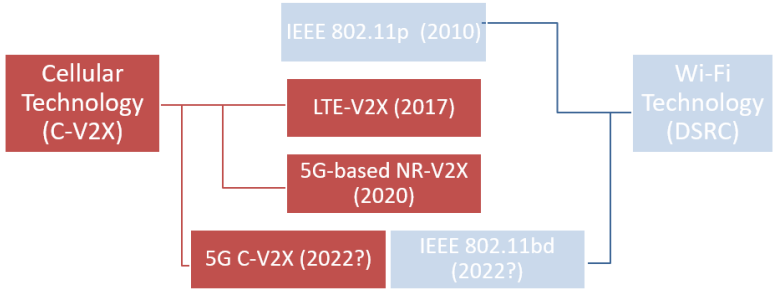
V2V Technologies: Part 2

Cellular Vehicle-to-Everything (C-V2X)

Overview

V2V Technology Evolution

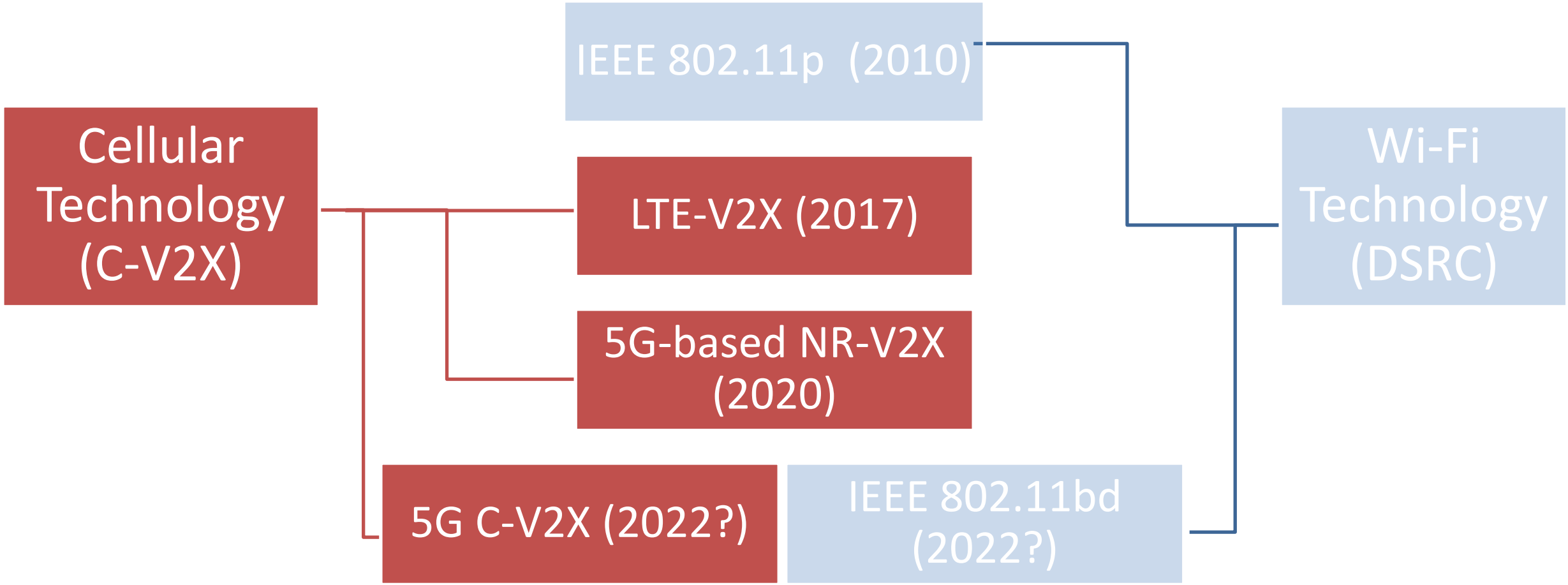


Key Concepts: Fundamentals of Wireless Communication

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

5G New Radio V2X (NR-V2X)

V2V Technology Evolution



Why Cellular?

- Designed for reliable *mobile* communication
  - Wi-Fi is not designed for high-speed mobility
  - High relative velocities, non-line-of-sight (NLOS) scenarios
- Support multiple simultaneous transmissions
- 5G will surpass (most) Wi-Fi capabilities
  - Data rate, range, reliability, etc.

Putting the 'Everything' in V2X

- C-V2X can leverage existing cellular infrastructure
  - V2I and Vehicle-to-Network (V2N)
- Communicate with cellular devices to further increase roadway safety
  - Vehicle-to-Pedestrian (V2P)
  - Vehicle-to-Bicycle (V2B)
  - Vehicle-to-Device (V2D)
- DSRC generally supports only V2V and (limited) V2I

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

- Release 17+ 5G C-V2X is a hybrid system
  - LTE for BSMs, NR for advanced uses (platoons, remote driving, …)

Key Concepts: Fundamentals of Wireless Communication

Periodic Wave

$$v(t) = A\sin(2\pi f t + \varphi)$$

A: maximum amplitude

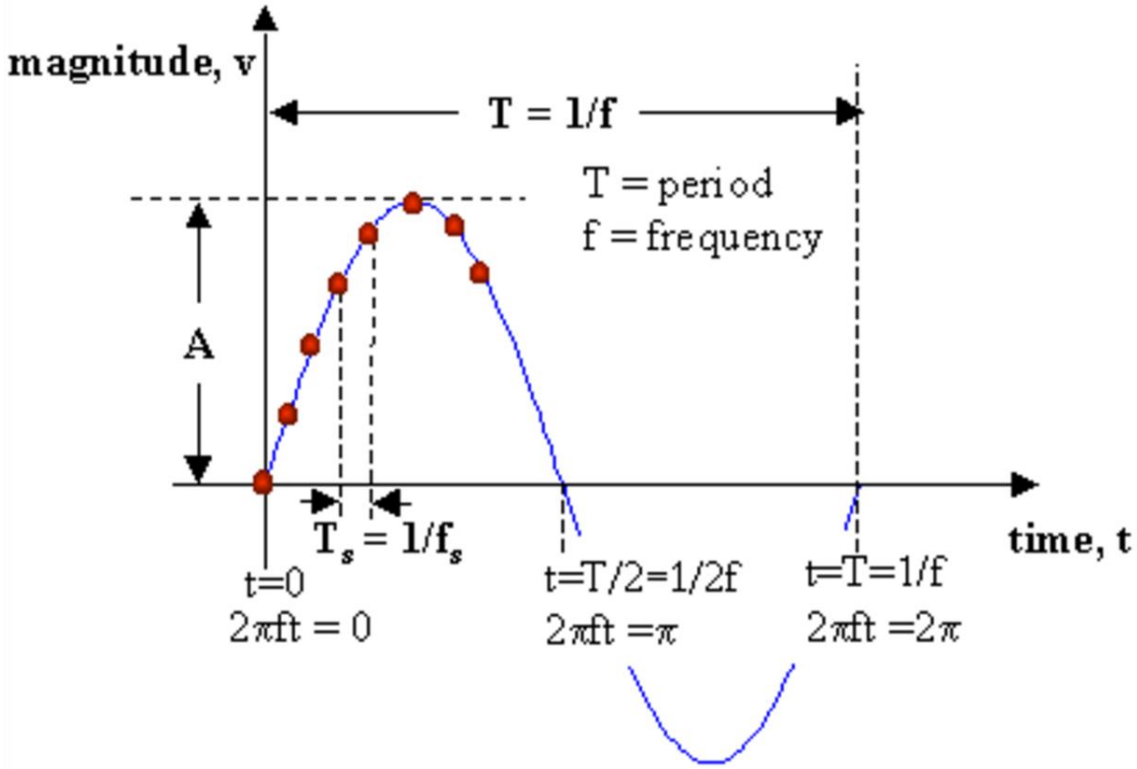
φ: phase

f: frequency (in Hz)

T: time period

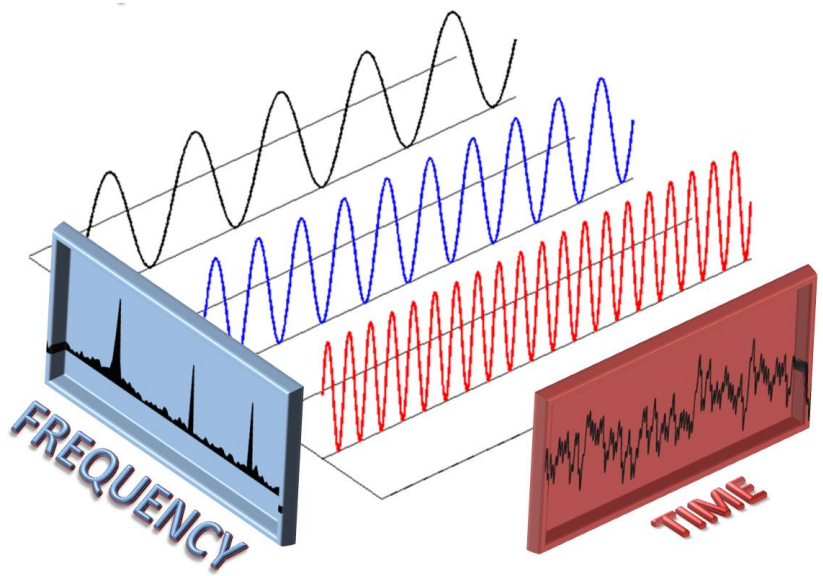
f_s: sampling rate

T_s: sampling interval



Wireless Signals

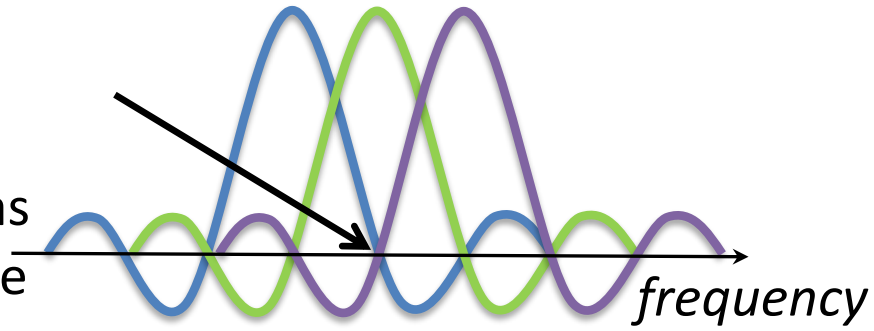
- Signals are periodic waves in time and frequency
- A signal may be composed of multiple waves, each with a different frequency
  - Each wave is referred to as a **frequency component**



OFDM

- Orthogonal Frequency Division Multiplexing
  - Widely used in nearly all modern systems
  - Carefully select frequency components
    - Frequency components → subcarriers
  - Each subcarrier carries data for one symbol
- Used in DSRC (802.11p)

Orthogonal:
Only one subcarrier has nonzero value



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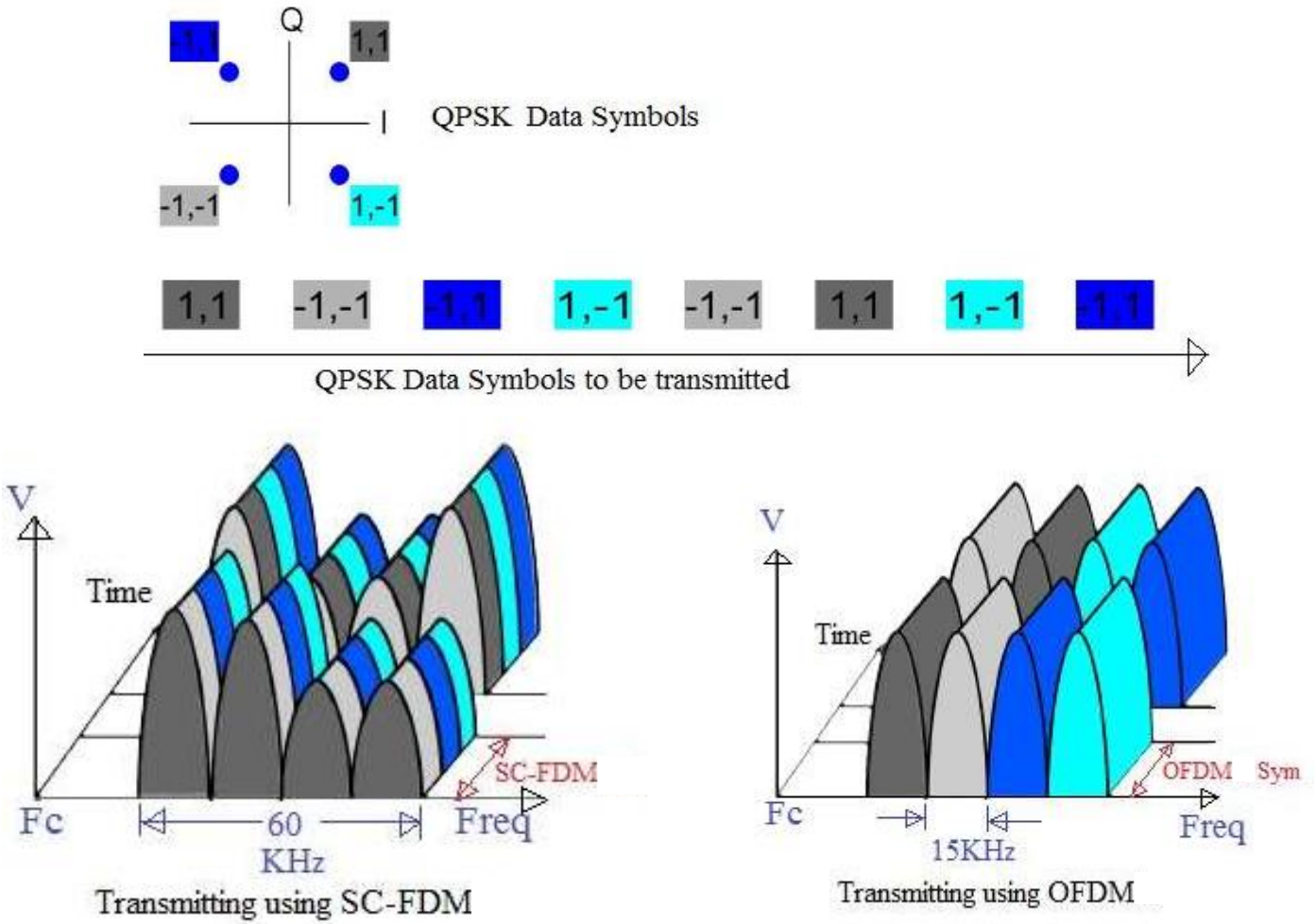
SC-FDM

- Single-Carrier Frequency Division Multiplexing
  - Only one wave rather than superposition of several
- Each subcarrier has data for all symbols
- More power-efficient than OFDM
- Takes longer to transmit a complete signal than OFDM

OFDM vs. SC-FDM (Visual)



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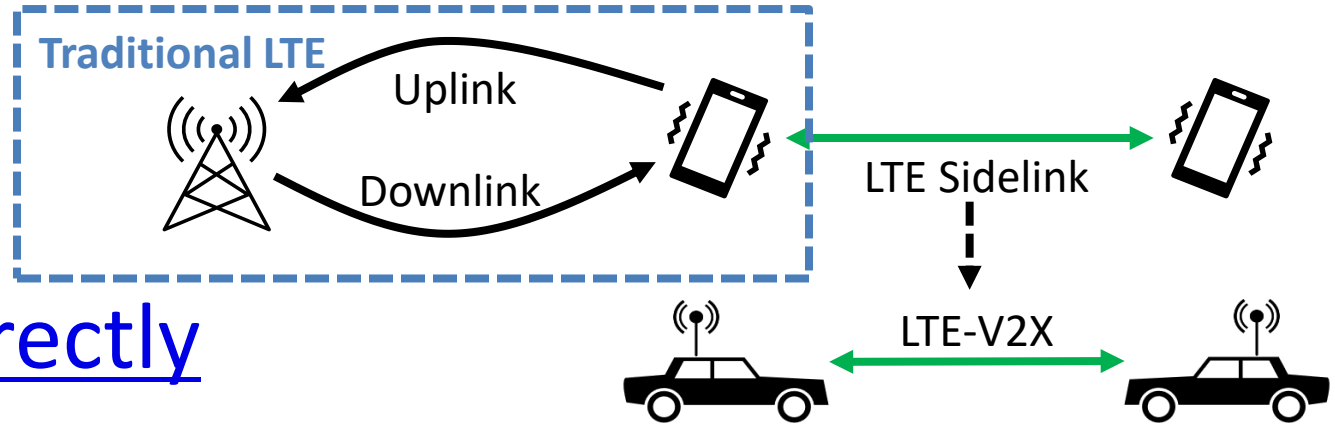
LTE-V2X: First-Generation of Cellular Vehicle-to-Everything

LTE-V2X (2017)



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

Overview - LTE-V2X PHY Layer

- Uses SC-FDM instead of OFDM
- Retransmissions reduce number of lost packets
  - Lower packet error rate (PER)
- Modern coding techniques improve SNR and range
  - Lower bit error rate (BER)

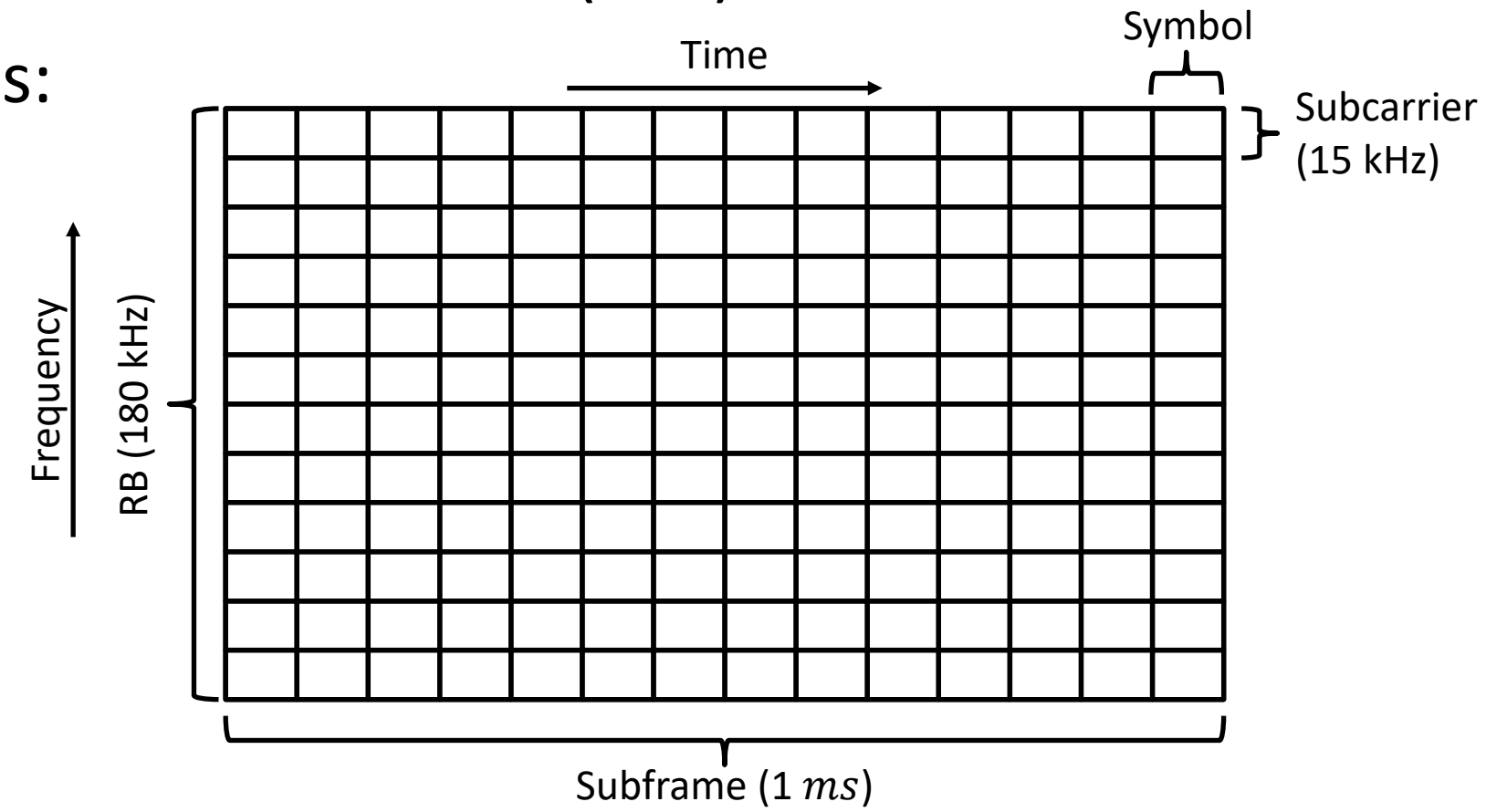
Feature	DSRC	LTE-V2X	Result
Channel coding	Convolutional	Turbo	$<$ 1% BER with 2 dB lower SNR 2x longer range
Modulation	OFDM	SC-FDM	3x link budget gain over DSRC
Retransmissions?	No	Yes (HARQ)	Greater reliability (lower PER)
Channel bandwidth	10 MHz	10 or 20 MHz	Higher throughput (increased capacity)

Key Advantages over DSRC

- ~17% higher data rate (7 Mbps)
  - Lower latency, large messages (like Type 2 BSMs)
- Allows multiple simultaneous transmissions
- Use of turbo codes → lower bit error rate (BER)
  - Resistant to noise, interference, jamming
- 2x communication range (~1.2 km vs. 600 m)

LTE-V2X PHY-layer Structure

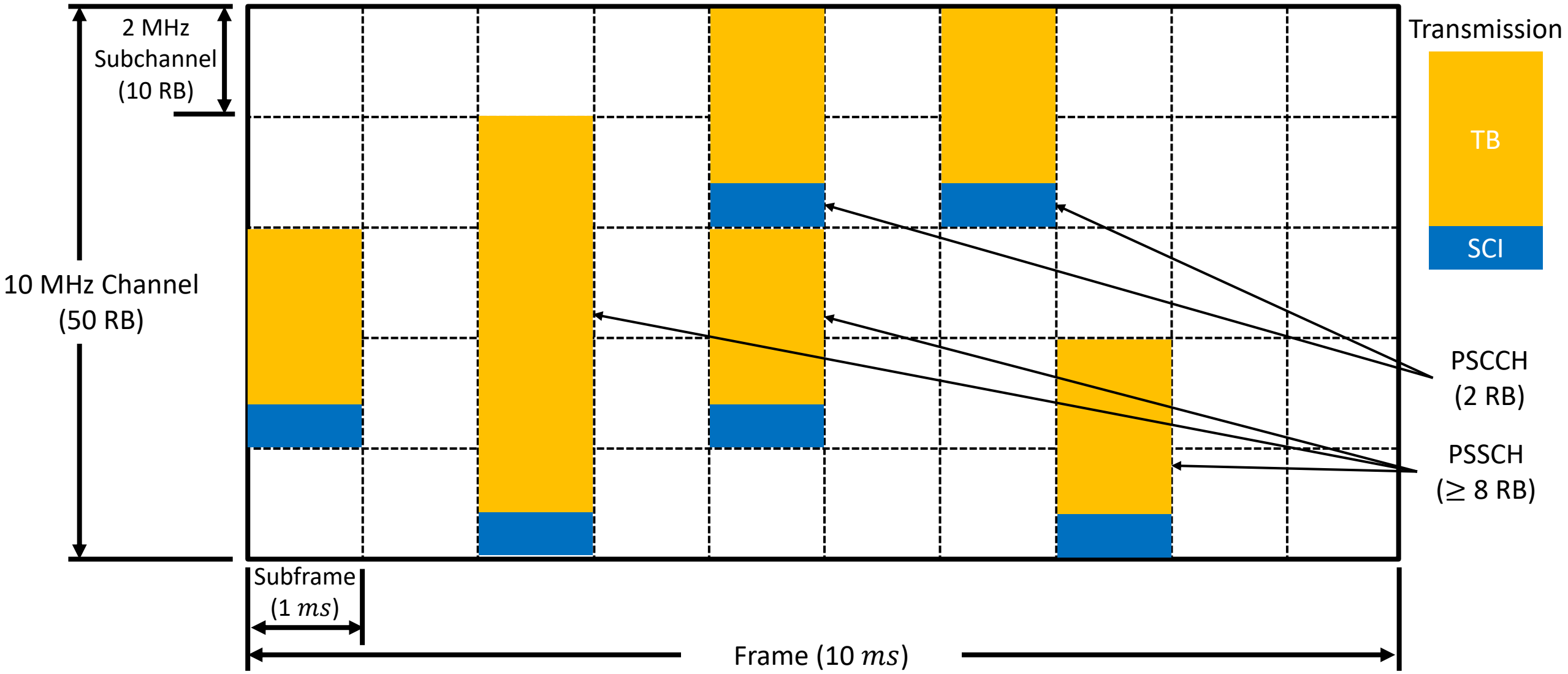
- 10 ms LTE frames divided into 1 ms subframes
- Channel divided into resource blocks (RBs)
- 180 kHz RB contains:
  - 12 subcarriers
  - 14 symbols



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 control and data channels
  - PSCCH (2 RB) = Physical Sidelink Control Channel
  - PSSCH = Physical Sidelink Shared Channel (for data)
- A transmission requires two messages in one subframe
  - Sidelink Control Information (SCI) in PSCCH
  - Transport Block (TB) in PSSCH
- Without SCI, associated TB cannot be recovered

10 MHz Frame (5 Subchannels)



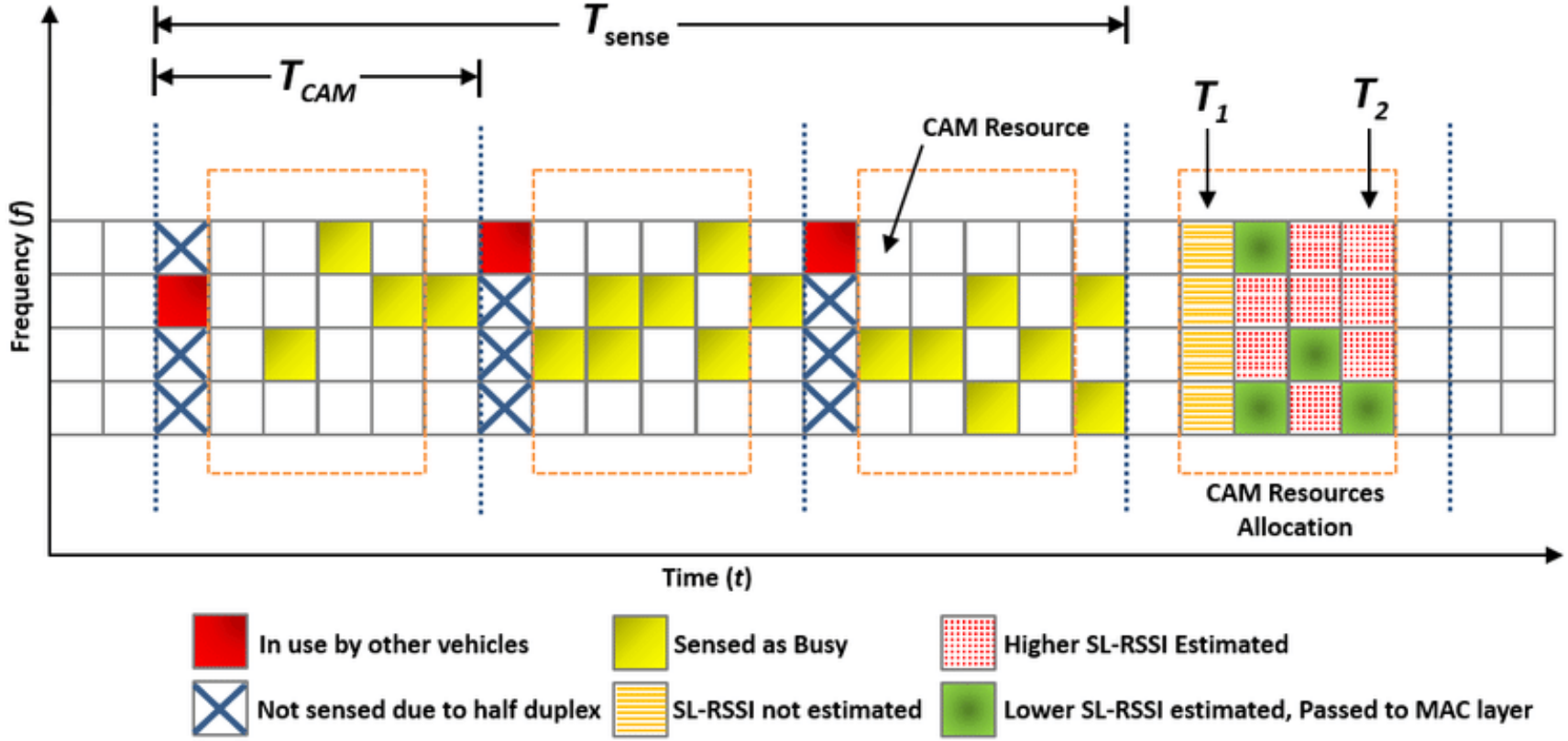
LTE-V2X MAC Layer

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

Semi-persistent scheduling (SPS)

- Autonomously select resources to transmit BSMs
  - Resources = time (subframe) and frequency (subchannels)
- Sensing-based algorithm
  - Listen to the channel
  - Determine resources where other vehicles are transmitting
    - Remember – V2V messages are usually periodic
  - Choose to transmit on resources least likely to be used in future
- Repeat every $c \in \{5, \ldots, 15\}$ messages
  - c randomly chosen each time

SPS Visual



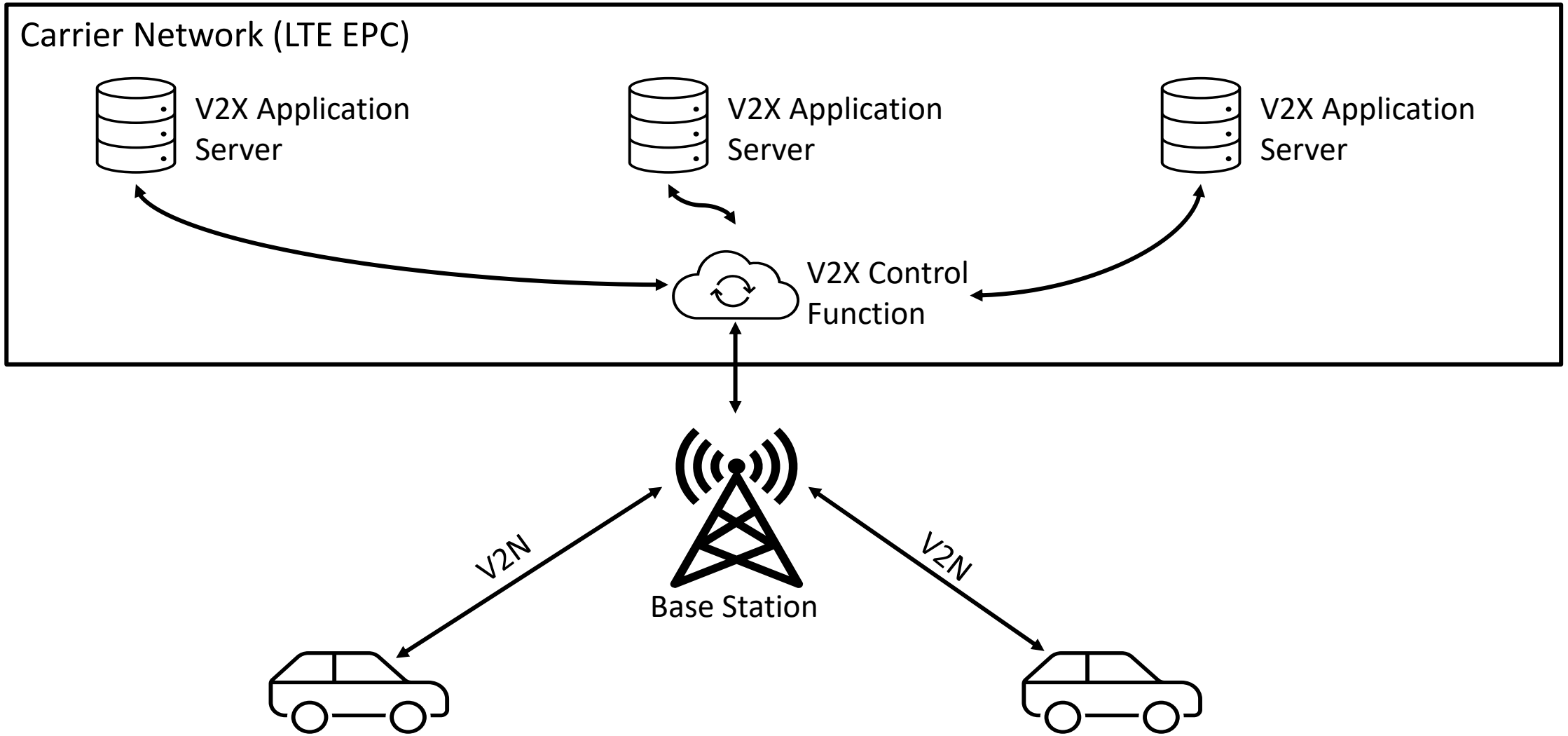
Haider and Hwang, "Adaptive Transmit Power Control Algorithm for Sensing-Based Semi-Persistent Scheduling in C-V2X Mode 4 Communication," *Electronics*, vol. 8, no. 8, p. 846, Jul. 2019. doi:10.3390/electronics8080846.

- CAM = Cooperative Awareness Message (E.U. term for BSM, no functional difference)

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

- Unique capability of C-V2X technologies
- Vehicles talk to network services through base stations
  - Leverage existing infrastructure (and coverage)
  - Reduce costs – less need to install new roadside units
- Propagate information over wider area (than V2V)
  - Lane obstructions, hazardous road conditions, etc.
- Access cloud-based application servers
  - Infotainment, real-time traffic updates & navigation, ...

LTE-V2X V2N Architecture



5G New Radio V2X (NR-V2X)

NR-V2X (2020)

- Based on 5G "New Radio" (NR) technology
- NR-V2X operates alongside LTE-V2X
  - LTE-V2X for periodic broadcasts (like BSMs)
  - NR-V2X for multicast and advanced use cases
- Long-term coexistence is planned
  - LTE-V2X + NR-V2X = "5G C-V2X Sidelink"

NR-V2X Standards

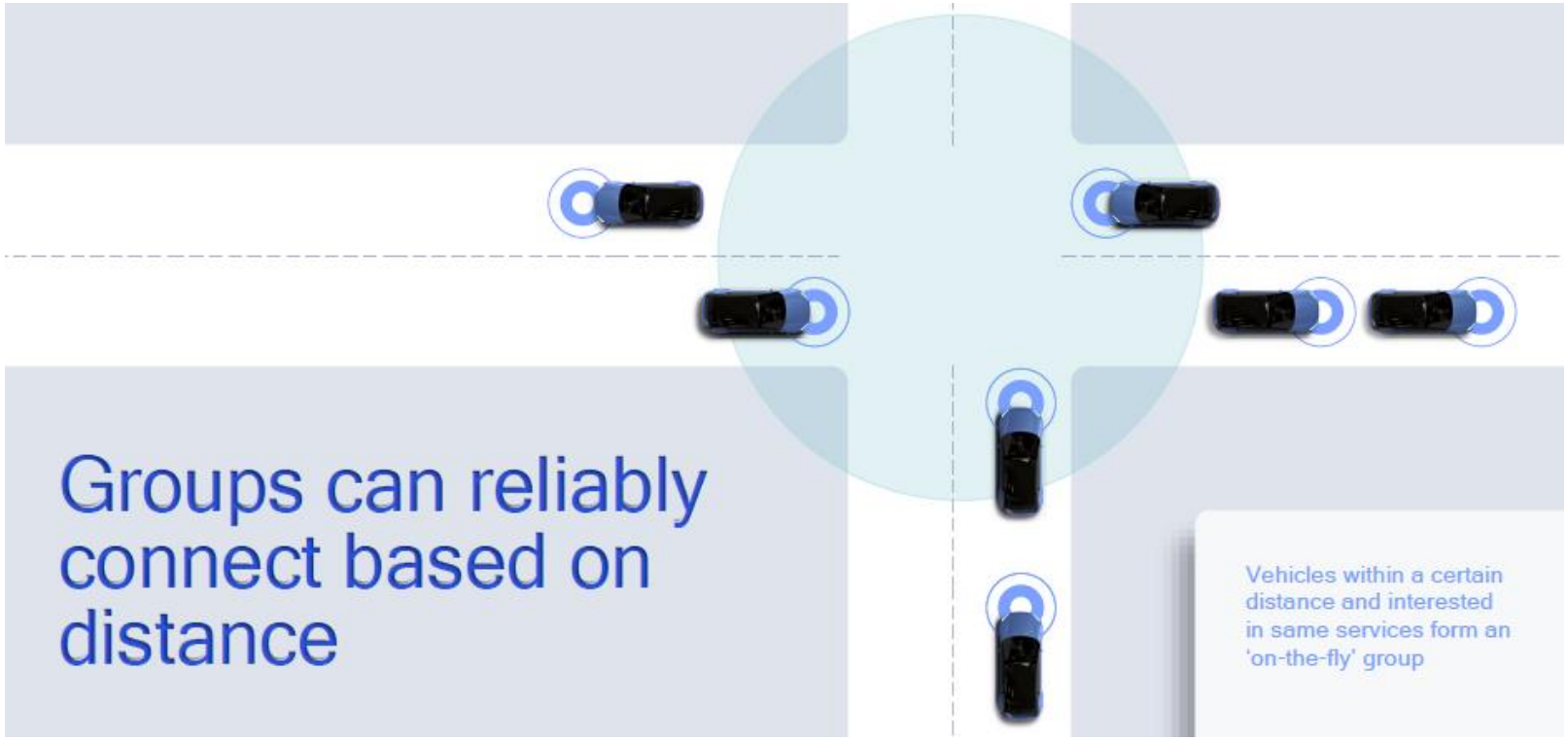
- Release 16 (2020)
  - First usable NR-V2X definitions
  - NR-V2X functionality for advanced use cases
- Release 17 (2022?)
  - "5G Phase 3"
  - Very little is certain right now
  - Will provide 5G system enhancements moving in the direction of increased vehicle autonomy and group coordination

V2V in NR-V2X

- LTE-Sidelink Mode 4 → NR-Sidelink Mode 2
  - Similar in design and operation
- PHY/MAC improvements over LTE-V2X
  - Scalable OFDM → improved spectral efficiency
    - Sub-carrier spacing, # of reference symbols, etc. are dynamic
  - Flexible slot structure → unicast, multicast communication
  - On-demand retransmission via negative acknowledgments (NACK)

NR-V2X Example Use Case

- Vehicle can form on-the-fly groups as needed
- 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.

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	On-demand (NACK)	Lower PER and far more efficient than HARQ
Channel bandwidth	10 MHz	10 or 20 MHz	Up to 400 MHz	Huge increase in channel capacity

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

New Features in NR-V2X

- Technical advances to efficiently use spectrum
- Scalable OFDM
  - Variable sub-carrier spacing for maximum efficiency at high speeds
    - 15, 30, or 60 kHz subcarrier spacing
  - Wideband 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 DMRS symbols for lower BER
  - Optimize balance of throughput and reliability

NR-V2X Features (cont.)

- Flexible slot structure for efficient and reliable multicast
- Negative acknowledgements (NACKs)
  - If error in decoding, vehicle “NACKs” to request retransmission
- Single-frequency network (SFN)
  - Vehicles that need to NACK use the same time slot and frequency
  - Keep constant feedback overhead regardless of # of NACKs