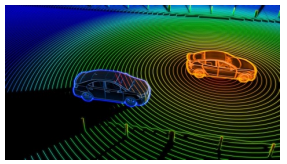
https://en.wikipedia.org/wiki/Platoon_(automobile)

V2V for Safety

- Each vehicle broadcasts basic safety messages (BSMs)
  - Periodically update all nearby vehicles (every 100 ms)
  - Key step towards (partial / conditional / full) driving automation
  - Onboard sensors work mainly in LOS :

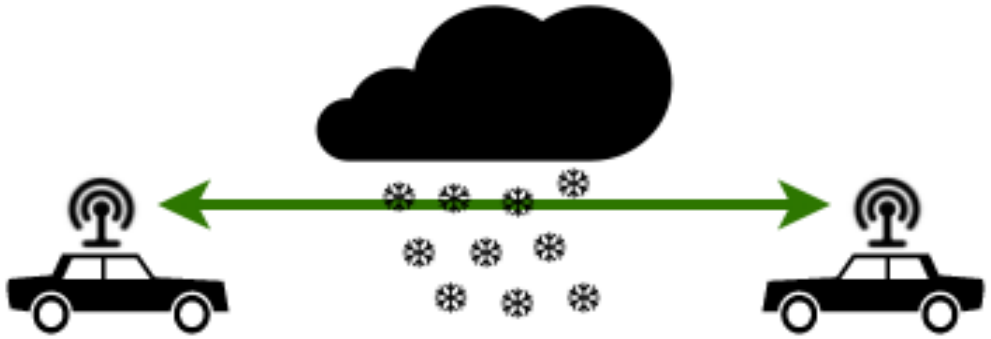
Camera


Radar


LiDAR

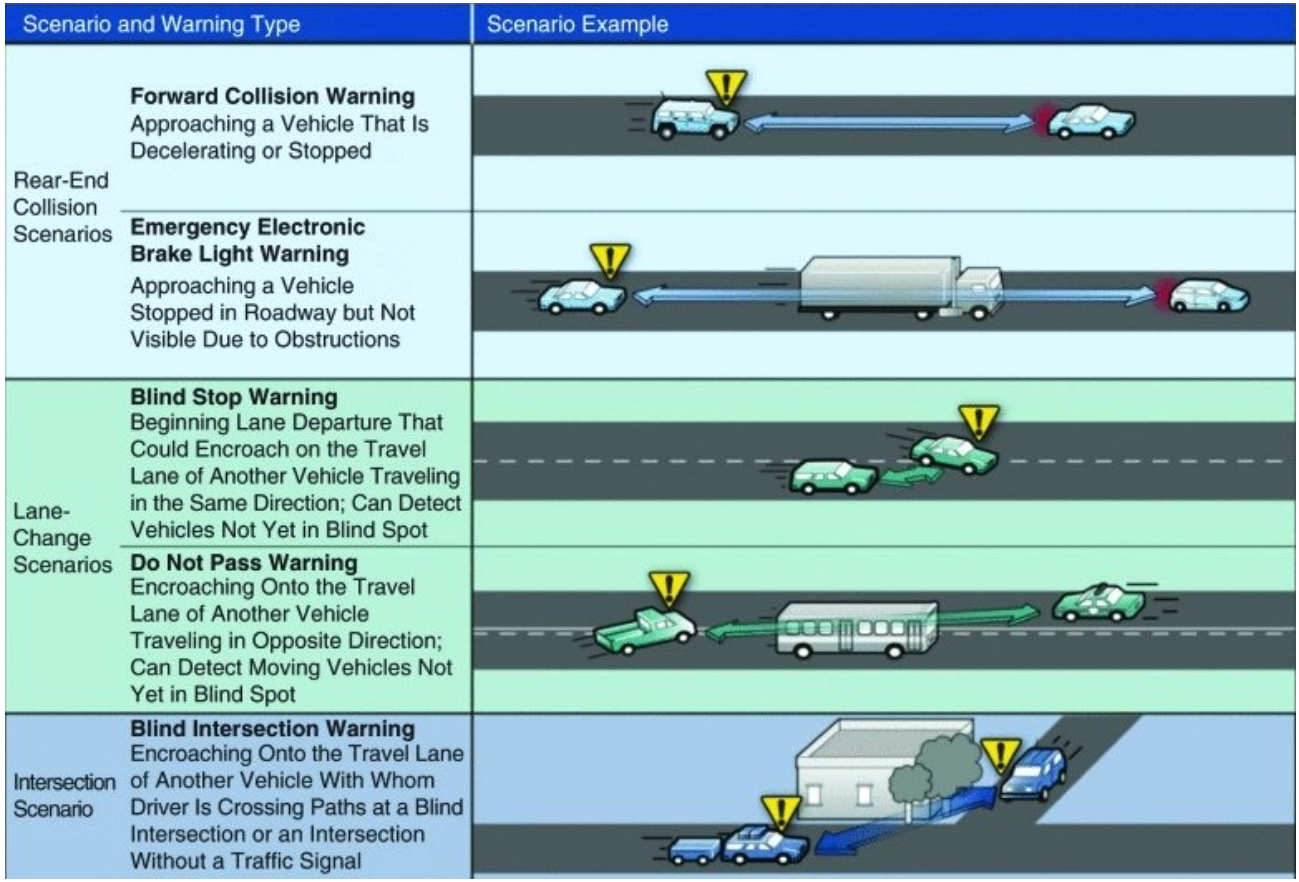
  - V2V complements sensors to "see" (in NLOS) what sensors cannot → 360°

Cameras can only detect what they can see (LOS)


V2V can often penetrate obstructions (NLOS)

BSM Types

- Type 1: Core kinetics status
  - Vehicle's position, speed, heading, size, brake status, ...
- Type 2: Event-based
  - Collision warning, brake failure, …
  - Attached to Type 1 as necessary
  - Three examples:

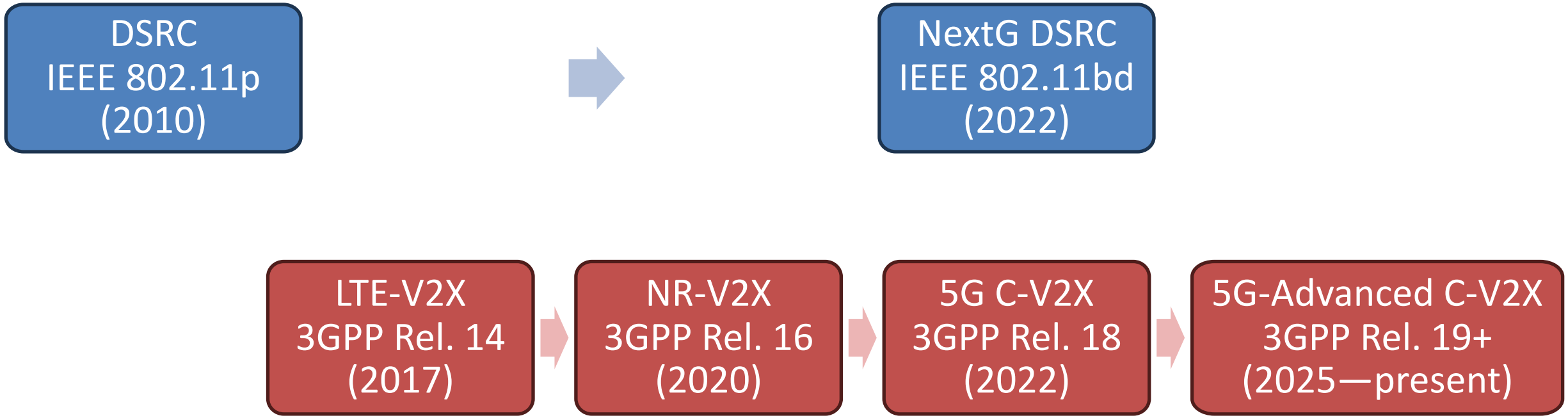


S. Stone, "Connected, Autonomous Cars: Passive Pothole Patrollers," in *IEEE Potentials*, vol. 39, no. 1, pp. 52-58, Jan.-Feb. 2020.

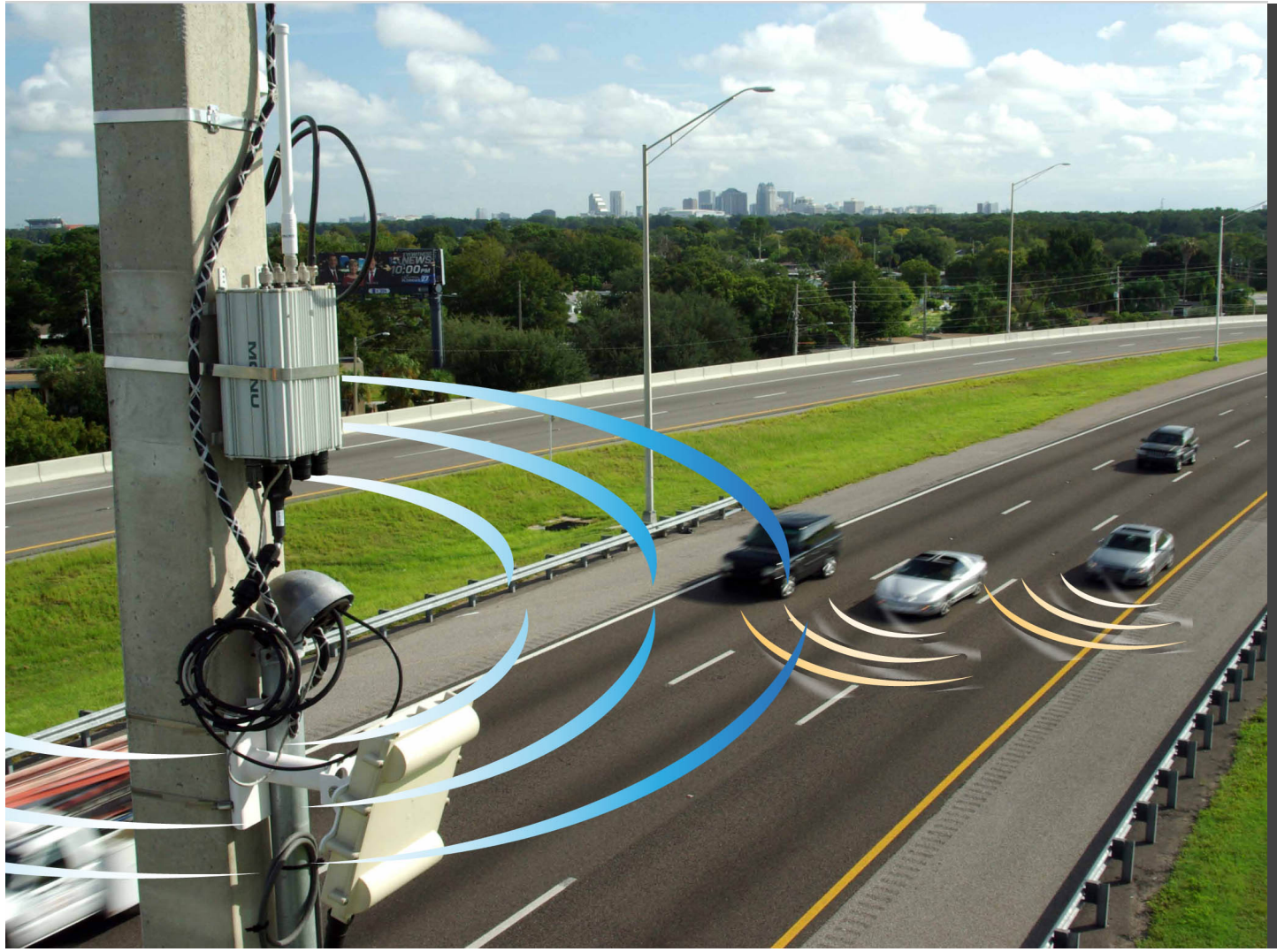
V2V Design Challenges

- Environmental complexity
  - **High mobility:** Doppler shifts, varying neighbors, packet error fluctuations
  - **High density:** Must process, verify, and consume thousands of messages/sec
- Real-time requirements
  - **Safety Margin:** Millisecond processing of a collision warning is vital to trigger braking before impact
  - **Industry Standard:** < 50 ms processing latency for safety-critical actions (human reaction time budget is ~ 200 ms)
- Trust & spectrum constraints
  - Message authenticity while operating within narrow frequency bands

V2V Technology Evolution



Vehicle to Infrastructure (V2I)



Roadside Units (RSU)

- Devices installed along the roadway
- Capable of relaying V2X messages
- Can interface with traffic management systems like traffic light controllers

V2X: Global Perspective

Brief History of V2X in the U.S.

1996	OnStar® emergency assistance
1999	FCC allocates 75 MHz of the 5.9 GHz band exclusively for V2V
2004	IEEE Task Group formed to investigate V2V based on 802.11 (DSRC) protocol
2010	First V2V protocol - Dedicated Short-Range Communication (DSRC) based on 802.11
2013	First approved security protocol (IEEE 1609.2)
2016	Cadillac CTS becomes first U.S. model to hit the roads with DSRC
2017	Second V2V protocol - Cellular C-V2X based on LTE for sidelink
2019	Ford announces C-V2X on all models beginning in 2022 Toyota cancels plans for DSRC on all models beginning 2021
2020	FCC plans to cut V2V spectrum by 50% (now **30 MHz**), obsolesces DSRC in favor of C-V2X
2022	FCC officially disallows DSRC and adopts C-V2X as sole 5.9 GHz technology
2024	FCC officially adopts “C-V2X Auto Safety” rules allocating 5.895 – 5.925 GHz to C-V2X

V2X Around the World

- Adoption accelerating since 2015
- 2015 – Toyota models sold in Japan initially with DSRC
- 2017 – Initial push for DSRC (Cadillac CTS and VW Golf sedans)
- 2019 – Industry pivot toward C-V2X (Ford, Toyota, FCC)
  - 2020 – 5G C-V2X released, China begins mass-producing vehicles with C-V2X
- 2021 – Nationwide C-V2X deployment begins in China
- 2023 – FCC officially granted waivers allowing C-V2X deployment on US roadways (20 million vehicles by 2024)

Moving from DSRC towards C-V2X (except in the E.U.)

Global V2X Spectrum Landscape

- 5900 MHz bands are internationally common

Region	Frequency bands (GHz)	Supported technology
E.U.	$5.855 - 5.925$ (70 MHz)	Hybrid (C-V2X/DSRC)
U.S.	$5.895 - 5.925$ (30 MHz)	C-V2X only
Japan	$0.755 - 0.764$ (9 MHz)	DSRC focus (limited C-V2X)
China	$5.905 - 5.925$ (20 MHz)	C-V2X leader
Korea	$5.855 - 5.925$ (70 MHz)	Transition to C-V2X

- Additional bands are now under active consideration
  - IEEE 802.11bd is designed for 60 GHz
  - NR-V2X (5G) supports $24.25 - 52.6$ GHz in FR2