On 20 MHz Channel Spacing for V2X Communication based on 802.11 OFDM

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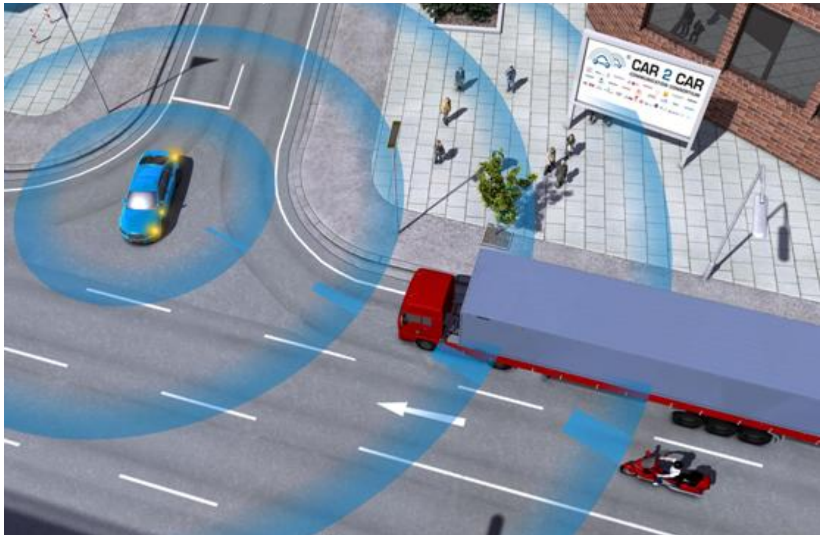
Outline

- V2X communication for cooperative traffic safety applications
- Congestion control options
- 802.11 OFDM modulation, coding, and bandwidth options
- ITS spectrum regulation in the EU
- Impact of 10 MHz→20 MHz: first-order transmission range analysis (path loss only)
- Doppler and RMS delay spreads for V2V channels
- Numerical results
- Conclusions

Cooperative Traffic Safety Applications



- Vehicle-to-vehicle (V2V) and vehicle-to-road infrastructure (V2I) are enablers
- Application requirements
  - Real-time with low latencies (sub 100 ms)
  - High reliability: no undetected errors
  - Scalable: support for many vehicles in the same area

- Current standards for V2V and V2I are based on IEEE 802.11p (WLAN technology)
- Is the 802.11p PHY able to meet the application requirements?
- The 802.11p MAC can be improved (see work by Katrin Sjöberg, et al.)

Graphics source: Car 2 Car Communication Consortium, http://www.car-to-car.org/

Application Requirements → Risk for Congestion

- Most safety application will rely on
  - periodic **broadcast** of status messages (CAM/BSM)
  - event-driven **broadcast** of warning messages (DENM)
- Back-of-the envelope calculation:
  - R_{CAM} = 10 Hz, N_{B} = 400 bytes CAM/BSM → 32 kbit/s per vehicle
  - PHY data rate R_{b} = 6 Mbit/s
  - Number of supported vehicles

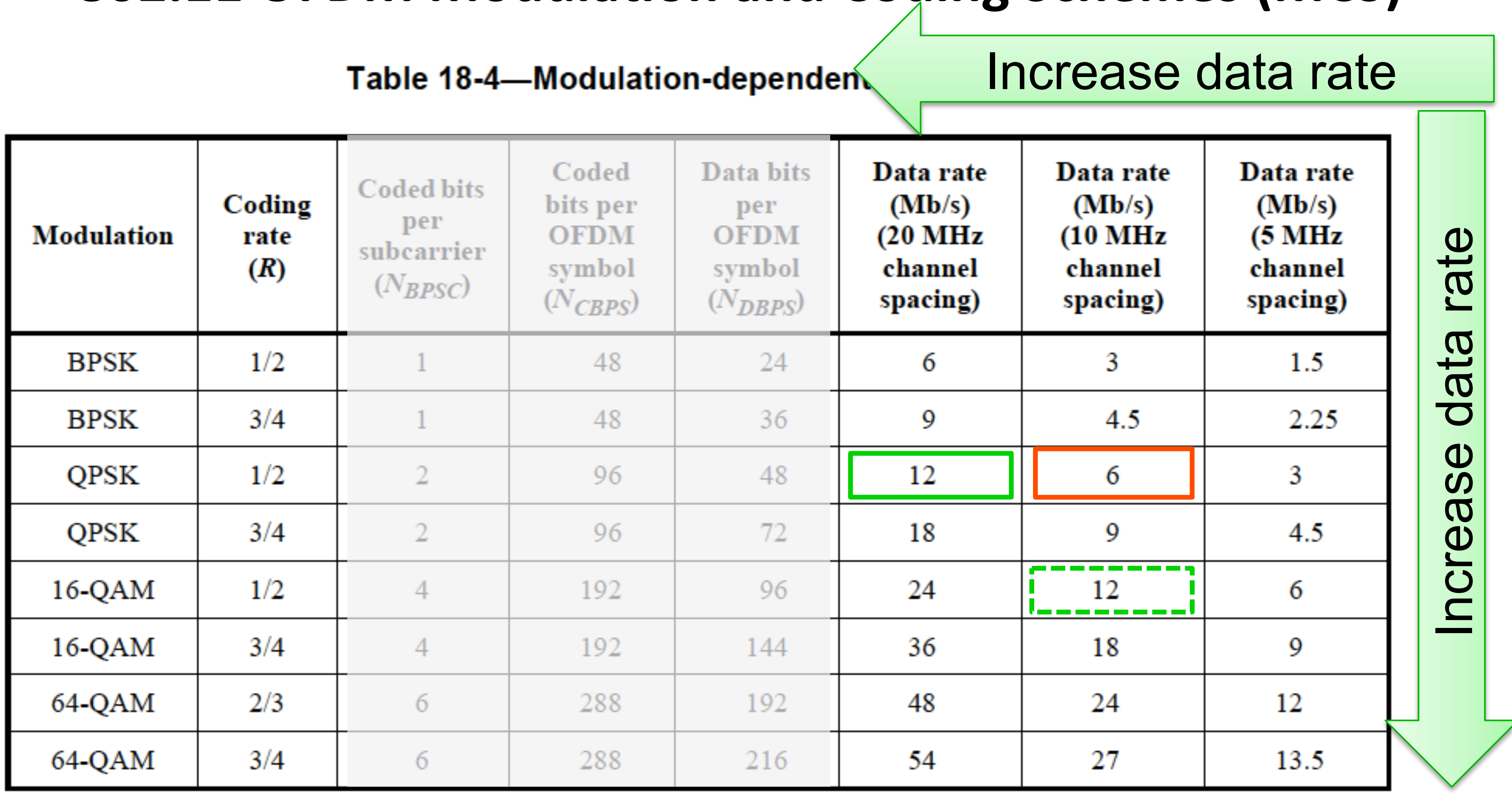
$$\frac{R_b}{8 \times N_B \times R_{\text{CAM}}} = \frac{6 \times 10^6}{8 \times 400 \times 10} \approx 187$$

- Note: very optimistic calculation since
  - PHY and MAC header overhead are ignored
  - Imperfect MAC coordination ignored

Dealing with Congestion

- Options on different layers
- **APP**
  - reduce CAM/BSM generation rate
  - reduced CAM/BSM payload size
- **MAC**
  - increase coordination efficiency
  - Power control
- **PHY**
  - Directional antennas (?)
  - Increase PHY transmission rate (bits/s)
    - Change modulation and coding scheme (MCS)
    - Increase bandwidth of transmitted signal
    - Multiple antenna transmission (MIMO)

802.11 OFDM Modulation and Coding Schemes (MCS)



Increase data rate

Table 18-4—Modulation-dependent

Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})	Data rate (Mb/s) (20 MHz channel spacing)	Data rate (Mb/s) (10 MHz channel spacing)	Data rate (Mb/s) (5 MHz channel spacing)
BPSK	1/2	1	48	24	6	3	1.5
BPSK	3/4	1	48	36	9	4.5	2.25
QPSK	1/2	2	96	48	12	6	3
QPSK	3/4	2	96	72	18	9	4.5
16-QAM	1/2	4	192	96	24	12	6
16-QAM	3/4	4	192	144	36	18	9
64-QAM	2/3	6	288	192	48	24	12
64-QAM	3/4	6	288	216	54	27	13.5

Increase data rate

IEEE 802.11-2012: Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, pp. 1-2793, March 29, 2012, DOI: 10.1109/IEEESTD.2012.617821

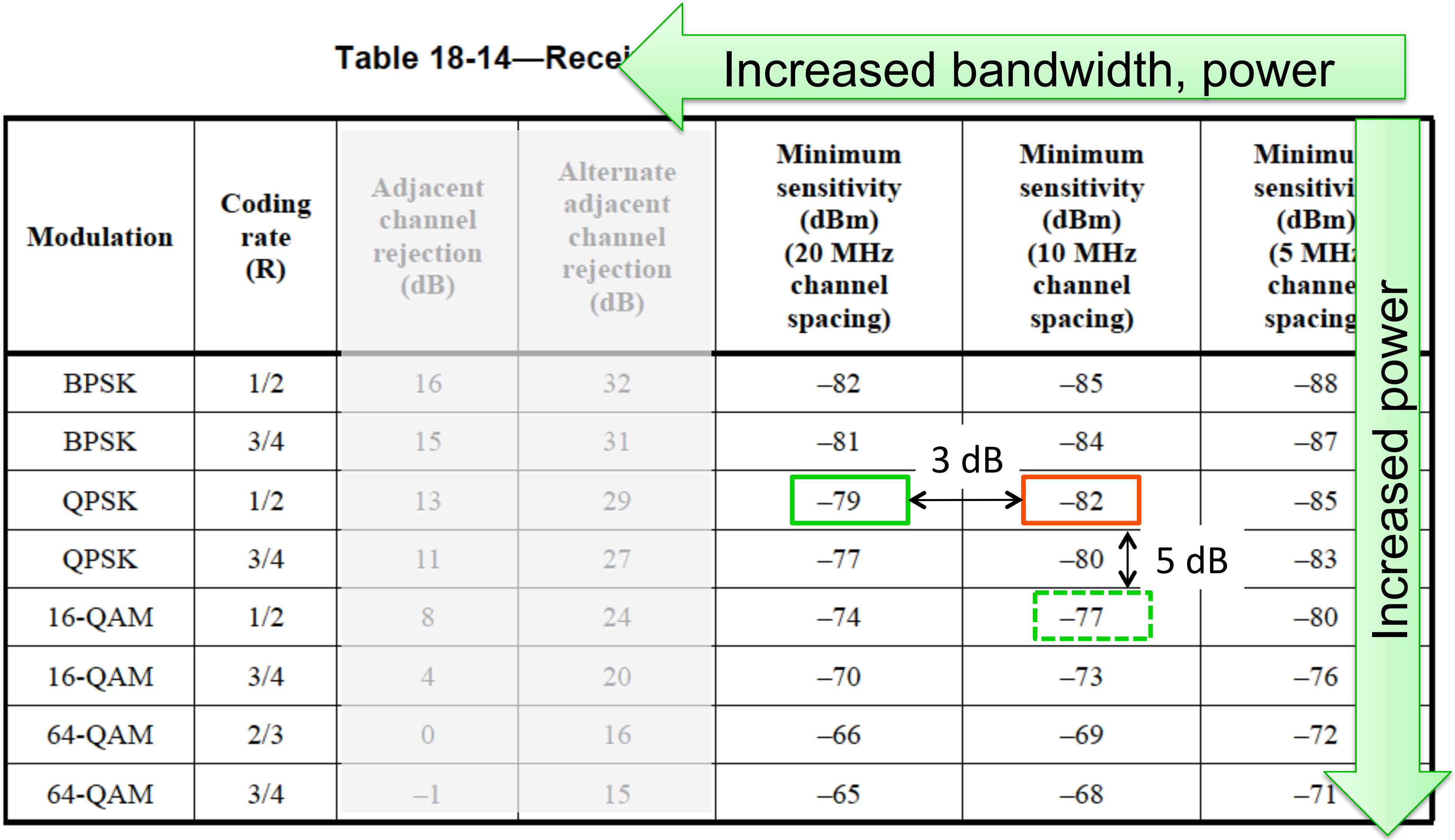


Table 18-14—Recei

Modulation	Coding rate (R)	Adjacent channel rejection (dB)	Alternate adjacent channel rejection (dB)	Minimum sensitivity (dBm) (20 MHz channel spacing)	Minimum sensitivity (dBm) (10 MHz channel spacing)	Minimu sensitivi (dBm) (5 MH channe spacing
BPSK	1/2	16	32	–82	–85	–88
BPSK	3/4	15	31	–81	–84	–87
QPSK	1/2	13	29	–79	–82	–85
QPSK	3/4	11	27	–77	–80	–83
16-QAM	1/2	8	24	–74	–77	–80
16-QAM	3/4	4	20	–70	–73	–76
64-QAM	2/3	0	16	–66	–69	–72
64-QAM	3/4	–1	15	–65	–68	–71

Increased bandwidth, power

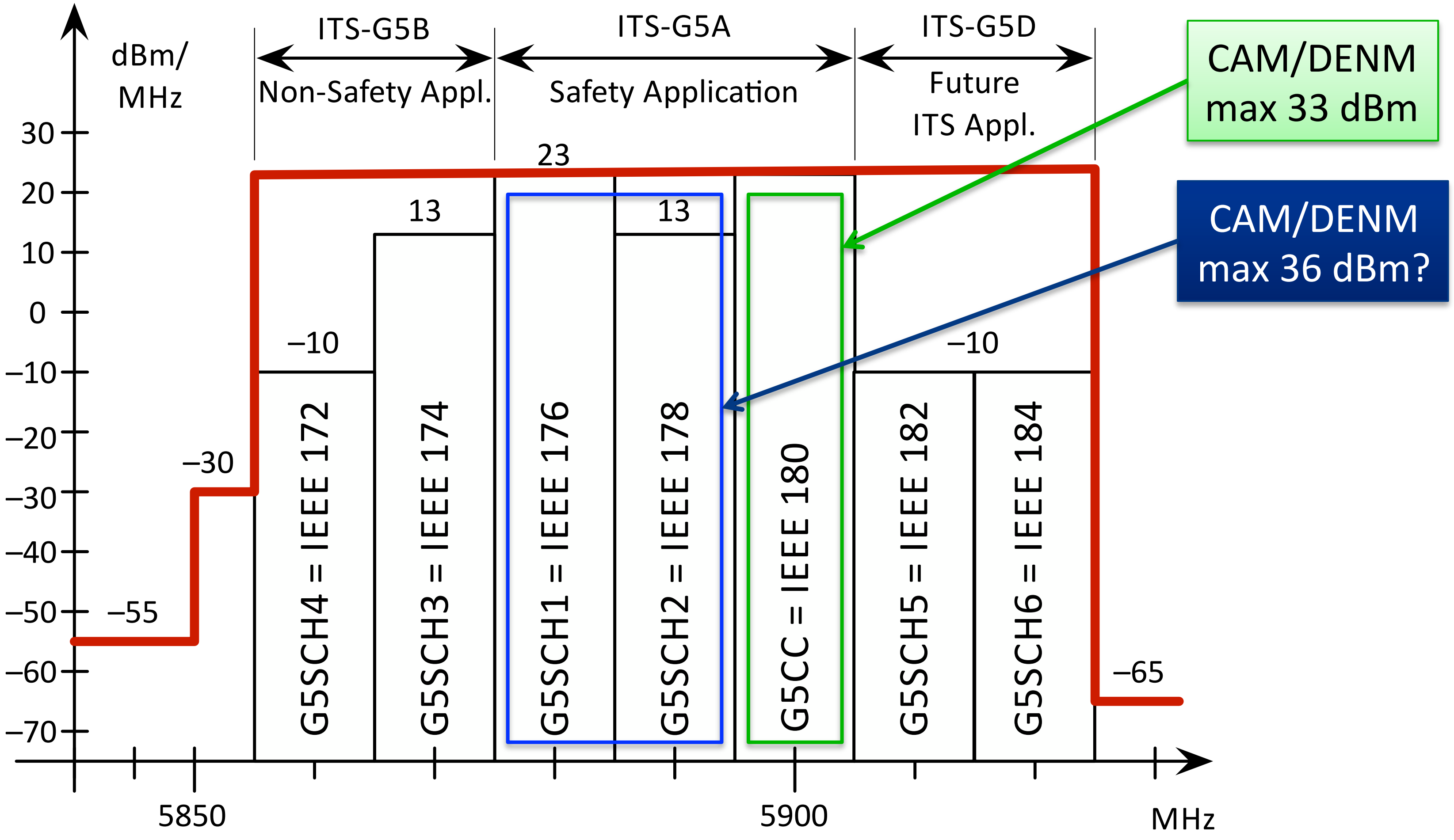
3 dB

5 dB

Increased power

IEEE 802.11-2012: Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, pp. 1-2793, March 29, 2012, DOI: 10.1109/IEEESTD.2012.617821

EU Spectrum Regulation

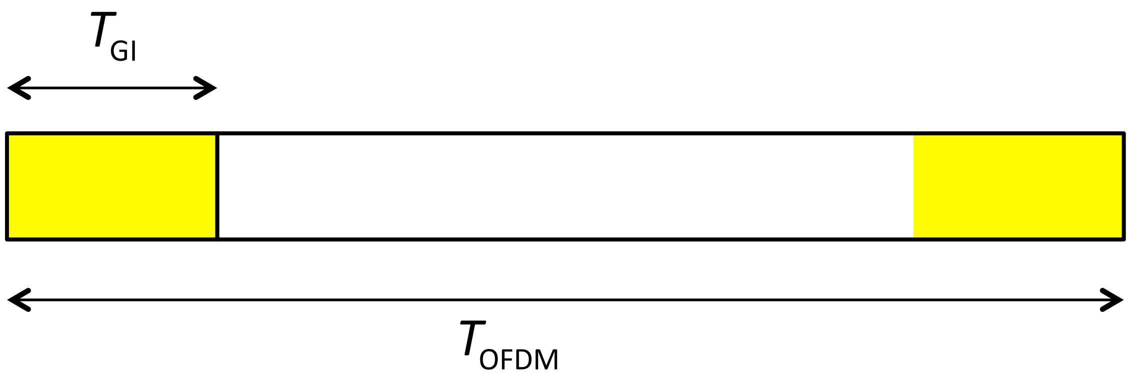


ETSI ES 202 663 (V1.2.1): “Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band”

10 → 20 MHz: First-Order TX Range Analysis

- The receiver sensitivity (min RX power for certain performance) will be degraded with 3 dB
- If the ***transmit power*** (dBm) is constant, then
  - 3 dB loss in sensitivity → 30% loss in range (path-loss exponent 2)
- If the ***transmit power density*** (dBm/MHz) is constant, then
  - TX power can be increased with 3 dB (from 33 dBm to 36 dBm)
  - transmission range remains constant
- In the US,
  - max TX power 40 dBm in IEEE channel 184 (public safety, including intersections)
  - max TX power 20 dBm in IEEE channel 172 (BSM, MAP, SPAT)
- The above analysis ignores small-scale fading effects that will improve performance for the 20 MHz system compared to a 10 MHz system

OFDM Design Rules (basics)



Rule 1

$$\boxed{T_{\mathrm{OFDM}} \ll \frac{1}{B_D}}$$

Rule 2

$$\boxed{T_{\mathrm{GI}} > \sigma_{T_m}}$$

$B_D = $ Doppler spread

$\sigma_{T_m} = $ RMS delay spread

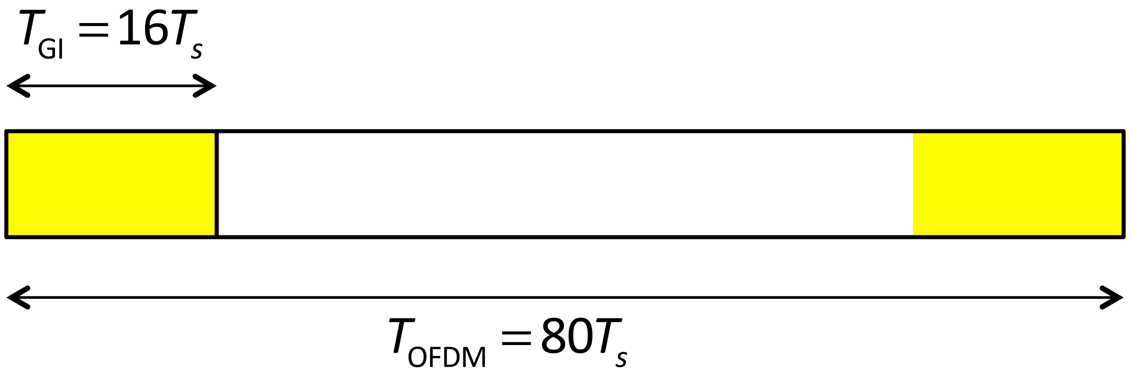
”Typical” V2V Channel Statistical Parameters

Parameter	Highway	Rural	Suburban	Urban	WLAN
RMS delay spread [ns]	40 – 400	20 – 60	104	40 – 300	< 50
Doppler spread [Hz]	100 – 1000	100 – 800	?	30 – 350	< 10

Most challenging V2V channel for OFDM

Mecklenbräuker, et al., ”Vehicular channel characterization and its implication for wireless systems design and performance,” Proc. of the IEEE, July 2011

802.11 OFDM PHY



- Data rates, timing, and bandwidth parameters are derived from the sample time T_s

Channel Spacing [MHz]	Sample Time [µs]	T_{OFDM} [µs]	T_{GI} [µs]
5	0.2	16	3.2
10	0.1	8	1.6
20	0.05	4	0.8

802.11 OFDM PHY and V2V Channels

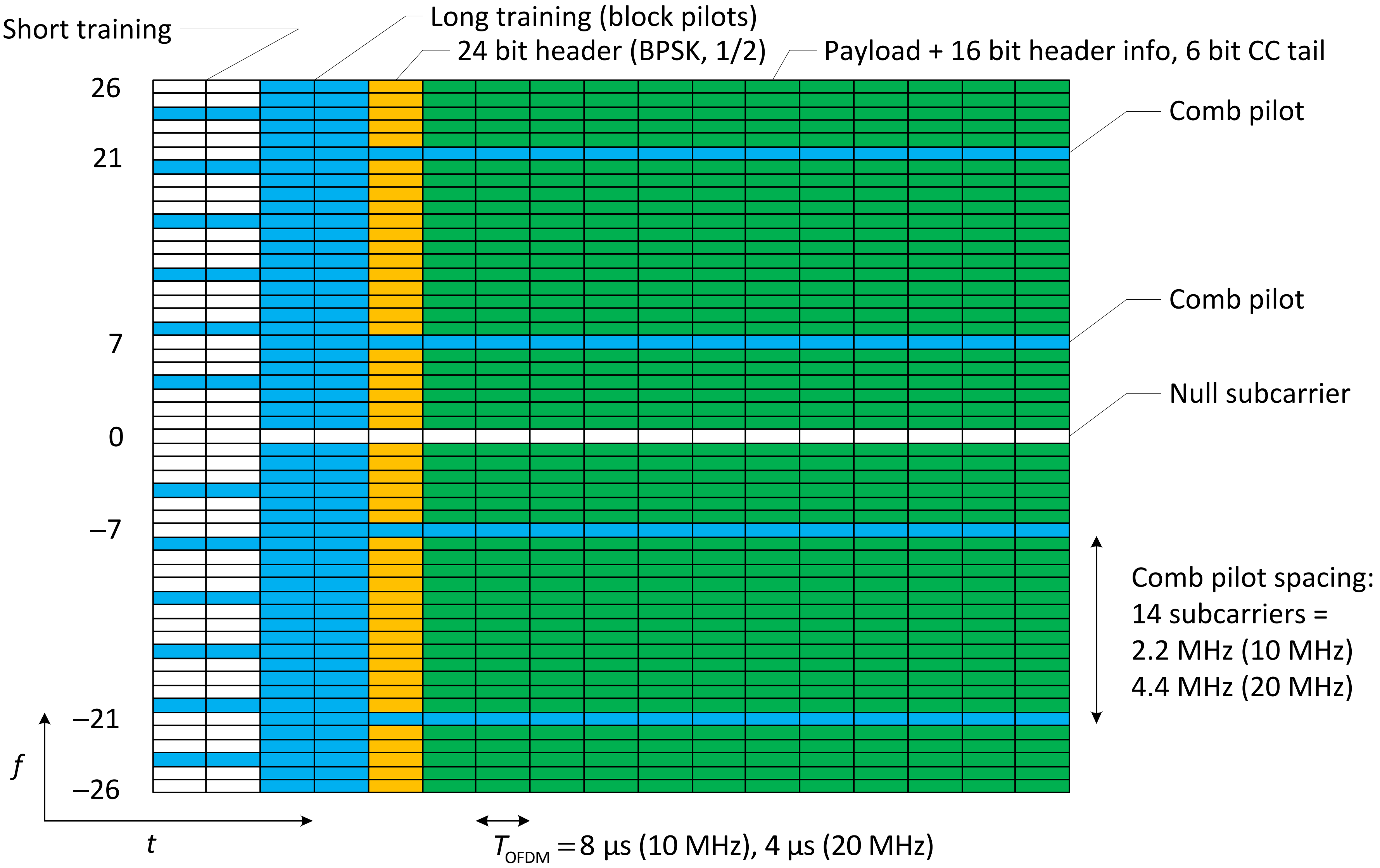
- Back-of-the-envelope calculation for “worst-case” V2V channel with Doppler spread 1000 Hz and RMS delay spread 0.4 µs
- OFDM design rules

Rule 1: Normalized Doppler spread: $B_D T_{\text{SYM}} \ll 1$

Rule 2: Normalized RMS delay spread: $\sigma_{T_m} / T_{\text{GI}} < 1$

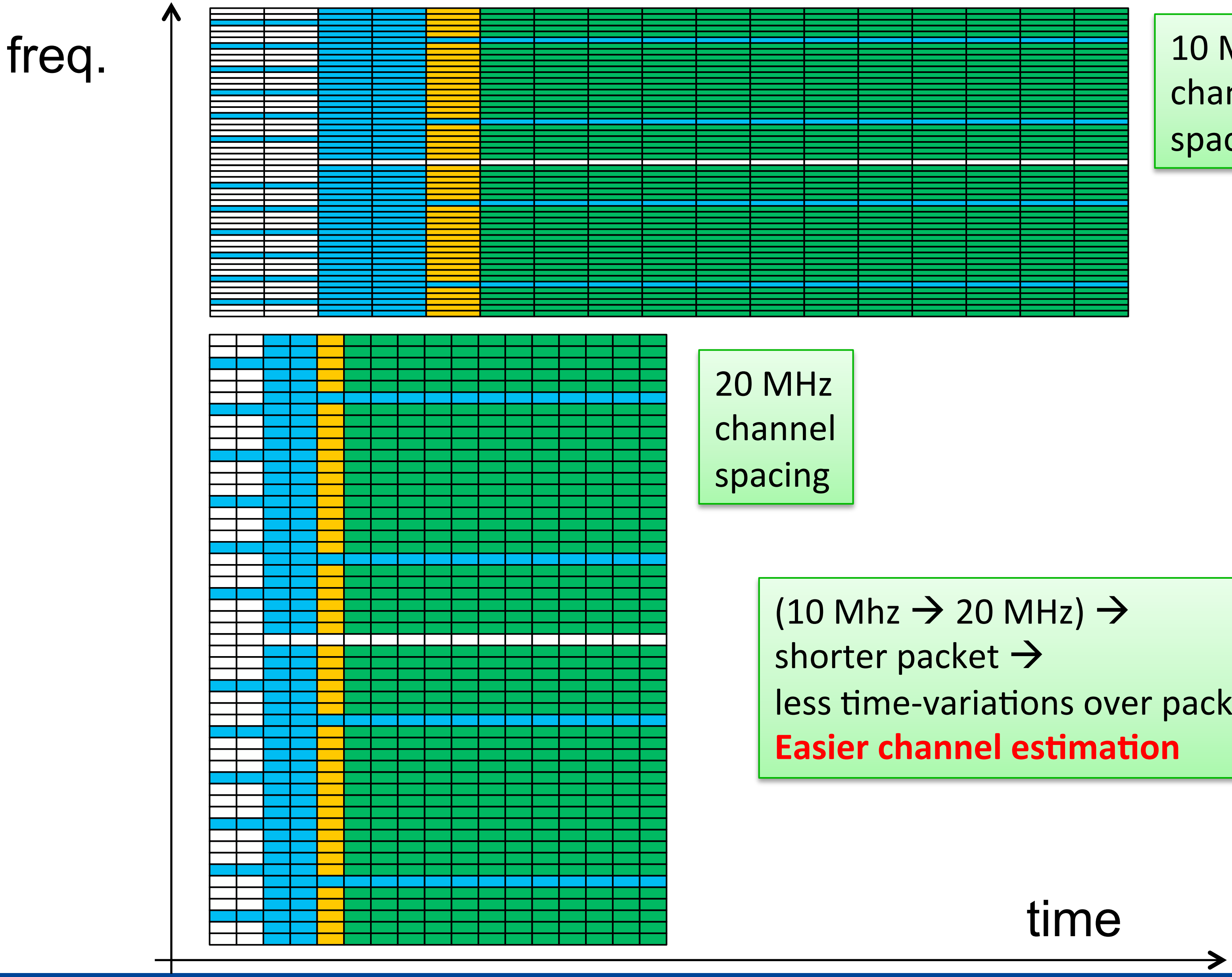
Channel Spacing [MHz]	T_{SYM} [µs]	Normalized Doppler spread	T_{GI} [µs]	Normalized RMS delay spread
5	16	0.016	3.2	0.125
10	8	0.008	1.6	0.250
20	4	0.004	0.8	0.500
		Rule 1: OK!		**Rule 2: OK!**

802.11 OFDM Frame Format for 10 and 20 MHz



Comb pilot spacing:
14 subcarriers =
2.2 MHz (10 MHz)
4.4 MHz (20 MHz)

$T_{\mathrm{OFDM}} = 8\ \mu s$ (10 MHz), 4 µs (20 MHz)



10 MHz channel spacing

20 MHz channel spacing

(10 Mhz → 20 MHz) →
shorter packet →
less time-variations over packet →
Easier channel estimation

Pros and Cons with Increased Channel Spacing

- For 802.11 OFDM, assuming all other factors are the same, increasing the channel spacing leads to the following main effects
- Impact on PHY
  - shorter packets → easier channel estimation
  - shorter OFDM symbols → more robust to time-variations (Doppler spread)
  - shorter guard interval → less robust to time-dispersion (delay spread)
  - ***possibly*** less energy per bit (symbol etc.) → reduced range
- Impact on MAC and higher layers
  - short packets → less congestion
- If power is allowed to double
  - same energy per bit (symbol etc.) → same range

Numerical Results

- 400 byte packets, QPSK rate ½ → 1 packet = 67 OFDM data symbols
- 5-tap iid Rayleigh-fading channel with uniform power-delay profile and tap-spacing 100 ns → max excess delay 400 ns
- Taps have Clarke's power spectrum, parameterized with the speed *v*, implying that the Doppler spread is approximately 20*v* Hertz
- Perfect channel estimation is computed as

$$\hat{H}_{\mathrm{p}}(f,n) \triangleq \frac{1}{T_{\mathrm{SYM}}} \int_{nT_{\mathrm{SYM}}}^{(n+1)T_{\mathrm{SYM}}} H(f,t)\,dt, \quad n = 0, \ldots, n_F - 1,$$

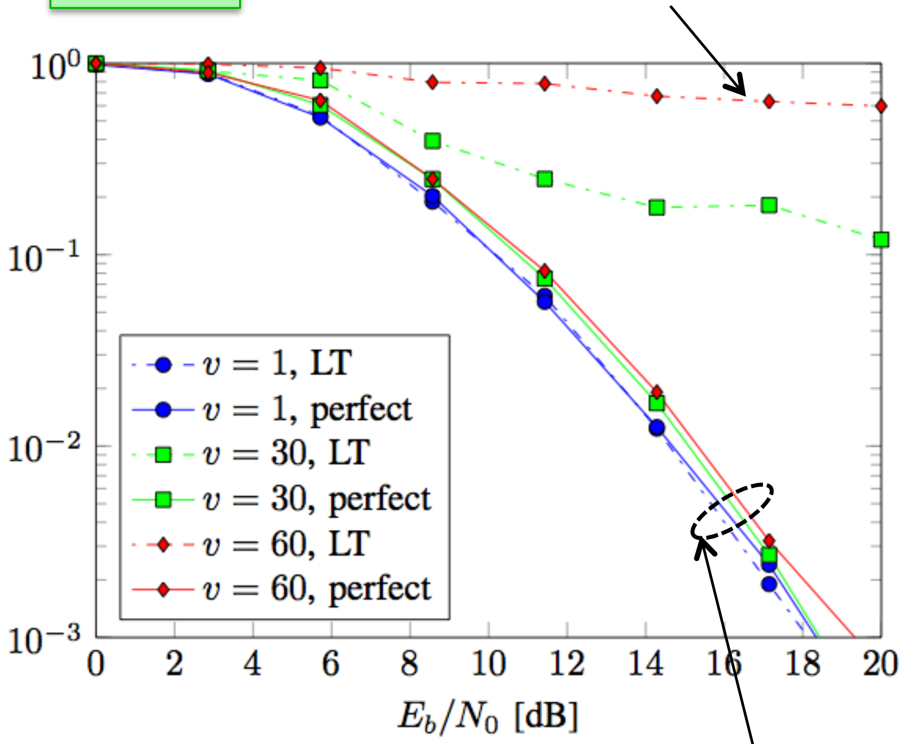
- Simple channel estimation based on the LT symbols is simulated as

$$\hat{H}_{\mathrm{LT}}(f,n) \triangleq \hat{H}_{\mathrm{p}}(f,0), \quad n = 0, \ldots, n_F - 1,$$

Frame Error Probability versus SNR/bit

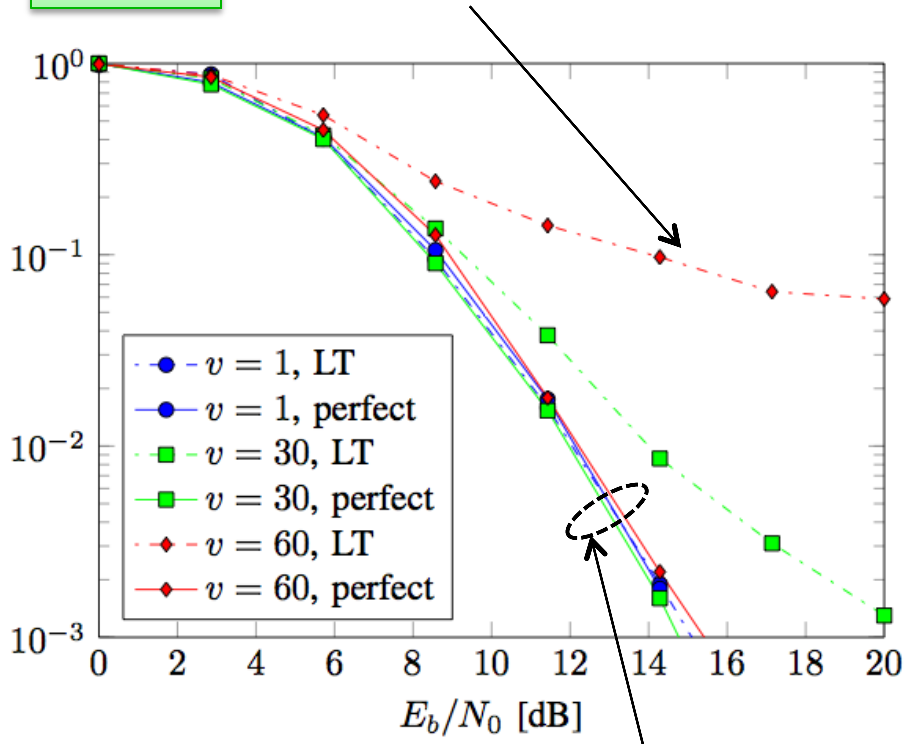
10 MHz

$B_D T_{\text{frame}} \approx 0.63$



20 MHz

$B_D T_{\text{frame}} \approx 0.31$

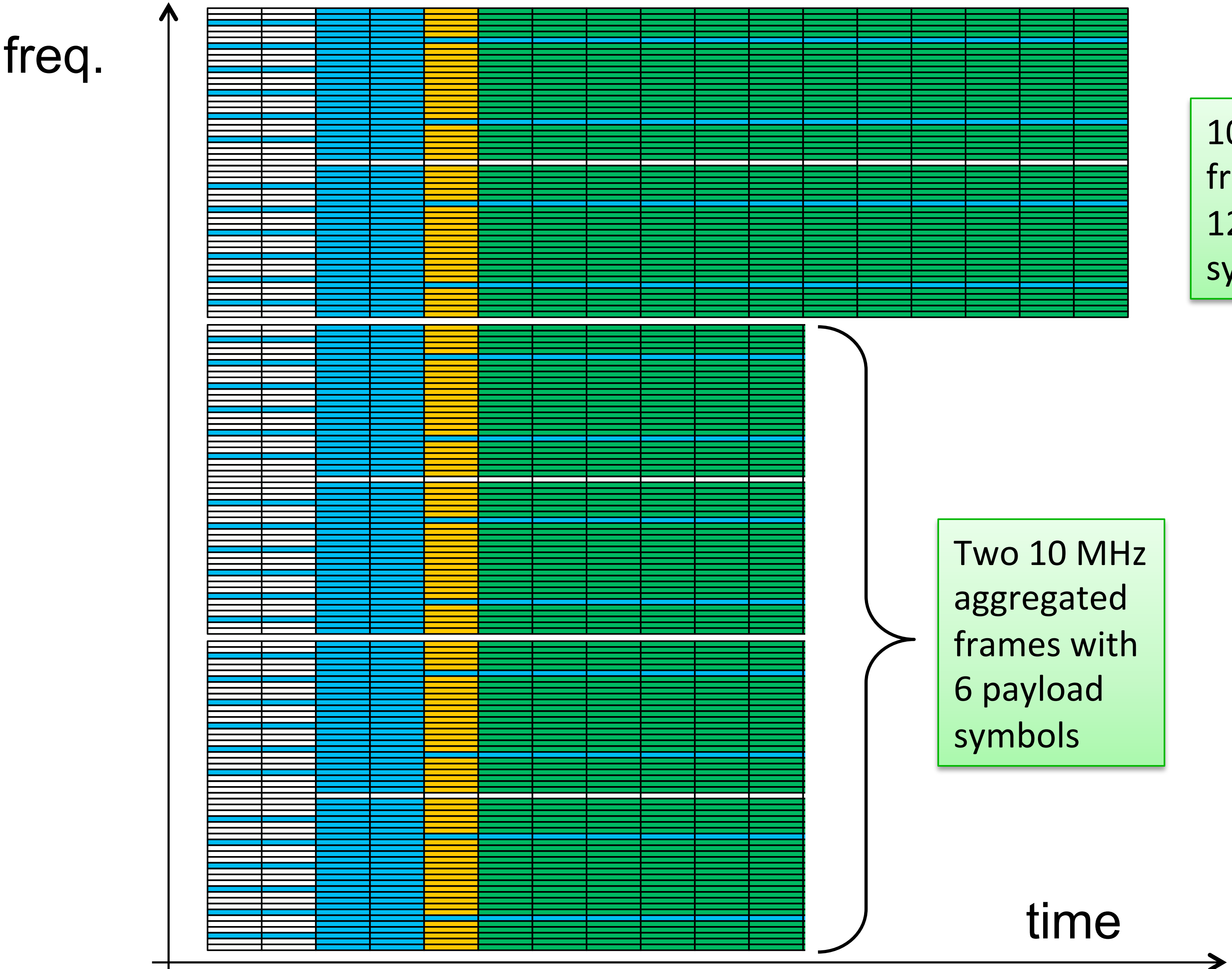


More frequency diversity → better high-SNR slope

Conclusions

- The current standards for V2V use 802.11p, which uses the 802.11 OFDM PHY (aka 802.11a) with 10 MHz channel spacing
- The literature ***usually*** reports V2V channel Doppler spread < 1000 Hz and RMS delay spread < 0.4 µs
- The 802.11 OFDM PHY can handle this for 5, 10, and 20 MHz channel spacing
- Change 10→20 MHz gives, for a TX power density constraint,
  - higher data rate for same MCS (lower congestion)
  - increased max range due to increased frequency diversity
- Bandwidth expansion is almost for free due to virtually unused channels next to the ITS-G5 control channel
- Transmitter energy consumption is not significantly effected even if TX power is doubled (energy per bit is constant)
- **Disclaimer**: if the delay spread is larger than 0.4 µs, the above conclusions need the be re-visited

Backup Slides

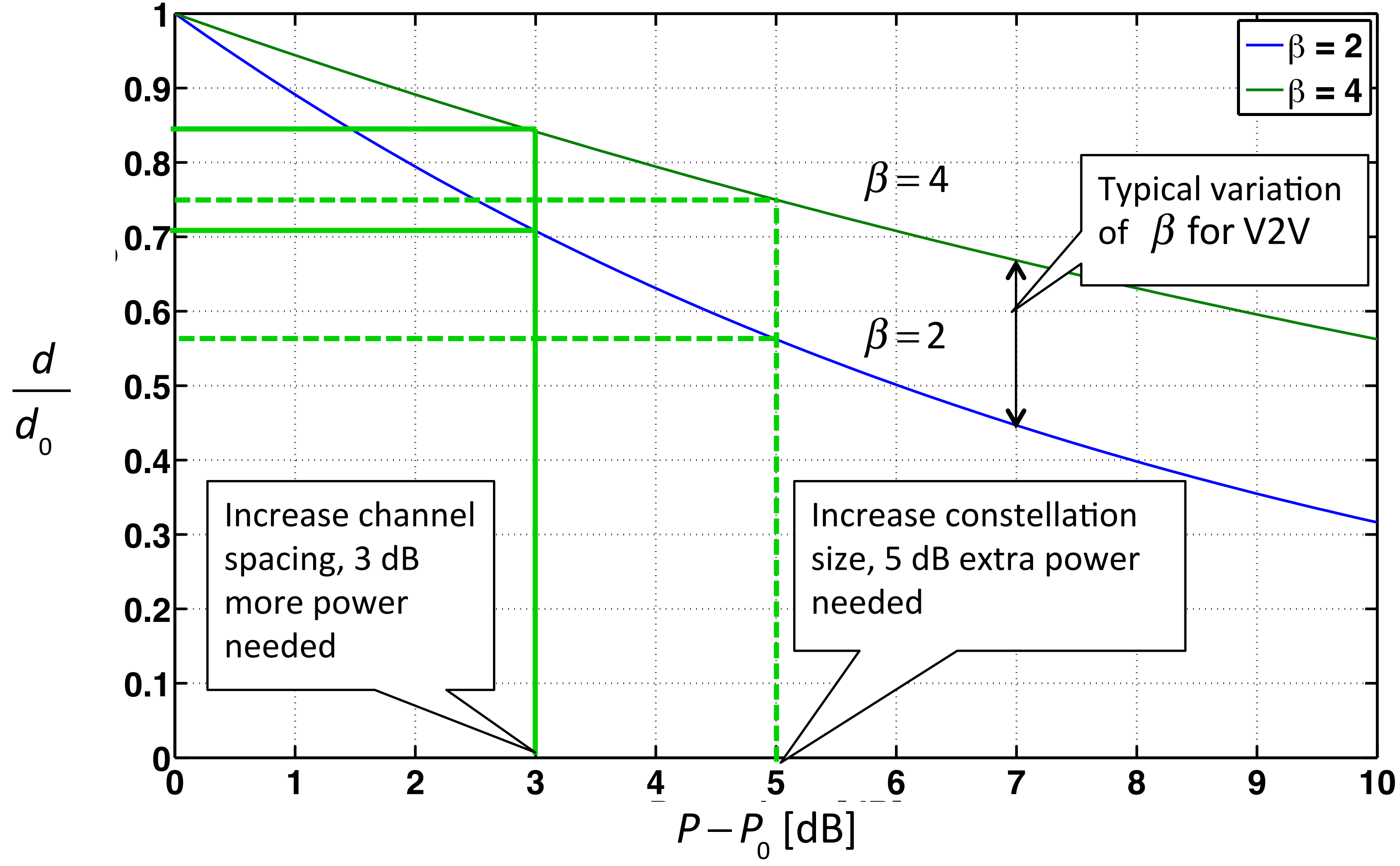


10 MHz frame
12 payload symbols

Two 10 MHz aggregated frames with 6 payload symbols

$$P = P_0 - 10\beta \log\left(\frac{d}{d_0}\right) \Rightarrow \frac{d}{d_0} = 10^{-(P-P_0)/10\beta}$$

Simple path-loss model, powers in dB-units
P_0 = power needed for 10 MHz, 6Mbit/s PHY for range d_0
P = power needed for other PHY mode
d = range for other PHY mode



Typical variation of β for V2V

Increase channel spacing, 3 dB more power needed

Increase constellation size, 5 dB extra power needed

10 → 20 MHz: First-Order TX Range Analysis

- A change from 10 to 20 MHz is done (in 802.11) by reducing all timing variables by a factor 2
  - rate variables are doubled (*x* = bit, symbol, frame, …)

$$T_x \to T_x/2 \Rightarrow R_x = 1/T_x \to 2R_x$$

- If the power density (dBm/MHz) is constant, then the power can double
  - all energies remain constant

$$\{T_x \to T_x/2, P \to 2P\} \Rightarrow E_x = PT_x = P/R_x \to E_x$$

  - range will not change due to reduced SNR

- If the power (dBm) is constant, then power is constant
  - all energies reduced with a factor of 2
  - range will be reduced due to reduced SNR

Other options to increase data rate

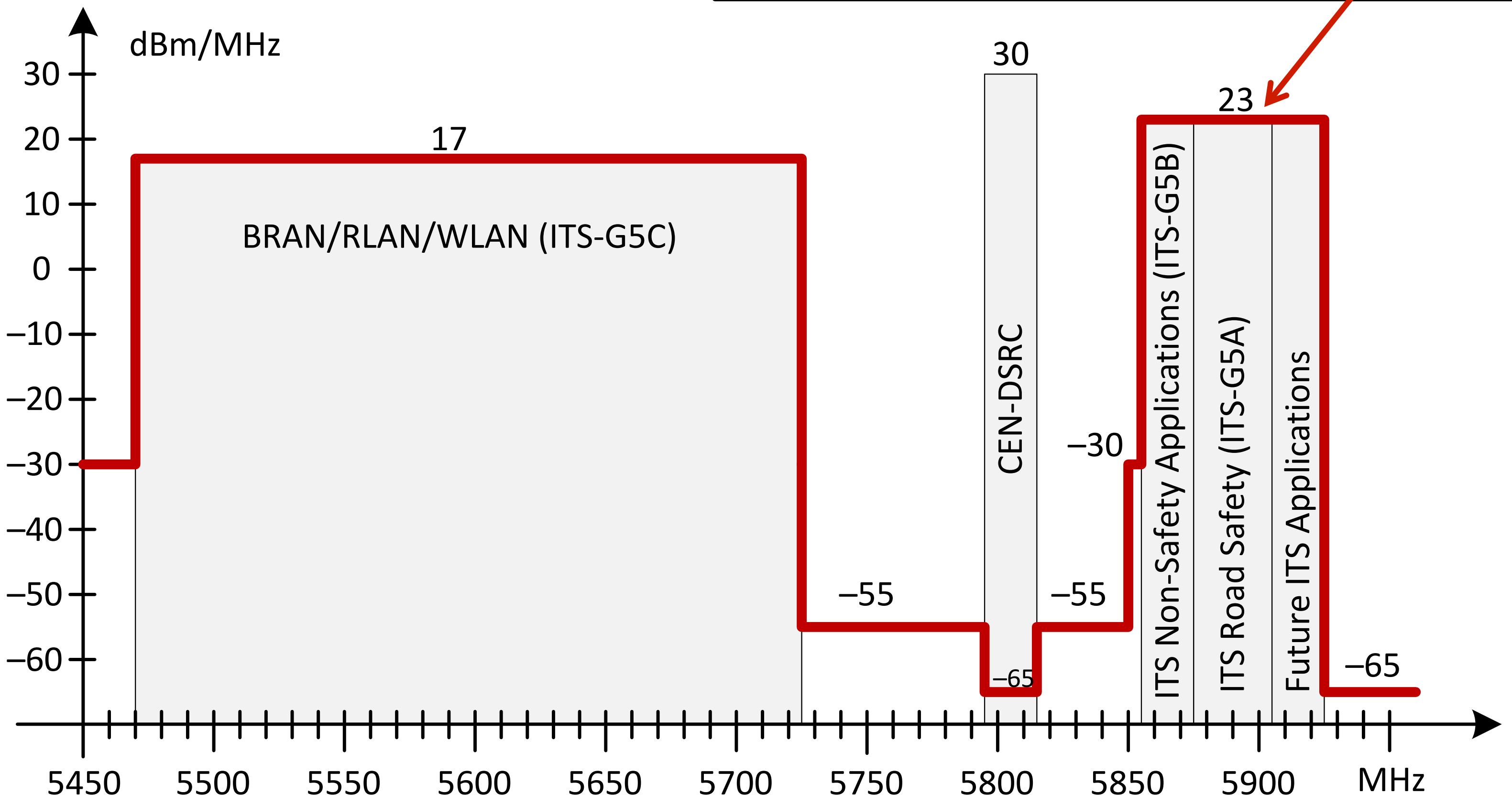
- Carrier aggregation as in 802.11n and 802.11ac
  - two 10 MHz channels are used by the same transmitter
  - data rate doubles, but cyclic prefix remain fixed → no loss in robustness towards delay spread
  - the overhead in time does not change → packet duration is not exactly halved

Questions/Discussion

- US spectrum allocation, latest news?
  - Feedback on TX power discussion (power density vs power contraints)
- What is the current thinking about
  - DCC
  - BSM (number of bytes, content, rates)
  - Channel switching
- Any discussion on 10→20 MHz or carrier aggregation (carrier bonding)?
- What will be the impact on MAC layer by increasing PHY layer transmission rate?
- How can we work together?

ITS Spectrum Allocation in Europe

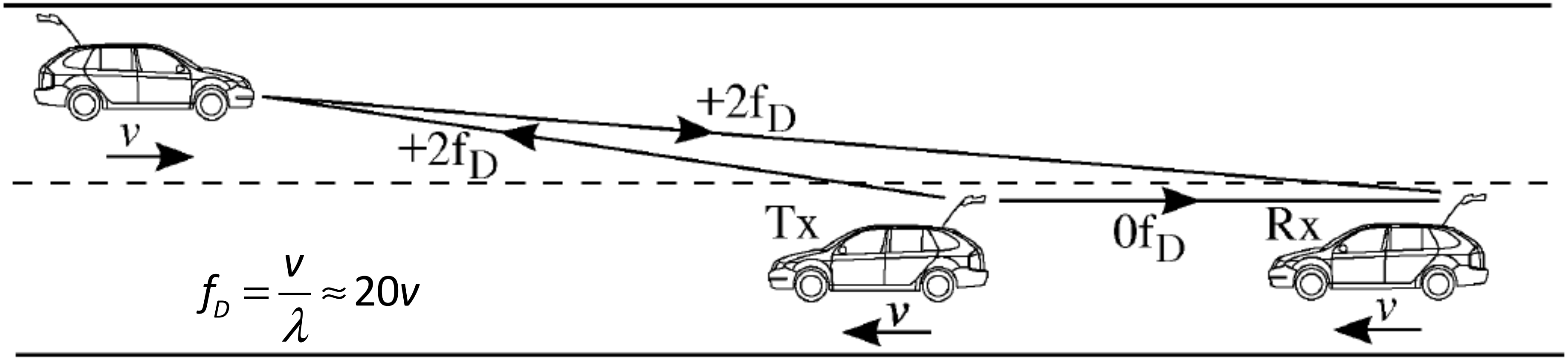
ITS-G5A: 30 MHz dedicated to traffic safety



ETSI ES 202 663 (V1.1.0): “Intelligent Transport Systems (ITS); European profile standard for the physical and medium access control layer of Intelligent Transport Systems operating in the 5 GHz frequency band”

Doppler Phenomena

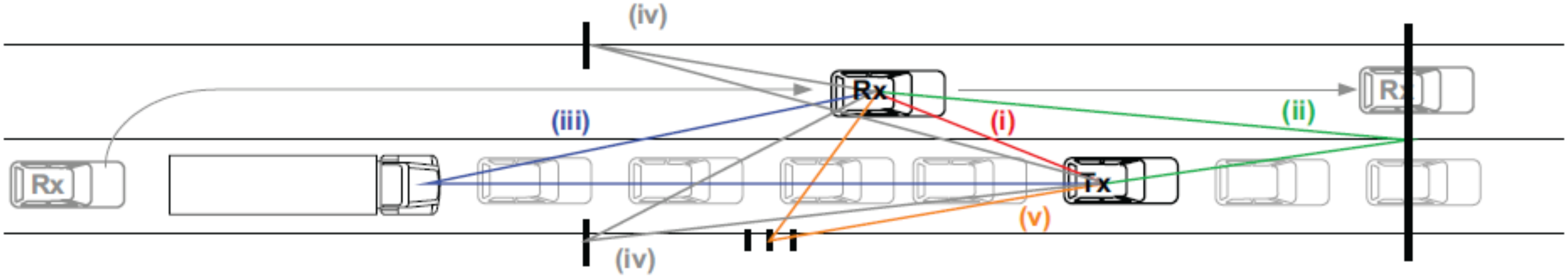
- Relatively large Doppler due to
  - high carrier frequency
  - mobility of both TX and RX
  - possible interaction with moving scatters

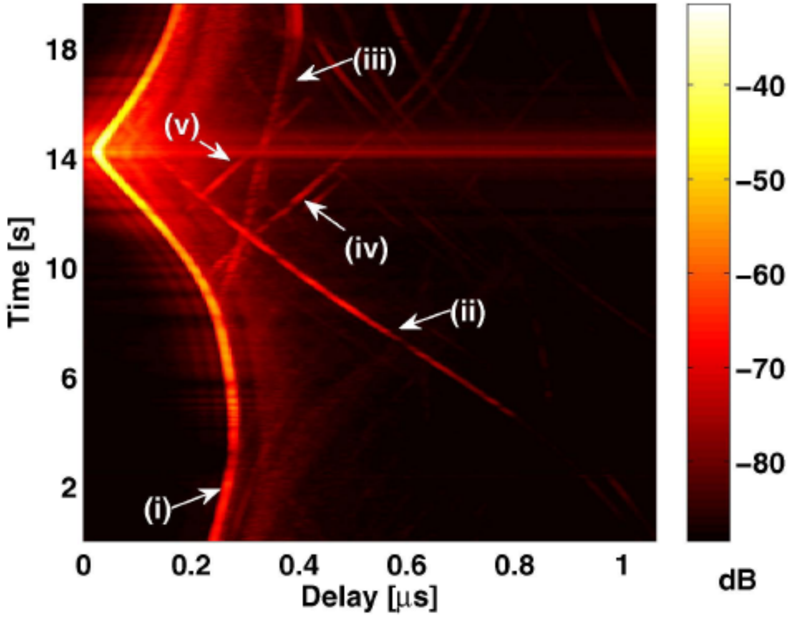


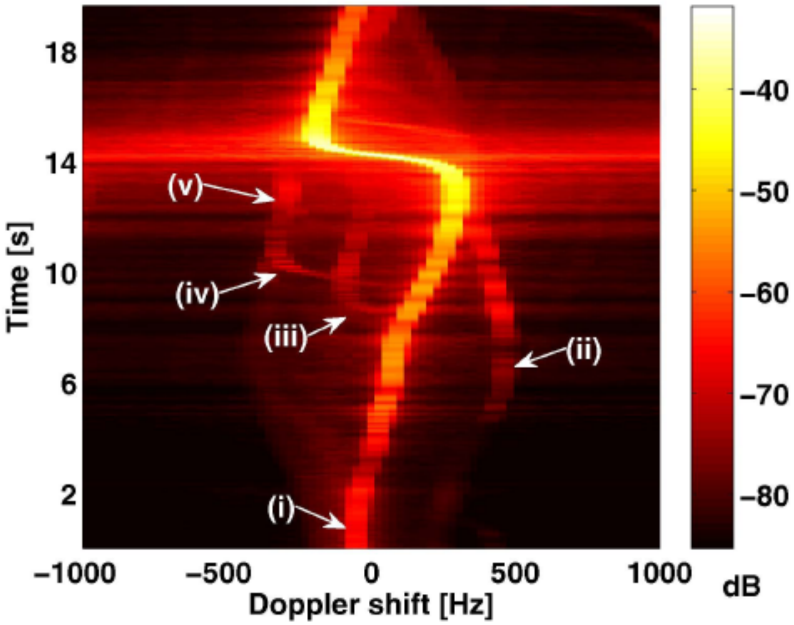
$$f_D = \frac{v}{\lambda} \approx 20v$$

Mecklenbräuker, et al., ”Vehicular channel characterization and its implication for wireless systems design and performance,” Proc. of the IEEE, July 2011

Delay-Doppler Characterization



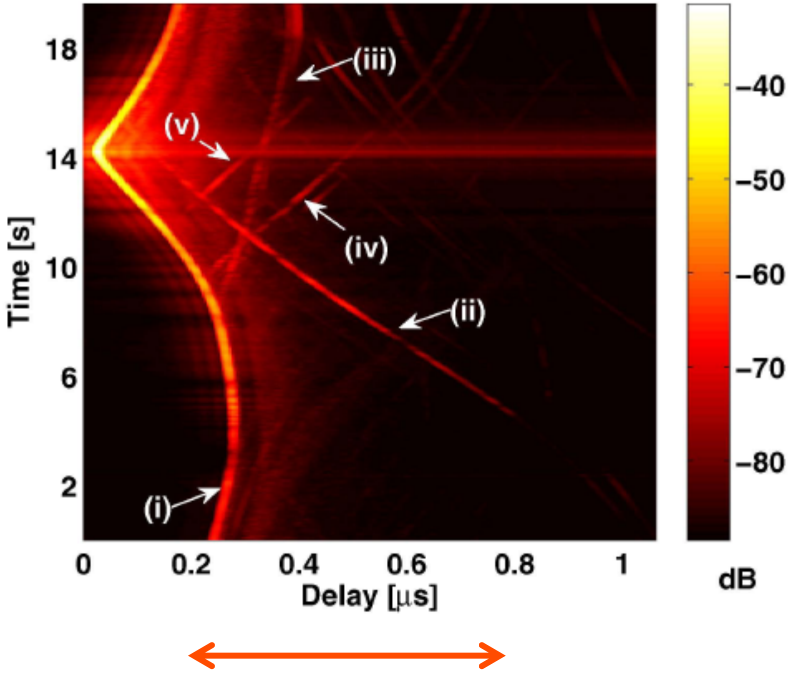


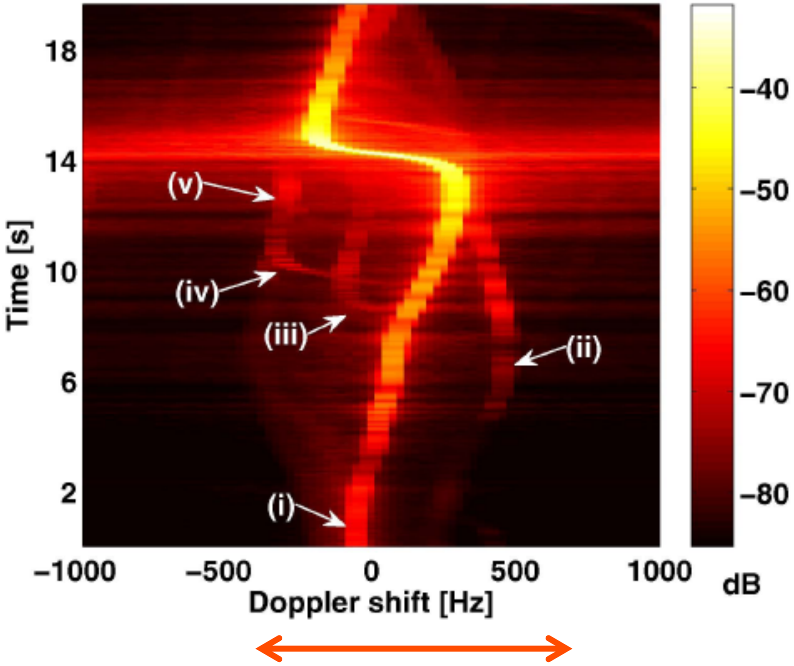


delay spread

Doppler spread

Delay-Doppler Characterization





delay spread → frequency variations

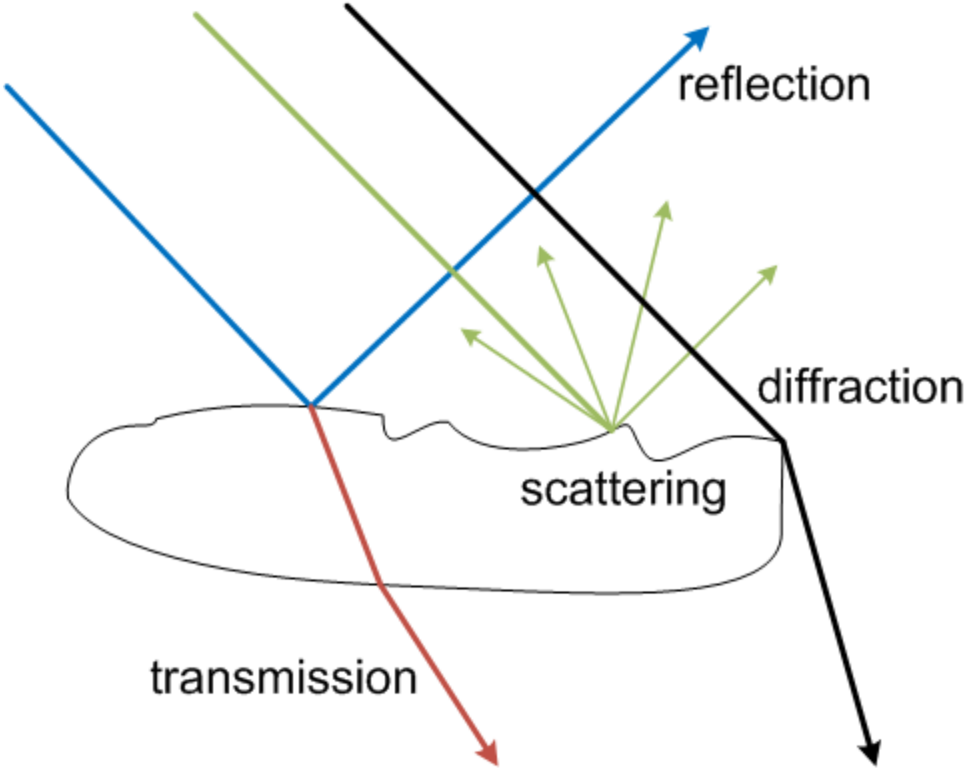
Doppler spread → time variations

RMS delay spread: σ_{T_m} [s]

Doppler spread: B_D [Hz]

A. Paier, et al., "Overview of vehicle-to-vehicle radio channel measurements for collision avoidance applications," VTC Spring, May 2010

Propagation at 6 GHz



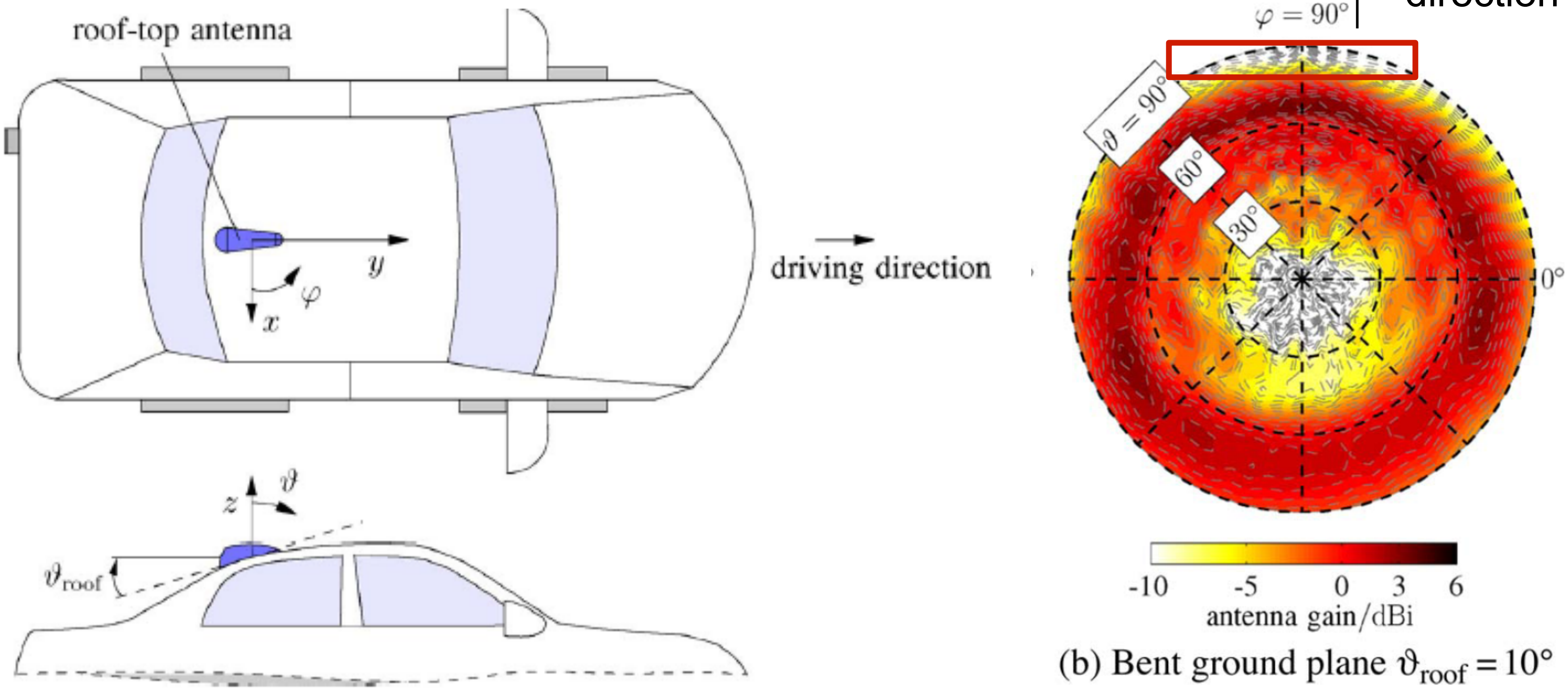
- **Reflection** on smooth surfaces
- **Transmission** through objects
- **Scattering** on rough surfaces
- **Diffraction** around sharp edges
- Smooth/rough, large/small are relative the wavelength
- 6 GHz corresponds to the wavelength

$$\lambda = \frac{c}{f_c} \approx \frac{3\times10^8}{6\times10^9} = 5\text{ cm}$$

We should expect little diffraction → NLOS problematic

Vehicular Antennas

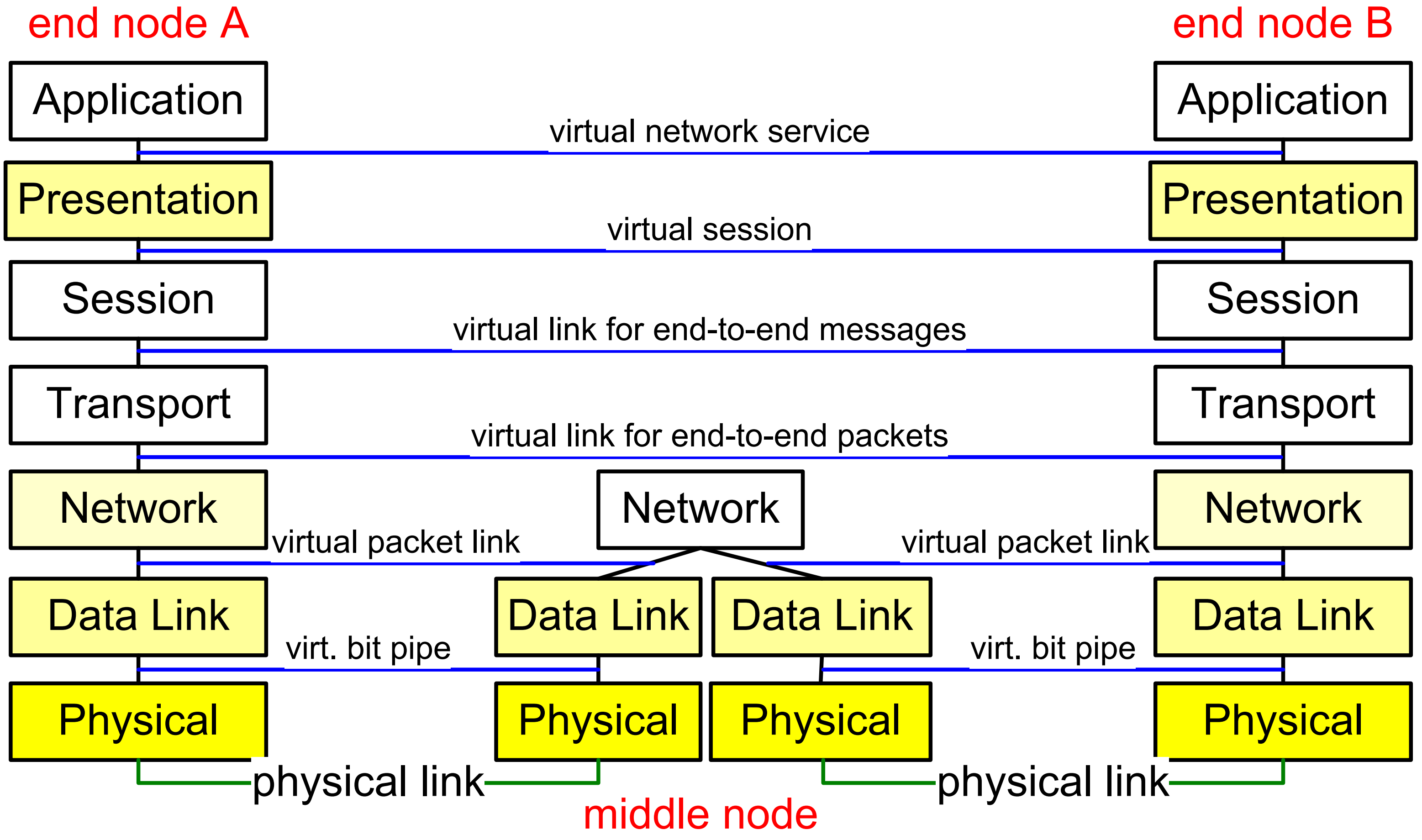
- Typically placed a low heights → significant shadowing can be expected
- Antenna placement constraints (design, cable problems, harsh physical environments, cost) will constrain radiation patterns



(b) Bent ground plane $\vartheta_{\mathrm{roof}} = 10°$

driving direction

OSI Layer Model



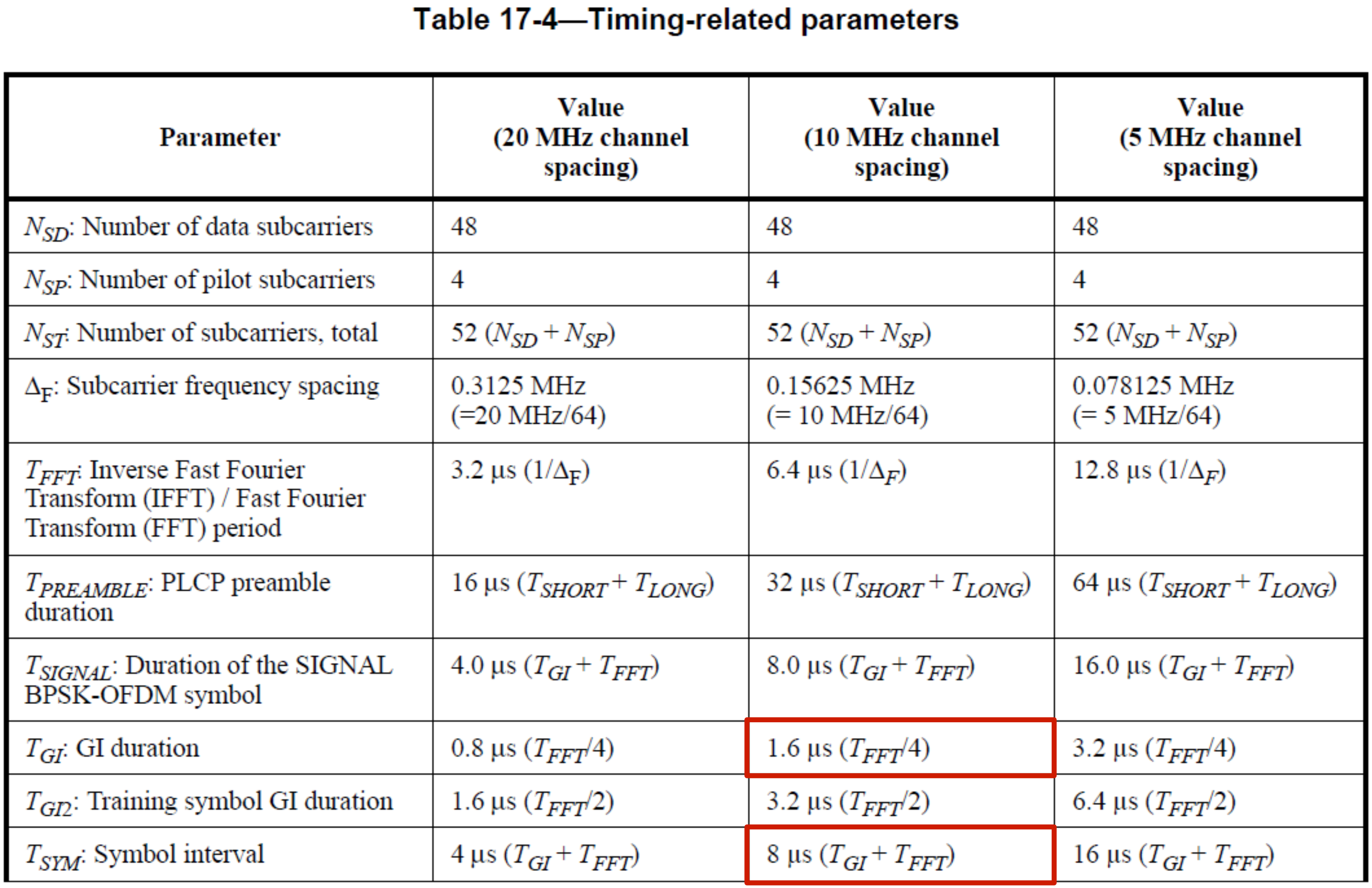
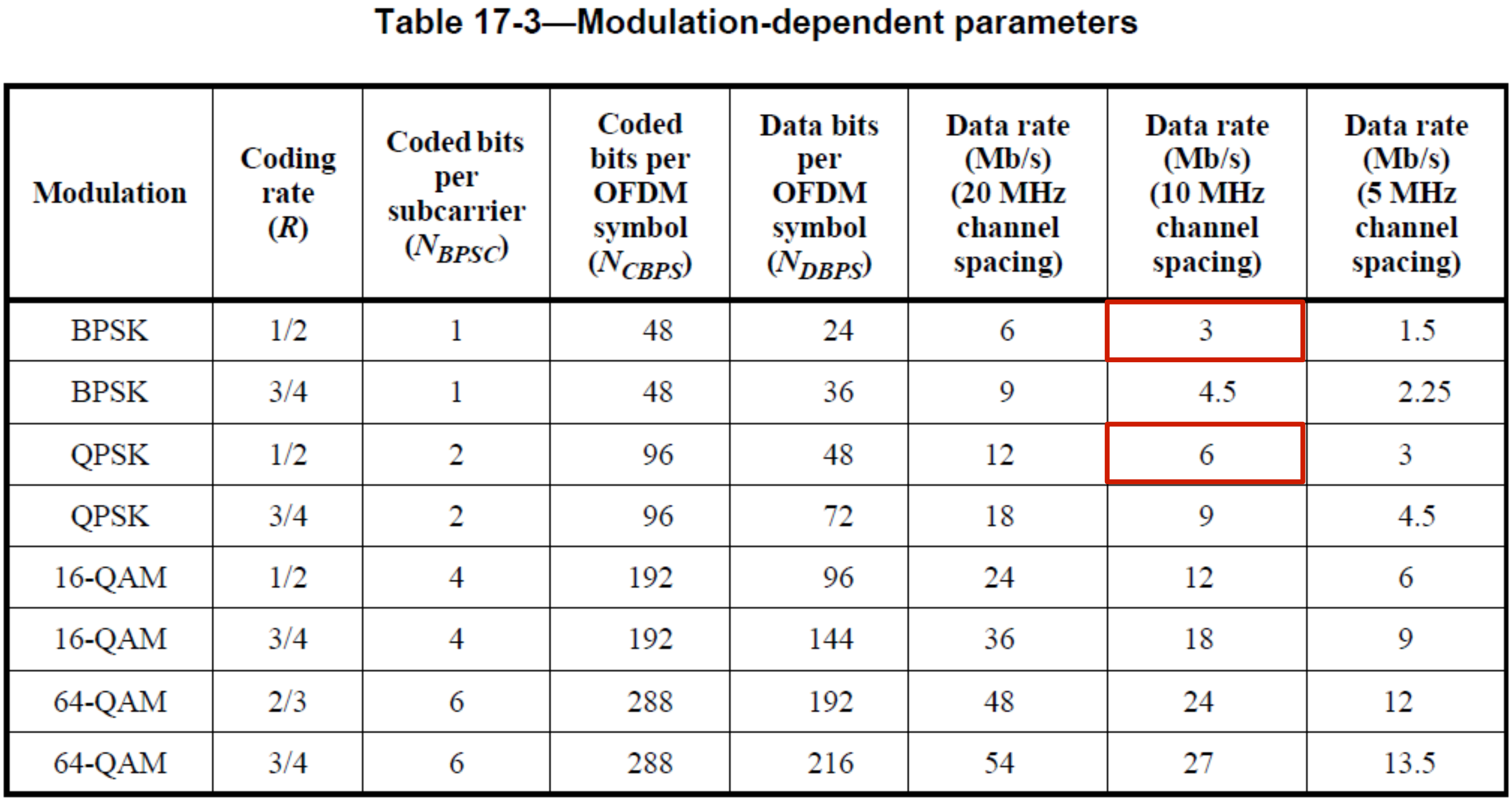


Table 17-4—Timing-related parameters

Parameter	Value (20 MHz channel spacing)	Value (10 MHz channel spacing)	Value (5 MHz channel spacing)
N_{SD}: Number of data subcarriers	48	48	48
N_{SP}: Number of pilot subcarriers	4	4	4
N_{ST}: Number of subcarriers, total	52 ($N_{SD} + N_{SP}$)	52 ($N_{SD} + N_{SP}$)	52 ($N_{SD} + N_{SP}$)
Δ_F: Subcarrier frequency spacing	0.3125 MHz (=20 MHz/64)	0.15625 MHz (= 10 MHz/64)	0.078125 MHz (= 5 MHz/64)
T_{FFT}: Inverse Fast Fourier Transform (IFFT) / Fast Fourier Transform (FFT) period	3.2 μs ($1/\Delta_F$)	6.4 μs ($1/\Delta_F$)	12.8 μs ($1/\Delta_F$)
$T_{PREAMBLE}$: PLCP preamble duration	16 μs ($T_{SHORT} + T_{LONG}$)	32 μs ($T_{SHORT} + T_{LONG}$)	64 μs ($T_{SHORT} + T_{LONG}$)
T_{SIGNAL}: Duration of the SIGNAL BPSK-OFDM symbol	4.0 μs ($T_{GI} + T_{FFT}$)	8.0 μs ($T_{GI} + T_{FFT}$)	16.0 μs ($T_{GI} + T_{FFT}$)
T_{GI}: GI duration	0.8 μs ($T_{FFT}/4$)	1.6 μs ($T_{FFT}/4$)	3.2 μs ($T_{FFT}/4$)
T_{GI2}: Training symbol GI duration	1.6 μs ($T_{FFT}/2$)	3.2 μs ($T_{FFT}/2$)	6.4 μs ($T_{FFT}/2$)
T_{SYM}: Symbol interval	4 μs ($T_{GI} + T_{FFT}$)	8 μs ($T_{GI} + T_{FFT}$)	16 μs ($T_{GI} + T_{FFT}$)

IEEE Standard 802.11-2007: Telecommunications and information exchange between systems– Local and metropolitan area networks– Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.



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BPSK	3/4	1	48	36	9	4.5	2.25
QPSK	1/2	2	96	48	12	6	3
QPSK	3/4	2	96	72	18	9	4.5
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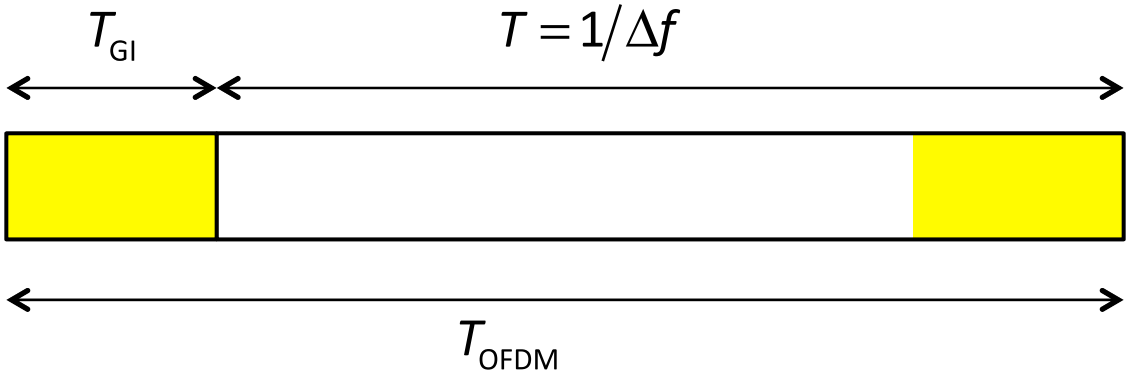
IEEE Standard 802.11-2007: Telecommunications and information exchange between systems–Local and metropolitan area networks– Specific requirements–Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications.

OFDM Design Rules (with details)



- Consider a WSS-US channel with coherence time T_c, coherence bandwidth B_c , maximum delay spread T_m, and RMS delay spread σ_{T_m}
- **Rule 1:** to avoid intercarrier interference (ICI)

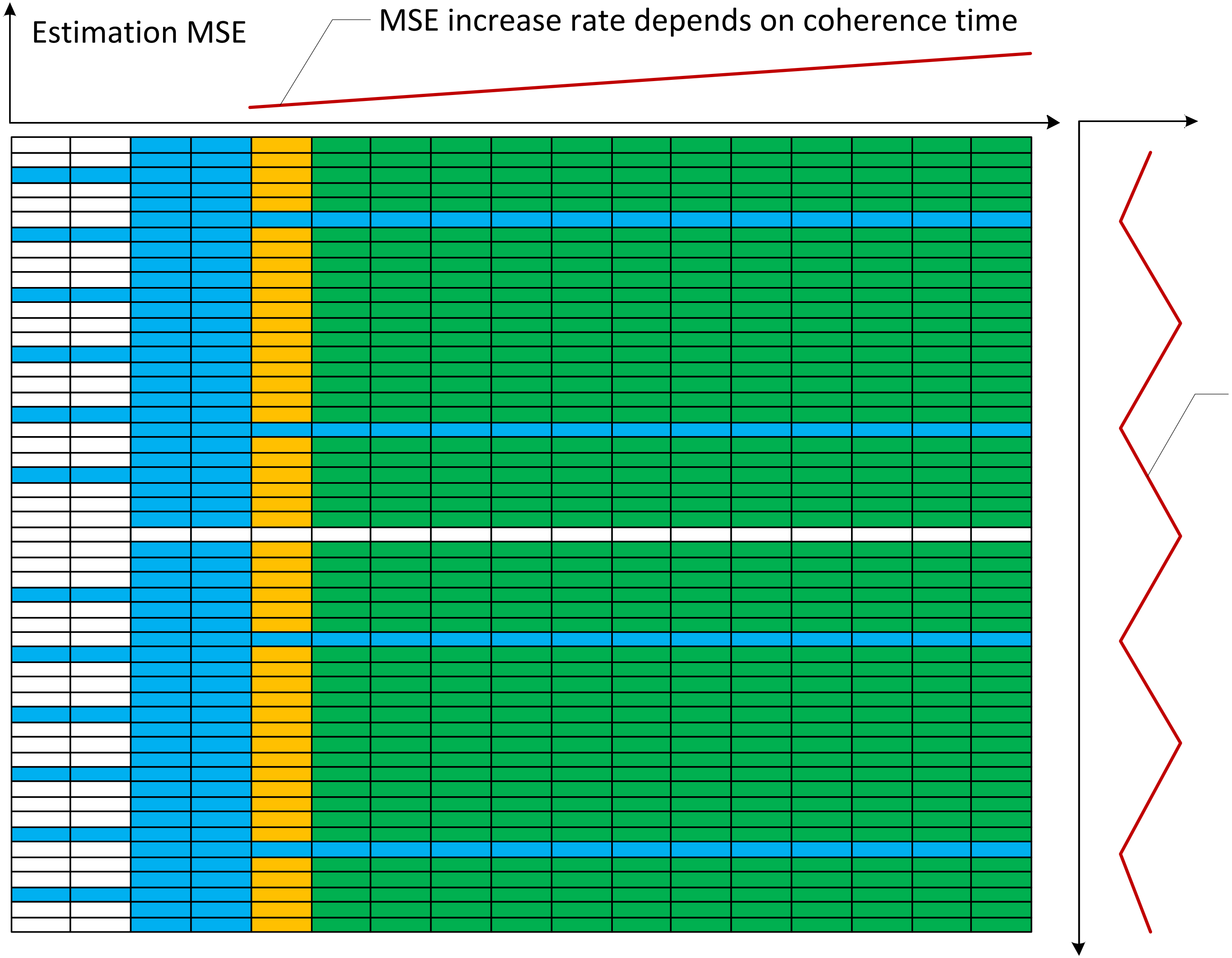
$$\boxed{\frac{T_{\mathrm{OFDM}}}{T_c} \ll 1} \quad \Leftrightarrow \quad B_D T_{\mathrm{OFDM}} \ll 1 \text{ (if } T_c = 1/B_D\text{)} \quad \Leftrightarrow \quad \frac{B_D}{\Delta f} \ll 1 \text{ (valid if } T_{\mathrm{CP}} \ll T\text{)}$$

- **Rule 2:** to avoid intersymbol interference (ISI) and ICI

$$\boxed{\frac{T_{\mathrm{GI}}}{T_m} > 1} \quad \Leftrightarrow \quad \frac{T_{\mathrm{GI}}}{\sigma_{T_m}} > 1 \text{ (less conservative)} \Leftrightarrow B_c T_{\mathrm{GI}} > 1 \text{ (valid if } B_c = 1/\sigma_{T_m}\text{)}$$

Pilot-Aided Channel Estimation

- For a pilot-symbol based system, we need to set the time and frequency spacing according to the coherence time and coherence bandwidth
- V2V channel: coherence time > 1 ms, coherence bandwidh > 2.5 MHz
- Hence, max pilot spacing in time is less than
  1 ms = 16 OFDM symbols (10 MHz) = 32 OFMD symbols (20 MHz)
- Hence, max pilot spacing in frequency is less than
  2.5 MHz = 16 subcarriers (10 MHz) = 8 subcarriers (20 MHz)
- Since the pilot spacing in frequency is 14 subcarriers, we could encounter problems in 20-MHz system using a simple pilot-based channel estimation scheme



MSE increase rate depends on coherence time

MSE increase rate depends on coherence bandwidth

Advanced Channel Estimation

- For WLAN channels, it usually enough to estimate the channel based only on the block pilots, but this will not suffice for V2V channels due to the much shorter coherence time
- Standard Wi-Fi chips might therefore not perform well in V2V applications
- More advanced channel estimation, e.g., iterative decision-feedback algorithms might be necessary
- Another (standard-breaking) approach would be to distribute the pilots in a more intelligent way

Interference

- Interference occurs due to
  - spectrum reuse: default data rate, 6 Mbit/s, is much less than the aggregated system data rate
  - imperfection in the MAC: 802.11 MAC will sometimes allow close-by transmitters access to the channel as the same time
  - adjacent channel interference (loose spectrum masks)
- Approaches for interference mitigation
  - rate and power control
  - 20 MHz channels gives higher data rates (.11p-breaking?)
  - enhanced MAC (standard-breaking)
  - MIMO for interference rejection, diversity reception (.11p-breaking?)
  - Multiuser detection