Cellular Vehicle-to-Everything (C-V2X)

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Overview

Why Cellular (C-V2X) Prevailed

- Optimized for *mobility*
  - Focused on reliable, high-speed mobile communications (more than Wi-Fi)
  - No CSMA/CA: Contention and collisions degrade performance at high mobility
  - Superior efficiency: Higher data rates, range, and spectrum efficiency
- More native support for dense, simultaneous transmissions
  - Time–frequency scheduling instead of carrier sensing → predictable latency and reliability

Key Wireless Communication Concepts

LTE-V2X: First-Generation of Cellular Vehicle-to-Everything

The 5G Leap: New Radio V2X (NR-V2X)

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Putting the "Everything" in V2X

- Architectural Superiority: Can leverage cellular infrastructure → connect to everything (V2N/V2P)
  - DSRC was limited to V2V and partial V2I
- Expanded safety envelope
  - Directly communicate with cellular devices
  - Enables Vehicle ↔ Pedestrian / Bicycle / Device / IoT (true V2X ecosystem)

C-V2X Protocols

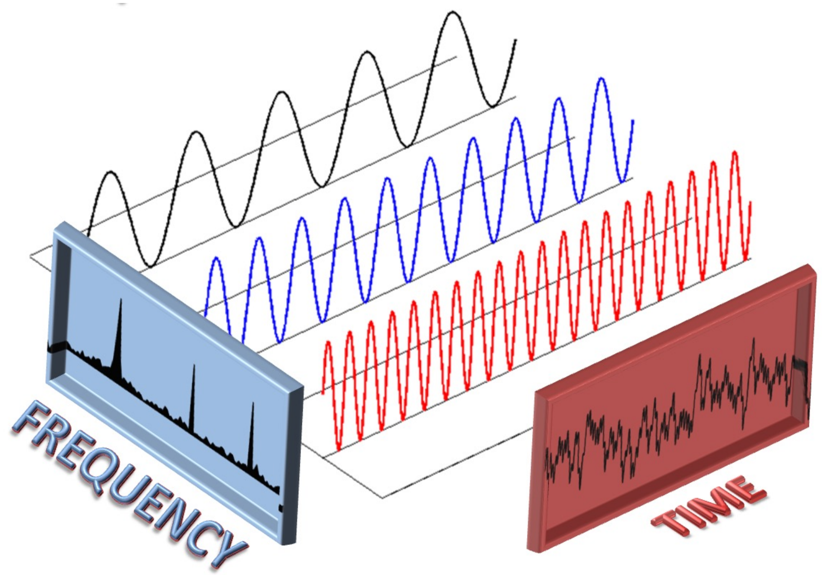
- Defined in 3GPP standards (“Releases”)

Standard	Year	Protocol	Technology
Release 14	2017	LTE-V2X	4G/LTE
Release 15	2018	LTE-V2X NR-V2X	4G/LTE 5G “New Radio”
Release 16	2020	NR-V2X (Phase 2)	5G
Release 17	2022	5G C-V2X	Hybrid LTE/5G
Releases 18–19	2024–2026	5G-Advanced C-V2X	Hybrid support maintained, moving towards full 5G
Release 20	2028?	6G C-V2X	Undetermined

Key Wireless Communication Concepts

Wireless Signals

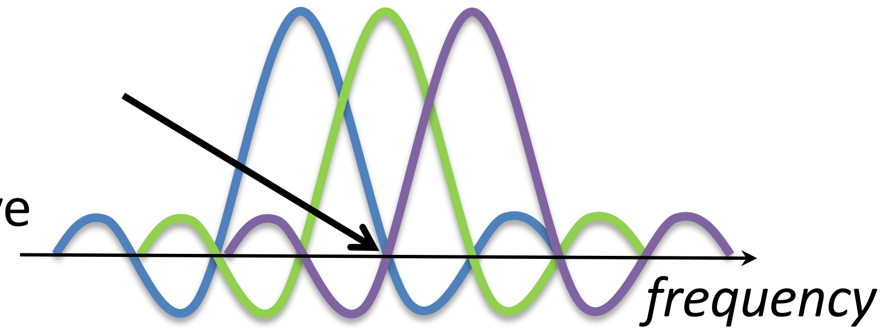
- A signal (or a symbol) can be composed of multiple periodic time-domain waves added together, each with a different frequency
  - Each wave is referred to as a **frequency component**



OFDM

- Orthogonal Frequency Division Multiplexing
  - Used in modern systems for adaptability and resilience to multipath fading
  - Carefully select frequency components and spacing to satisfy orthogonality
    - Frequency components → subcarriers
  - Each subcarrier carries an independent subset of data/symbols
- Used in DSRC (802.11p) and 5G C-V2X

Orthogonal:
Except *one*, all subcarriers have nonzero values



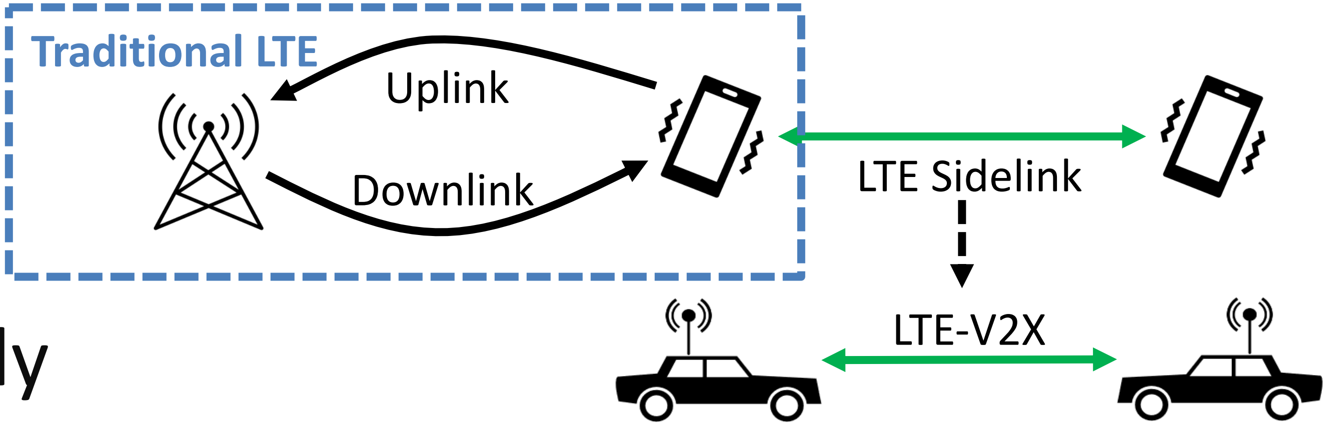
https://bit.ly/2VNb6iI

SC-FDM

- Single-Carrier Frequency Division Multiplexing
  - Uses multiple subcarriers but pre-processes them to behave like a single wave (rather than a superposition of independent waves)
  - Lower **PAPR** than OFDM→ more power-efficient amplifier
- Each subcarrier carries a piece of data from all symbols
- Requires a more complex receiver to match OFDM's robustness against frequency fading (used in 4G and 5G C-V2X)

LTE-V2X: First-Generation of Cellular Vehicle-to-Everything

LTE-V2X (2017)



- Based on 4G LTE Sidelink
  - Derived from LTE uplink
- Devices communicate directly
- V2V uses Sidelink Mode 4
  - No LTE network coverage required (everything is distributed)
- Designed for 5.9 GHz for BSMs, supports future 6 - 7 GHz bands
- Many advantages over DSRC due to PHY/MAC design

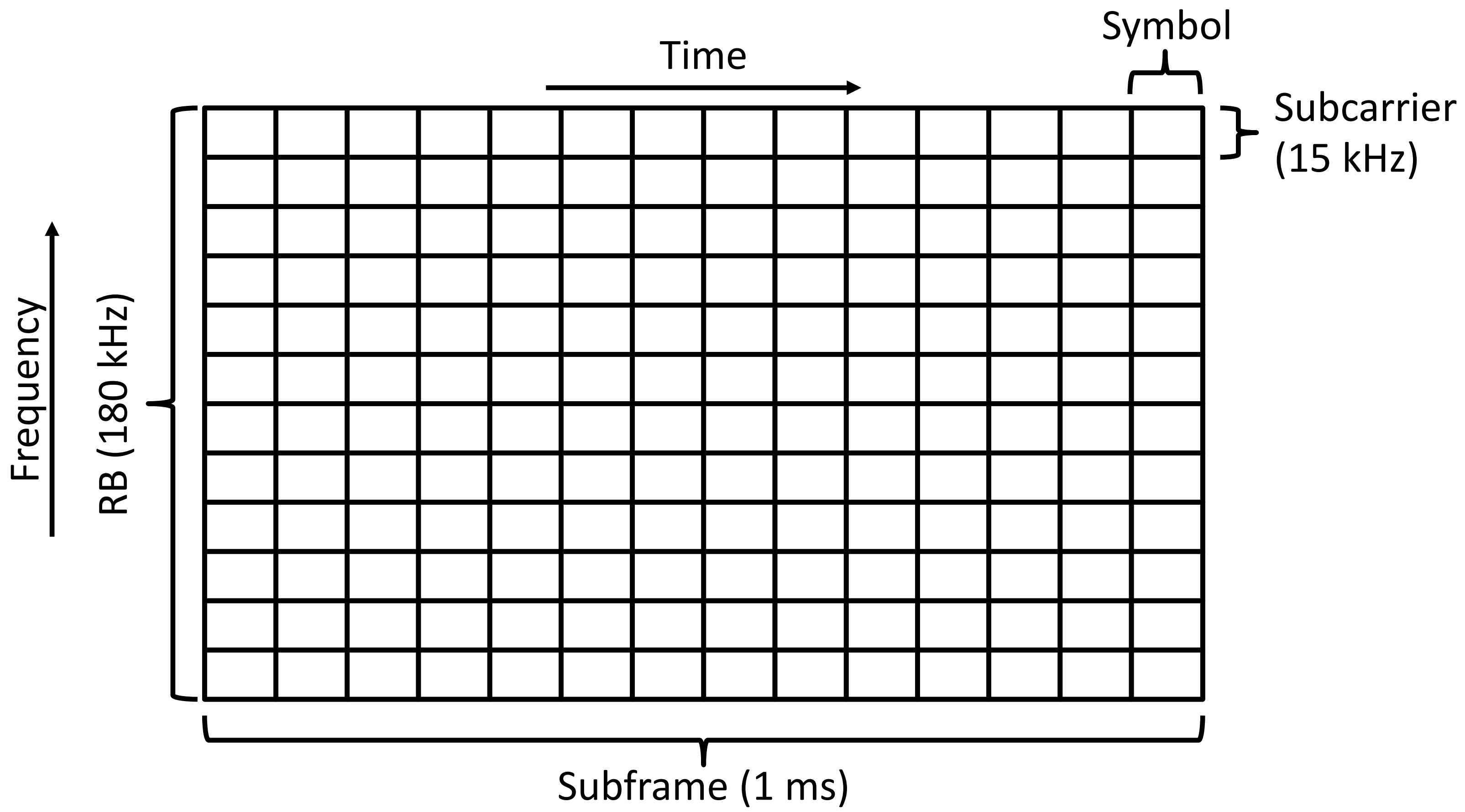
Overview - LTE-V2X PHY Layer

- SC-FDM waveform instead of OFDM
- Modern coding improves SNR, range → lower bit error rate (BER)
- Automatic retransmission lowers packet error rate (PER)
- +17% data rate (7 Mbps): ↓ latency, ↑ payload (e.g. Type 2 BSMs)

Feature	DSRC	LTE-V2X	Result
Channel coding	Convolutional	**Turbo**	< 1% BER with 2 dB lower SNR 2x longer range (~600m vs. 300m)
Modulation	OFDM	**SC-FDM**	3x link budget gain
Retransmissions?	No	**Yes (HARQ)**	Greater reliability (lower PER)
Channel bandwidth	10 MHz	**10 or 20 MHz**	Higher throughput (increased capacity)

LTE-V2X: PHY Layer Structure

- Time: 10 ms LTE frames divided into 1 ms subframes
- Frequency channel divided into resource blocks (RBs)
- 180 kHz RB contains:
  - 12 subcarriers
  - 14 symbols
- +20 kHz spacing
  - Guard bands
  - Roll-off regions
- → Effectively 200 kHz



LTE-V2X: PHY Layer Structure

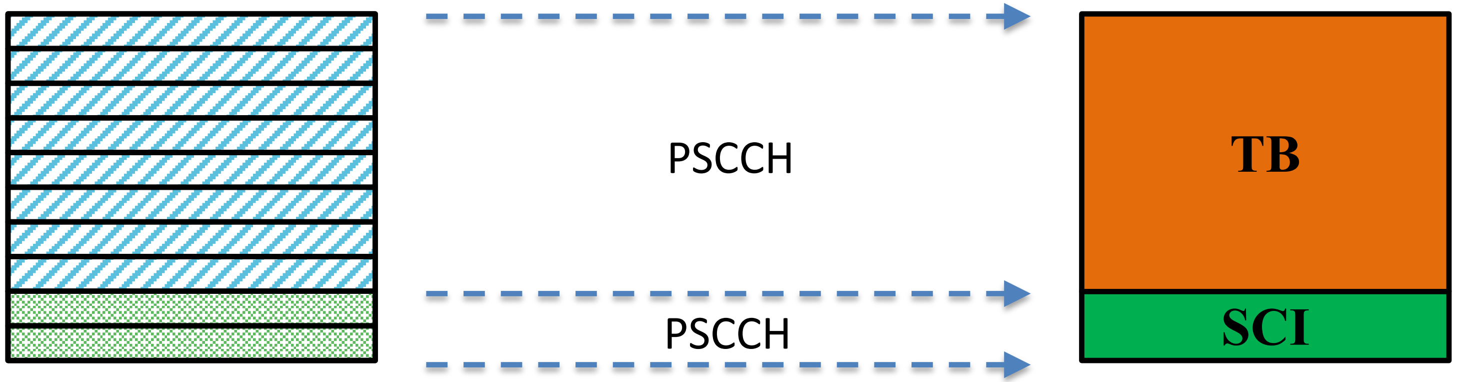
- A 10 MHz channel comprises 50 RBs (20 MHz → 100 RBs)
  - Divided into several equal-size subchannels
- Each subchannel divided into logical control and data channels
  - PSCCH (2 RB) = Physical Sidelink Control Channel
  - PSSCH = Physical Sidelink Shared Channel (for data)
  - Control + data (Transport Block) transmitted together in one subframe
- Rigid structure has strengths and vulnerabilities[1]

[1]Geoff Twardokus and Hanif Rahbari, "Towards Protecting 5G Sidelink Scheduling in C-V2X Against Intelligent DoS Attacks," *IEEE Transactions on Wireless Communications* (TWC), vol. 22, no. 11, pp. 7273-7286, November 2023.

LTE-V2X: PHY Layer Transmission

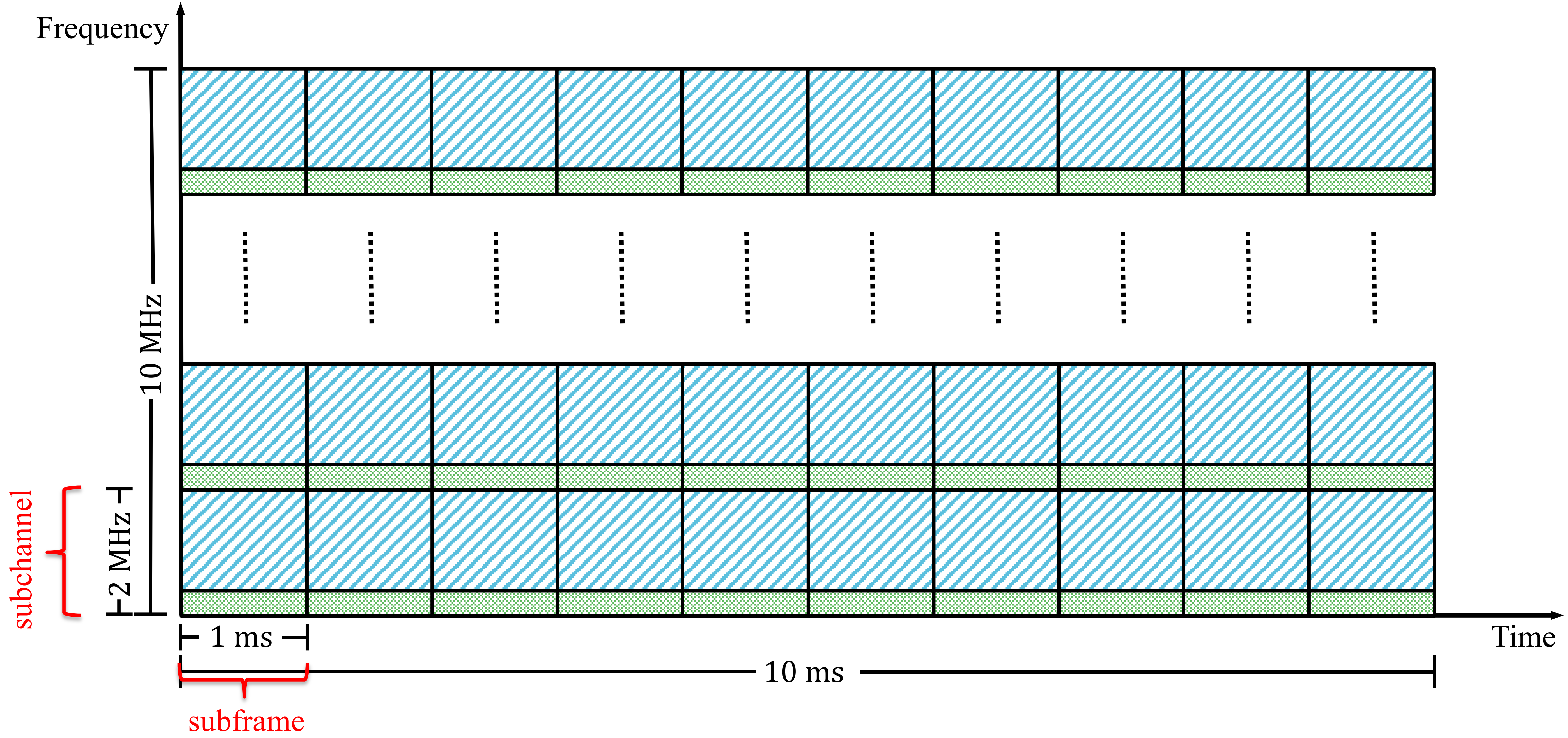
- Each transmission has two components in one subframe
  - Sidelink Control Information (SCI) in PSCCH: 2 RBs
  - Transport Block (TB) in PSSCH: ≥ 8 RBs (remainder + more subchannels)
- Single-subchannel (10-RB) transmission:

10×200 kHz RBs → 2 MHz subchannel

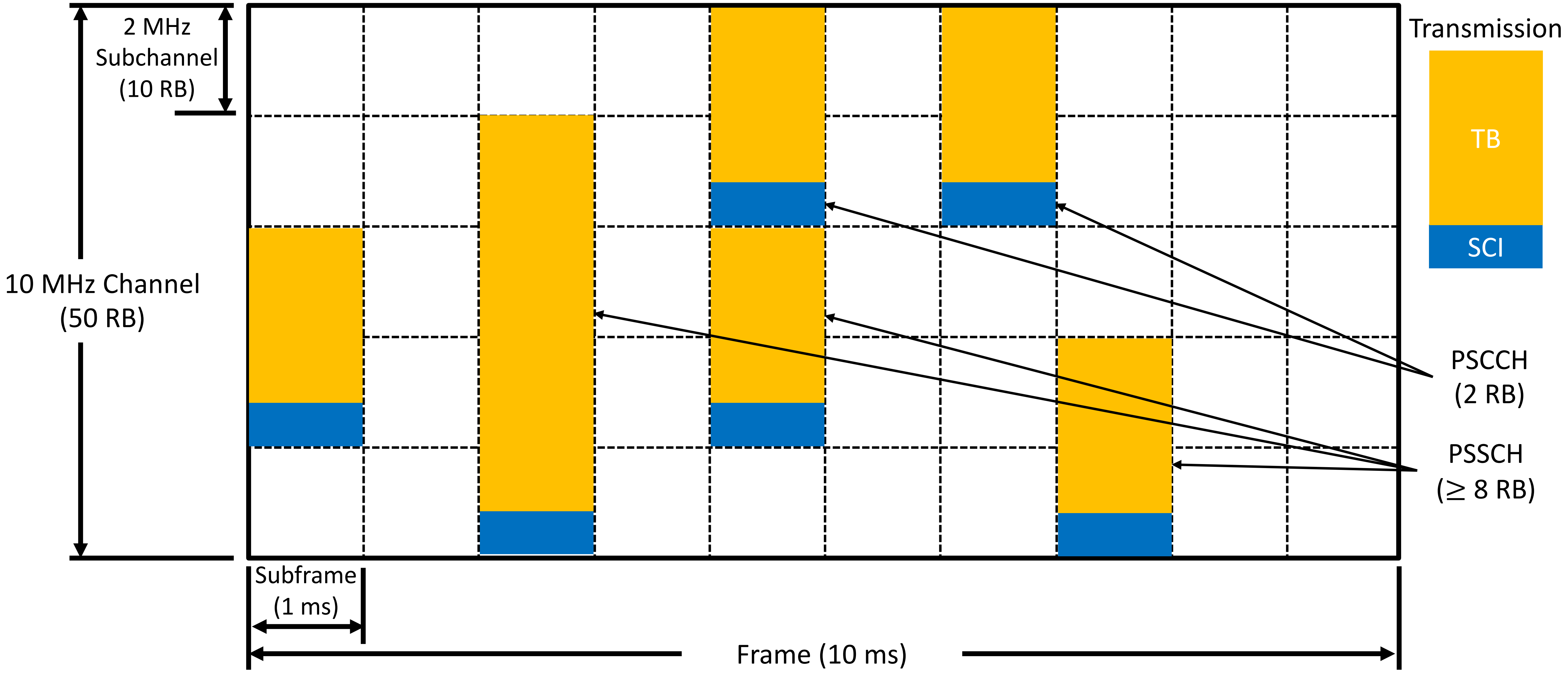


Without SCI, associated TB cannot be recovered

LTE-V2X: PHY-layer Example (10 MHz)



10 MHz Frame (5 Subchannels)



LTE-V2X: MAC Layer

- Transmission requires 1 subframe and n subchannels
  - n depends on size of TB (e.g., 2 subchannels for a standard BSM)

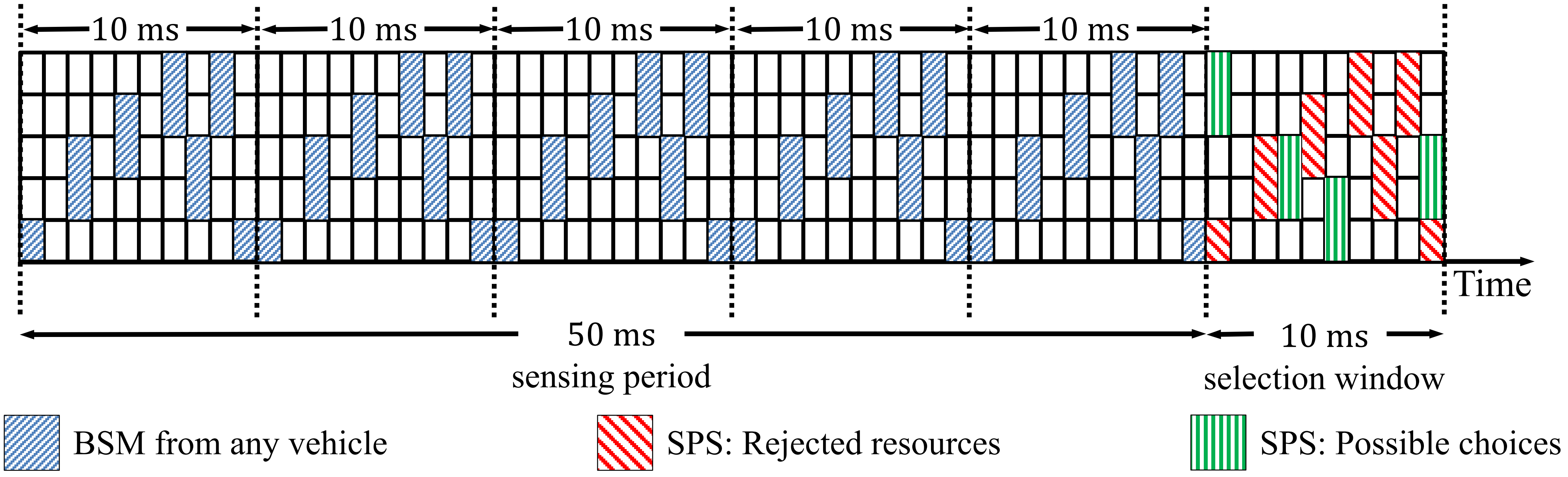
- How do vehicles choose when to transmit?
  - Simultaneous transmissions must use different subchannels!
  - Vehicles cannot coordinate directly
  - In Mode 4, no base stations to coordinate (no central coordination)

Semi-Persistent Scheduling (SPS)

- Select (autonomously in Mode 4) resources to transmit BSMs
  - Resources = time (subframe) and frequency (subchannels)
- Sensing-based scheduling
  - **Listen:** Monitor which subchannels are currently busy
  - **Predict:** Identify "gaps" in neighbors' transmissions
    - Remember – V2V messages are usually periodic
  - **Reserve:** Select the "least busy" (least likely) future resource (no CSMA/CA)
- Repeat every $c \in \{5, \ldots, 15\}$ messages to ensure stability
  - c randomly chosen each time

SPS – Illustrative Example

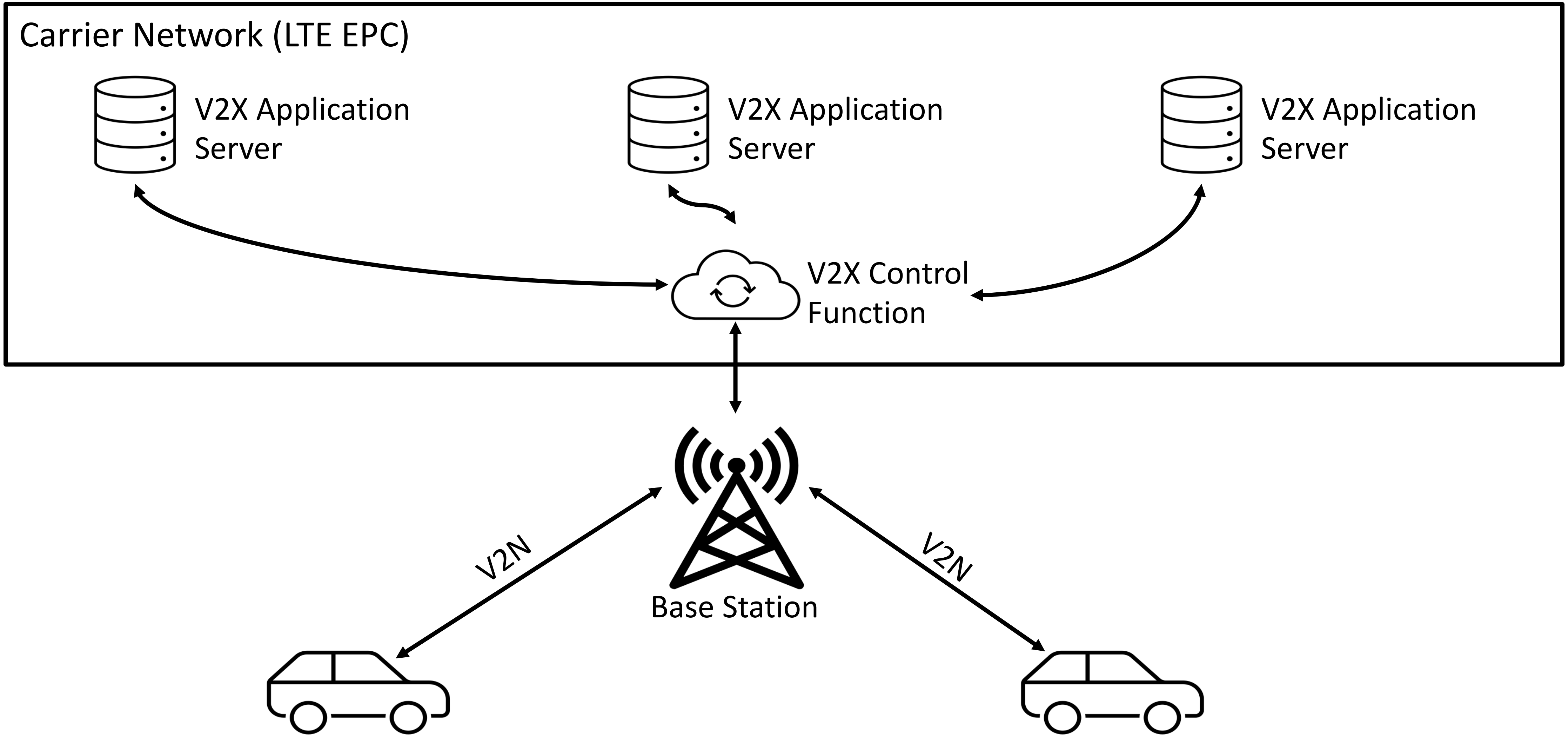
- Consider 10ms BSM interval, 50ms listening period
- BSMs are periodic ⟶ consecutive frames are similar



LTE-V2X: Vehicle-to-Network (V2N)

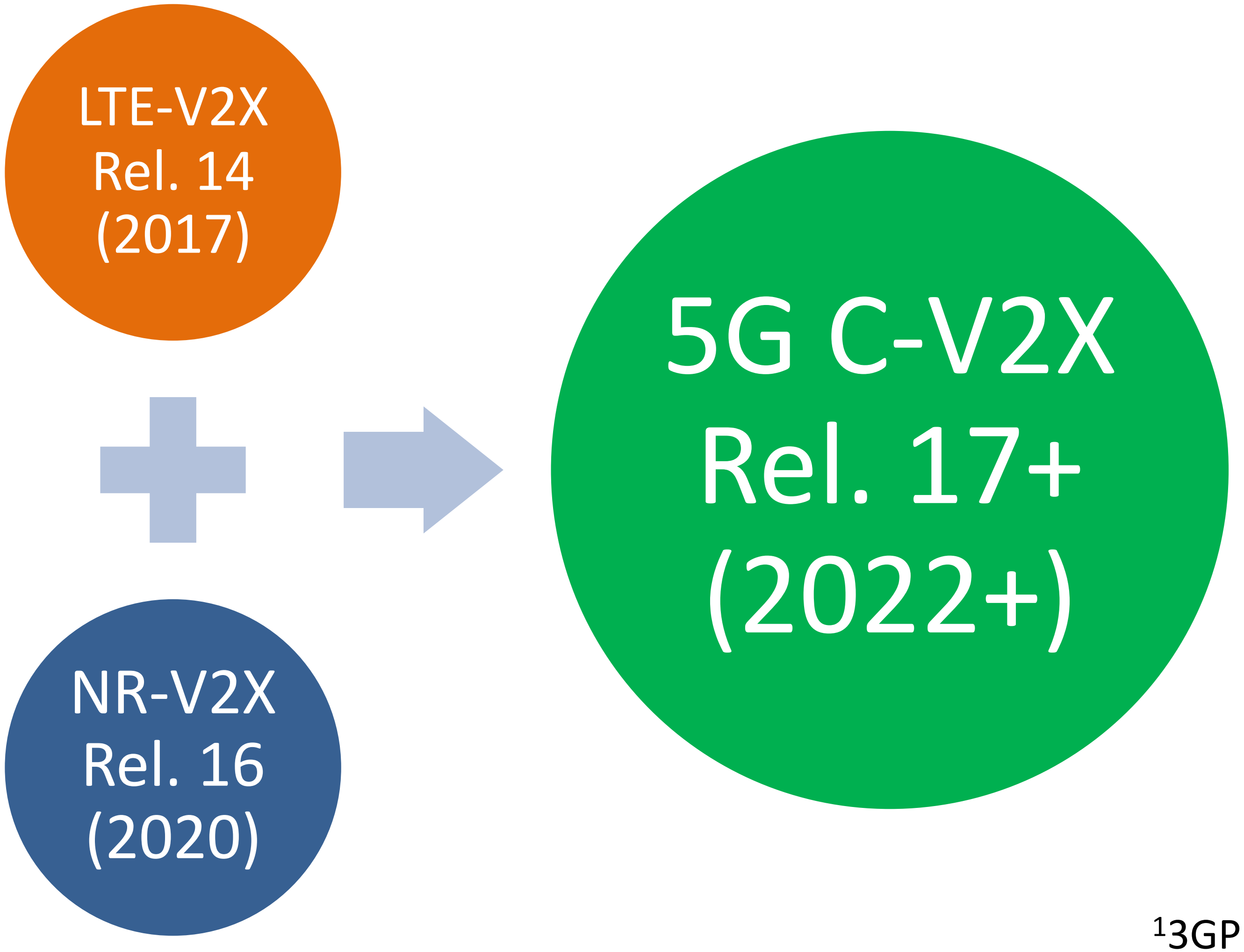
- Vehicles talk to network services through base stations
  - Existing infrastructure (and coverage), less need to install new roadside units
- Wide-area information dissemination (than V2V)
  - Lane obstructions, hazardous road conditions, etc.
  - Round-trip latency is typically between **75–200ms** (slower than Sidelink)
- Access cloud-based application servers (not planned in DSRC)
  - Infotainment, real-time traffic updates & navigation, ...

LTE-V2X V2N Architecture



The 5G Leap: New Radio V2X (NR-V2X)

5G C-V2X: State-of-the-art V2V



Hybrid protocol with complementary 4G/5G technologies

NR-V2X is **not** a replacement for LTE-V2X[1]

[1]3GPP Technical Report 38.913 (Release 17), Jul. 2020.

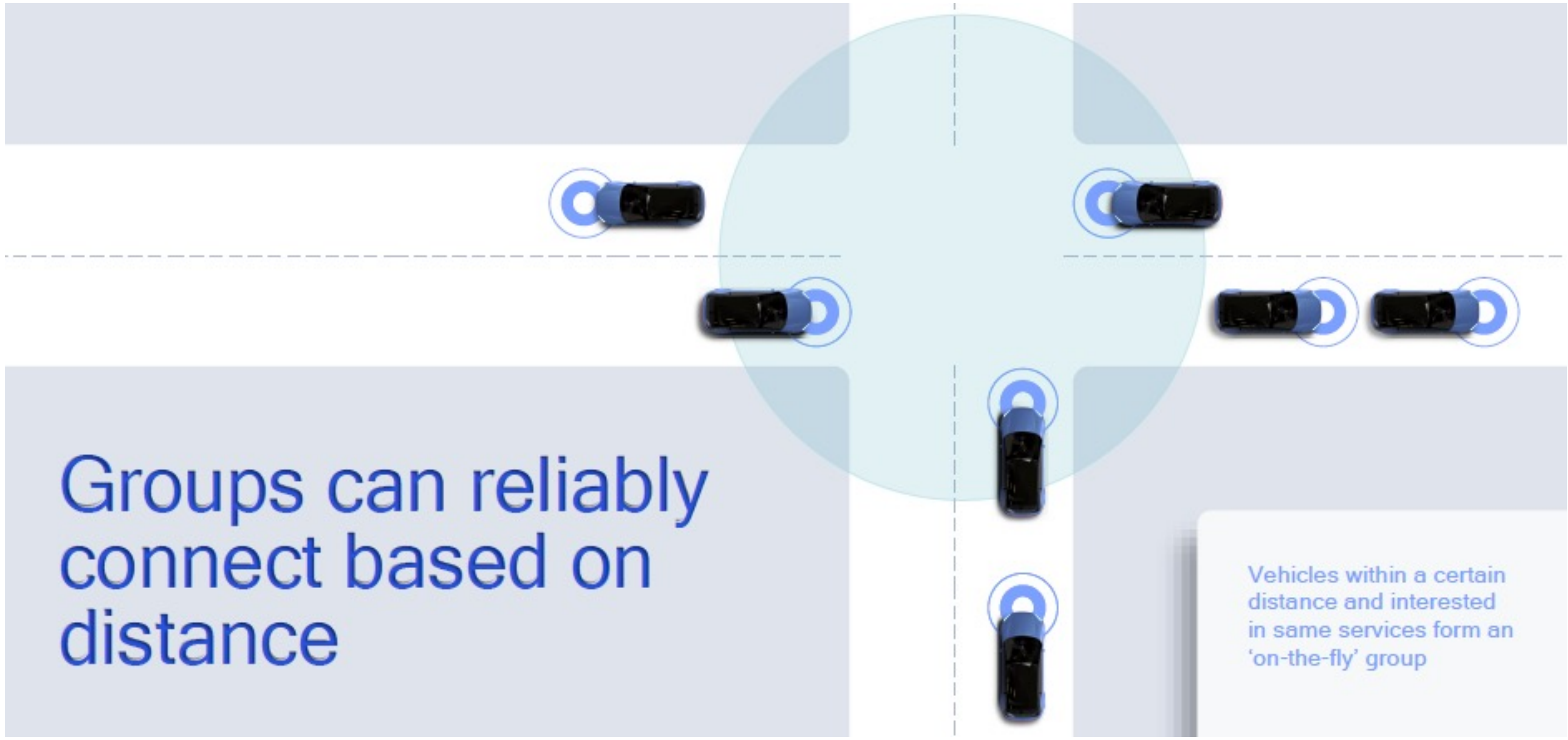
NR-V2X (2020, Release 16+)

- Based on 5G “New Radio” (NR) technology
  - LTE Mode 4 → NR-V2X Mode 2
- NR-V2X coexists with LTE-V2X
  - LTE-V2X for periodic broadcasts (e.g., BSMs)
  - NR-V2X for multicast and advanced use cases (e.g., intent sharing)
  - LTE-V2X + NR-V2X = “5G C-V2X Sidelink”

For the interested reader, a comprehensive, high-quality tutorial on NR-V2X (as of Release 16) is available from the *IEEE Communications Surveys & Tutorials* at https://doi.org/10.1109/COMST.2021.3057017.

NR-V2X Example Use Case

- Vehicle can form groups on-the-fly
- Example: vehicles approaching an intersection



S. Patil, "How NR based sidelink expands 5G C-V2X to support new advanced use cases," presented in a Qualcomm Technologies Webinar, Online, Mar. 2020.

V2V in NR-V2X

- LTE-Sidelink Mode 4 → NR-Sidelink Mode 2
  - Similar in design and autonomous operation
- PHY/MAC improvements over LTE-V2X
  - Scalable OFDM *numerology* → improved spectral efficiency
    - Subcarrier spacing, # of reference symbols, etc. are configurable
  - Flexible slot structure → unicast, multicast (e.g., platoon)
  - On-demand retransmission via negative acknowledgments (NACK)
    - Single-frequency network (SFN): Vehicles that need to NACK use the same resource, keep constant feedback overhead regardless of # of NACKs

NR-V2X vs. Other Technologies

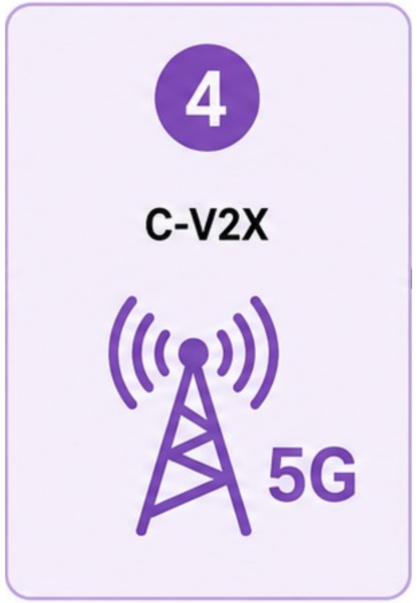
Feature	DSRC	LTE-V2X	NR-V2X	Result
Channel coding	Convolutional	Turbo	**LDPC/Polar**	Lower BER/PER and higher data rate than others
Modulation	OFDM	SC-FDM	**OFDM** **SC-FDM**	Devices choose to prioritize power efficiency (SC-FDM) or data rate (OFDM)
Retransmissions	None	HARQ (for broadcast)	**On-demand (NACK)**	Lower PER and more efficient for unicast/multicast
Channel bandwidth	10 MHz	10 or 20 MHz	**Up to 400 MHz** (in theory)	Huge increase in channel capacity

Takeaway: NR-V2X offers across-the-board improvements

Technical Advances in NR-V2X

- Scalable OFDM
  - Variable subcarrier spacing for maximum efficiency at high speeds
    - 15, 30, or 60 kHz subcarrier spacing (→ *numerology*); 1, ½, or ¼ ms slots, resp.
  - Allows channels up to 400 MHz (20x larger than LTE-V2X)
- Adaptive demodulation reference signals (DMRS)
  - Each subcarrier has between 2-4 DMRS
  - Higher vehicle speeds → more DMRSs and fewer data symbols for lower BER
    - Optimize balance of throughput and reliability

We just covered:



What's up next:

For questions or to provide feedback on the content, please reach out to Hanif Rahbari (hanif.rahbari@rit.edu) or Geoff Twardokus (twardokg@gvsu.edu)