The IEEE 802.11 family of standards

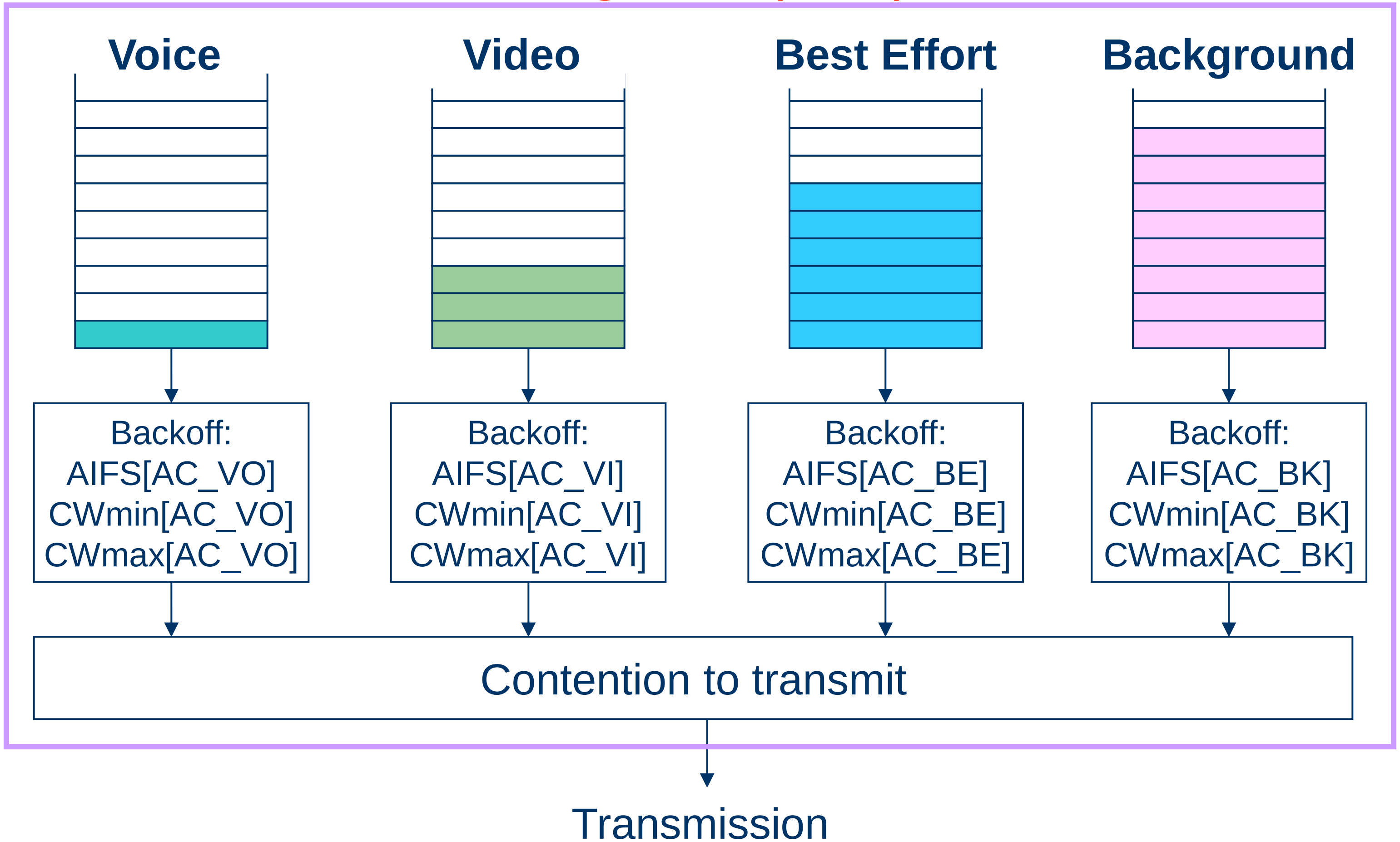
continued

Extensions introduced by 802.11e

- AP is called Hybrid Coordinator (HC) implementing Hybrid Coordination Function (HCF) that includes two modes of operation:
- EDCA (Enhanced Distributed Coordination Access): Different traffic classes in DCF with different behavior and medium access probabilities
- HCCA (HCF Control Channel Access): Improving weaknesses of PCF (beacon transmission, controlled reservation time, queue size information)

EDCA
(Enhanced Distributed Coordination Access)

- CSMA/CA and Exponential Backoff
- Four Access Categories (ACs) within one station



EDCA
(Enhanced Distributed Coordination Access)

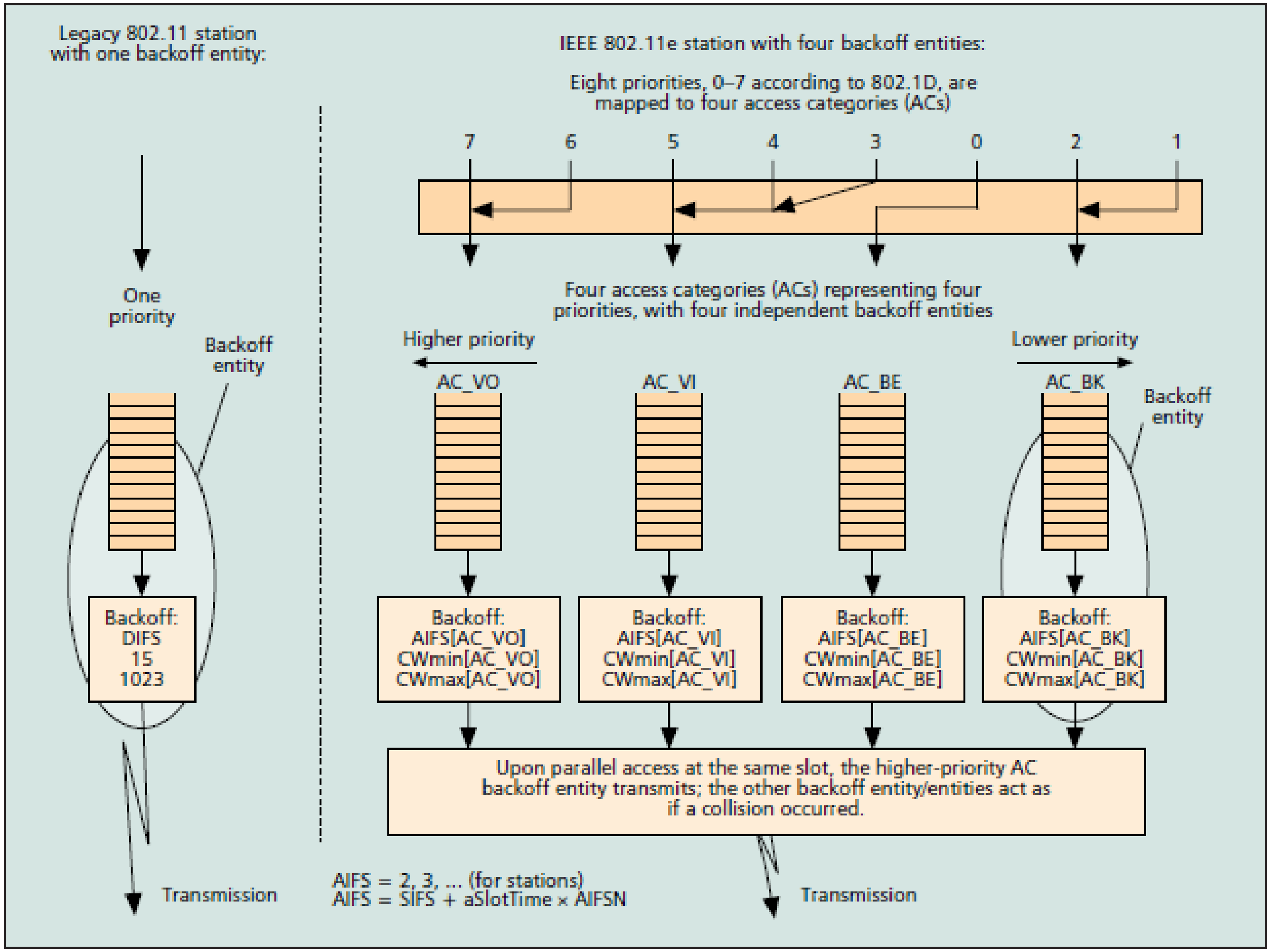
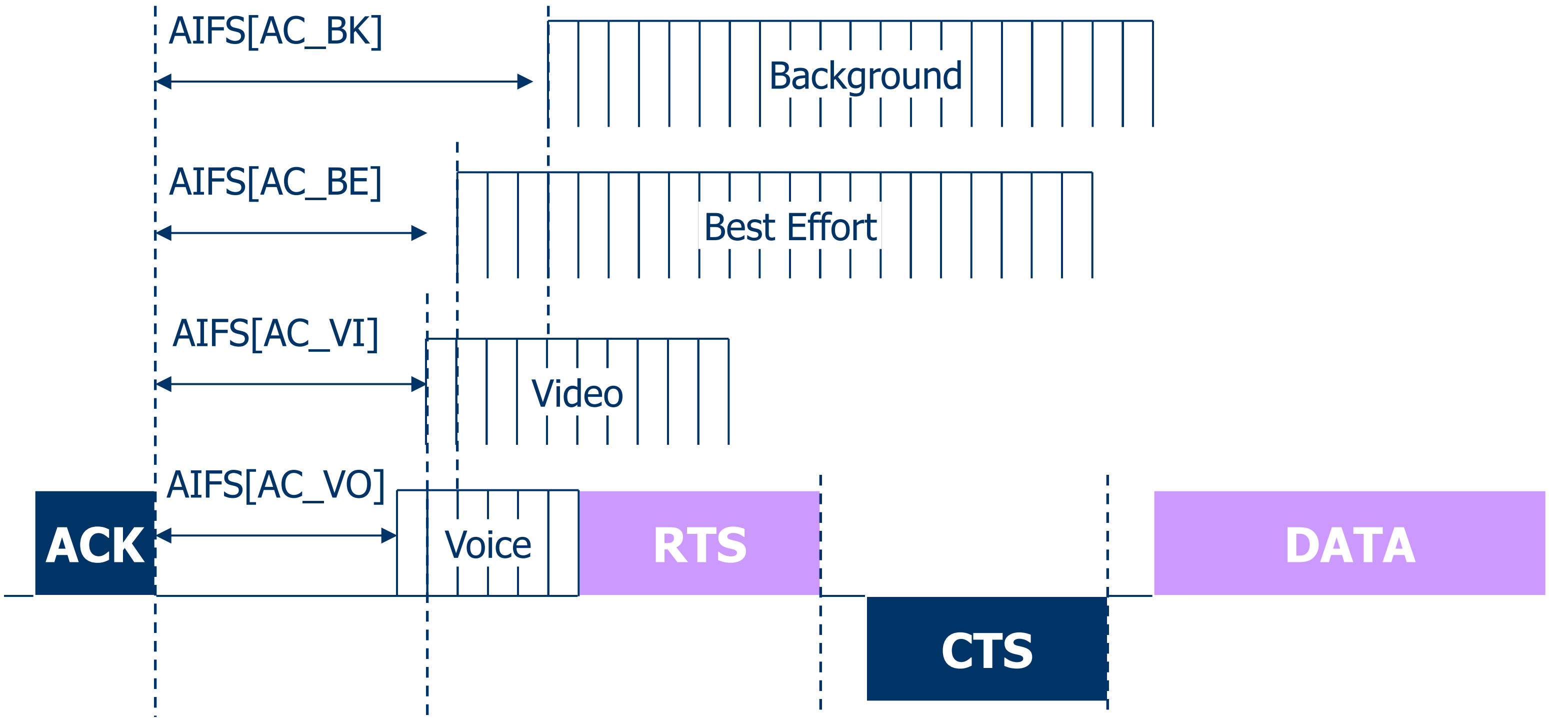
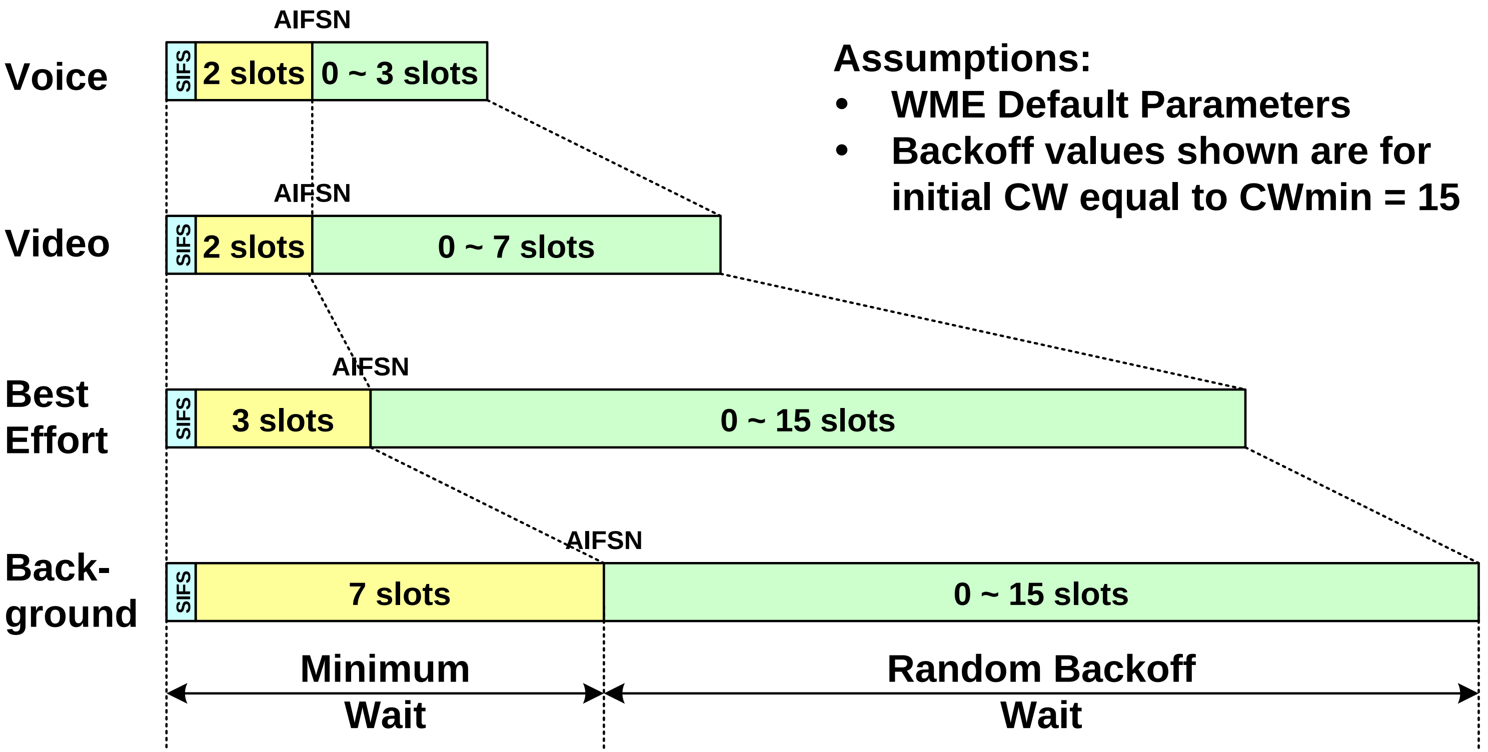


Figure 4. *[3] Legacy 802.11 station and 802.11e station with four ACs within one station.*

Inter Frame Space και Contention Window



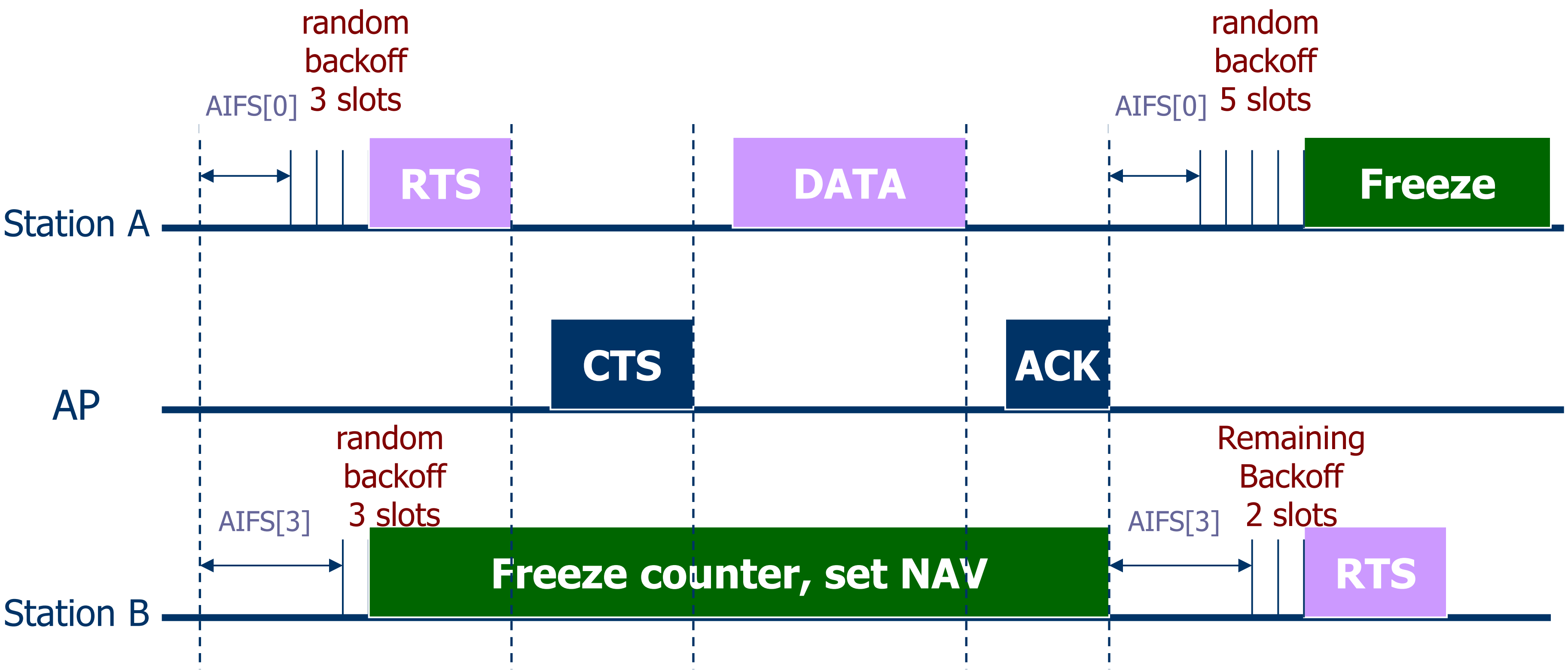
Inter Frame Space και Contention Window



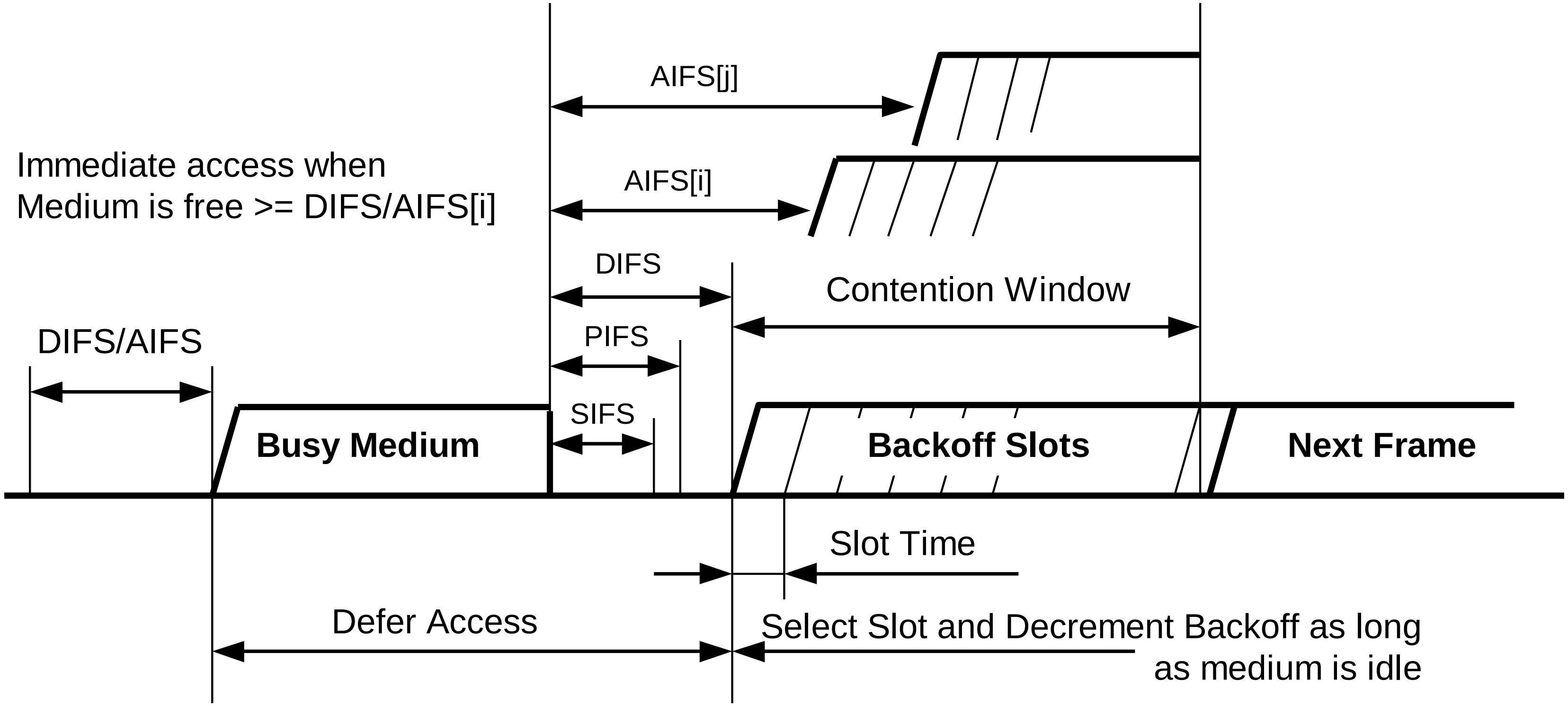
Assumptions:

- **WME Default Parameters**
- **Backoff values shown are for initial CW equal to CWmin = 15**

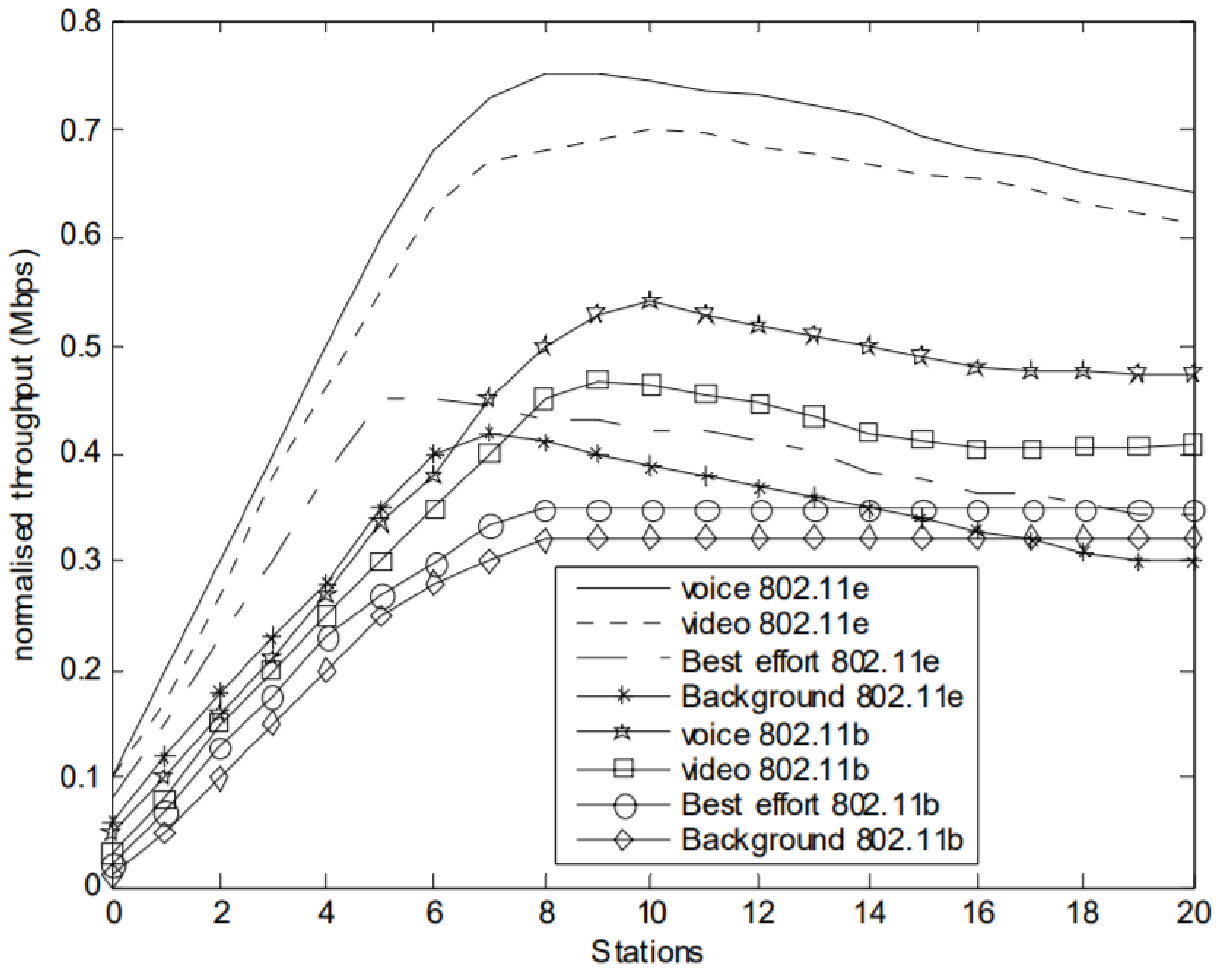
Contention in EDCA



Contention in EDCA



EDCA performance



Transmission Opportunity (TXOP)

- A TXOP is defined by a starting time and a maximum duration.
- Two types of TXOP: *EDCA TXOP* and *Polled TXOP*.
  - An EDCF TXOP begins when the wireless medium is determined to be available under the EDCA rules, and the length of TXOP is specified in beacon frames.
  - An Polled TXOP begins when a QSTA receives a QoS(+)CF-Poll from HC, and the length of TXOP is specified in the QoS(+)CF-Poll.

HCF Controlled Access – Introduction

- Differences between hybrid coordinator (HC) and point coordinator (PC):
  - HC can poll QSTAs in both CP and CFP
  - HC grants a polled TXOP to one QSTA, which restricts the duration of the QSTA's access to the medium.

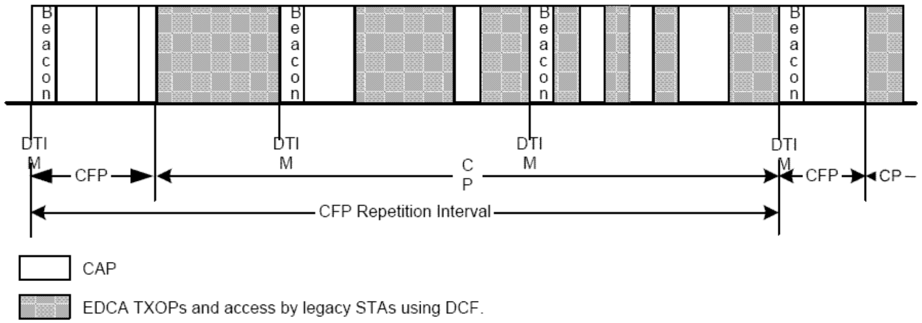
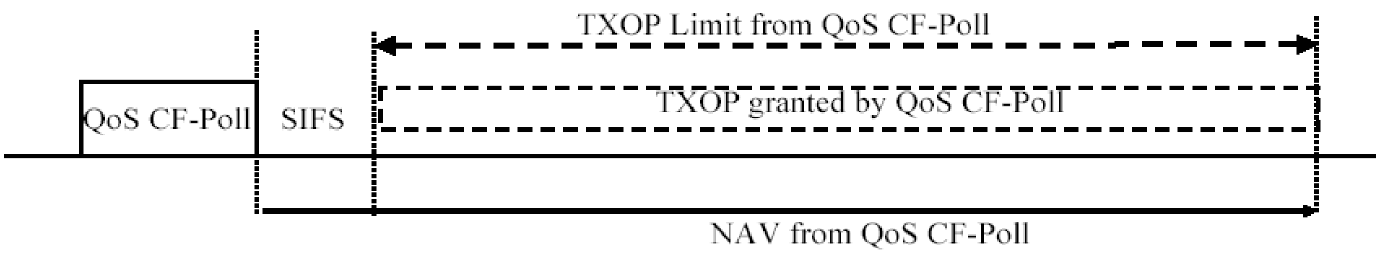
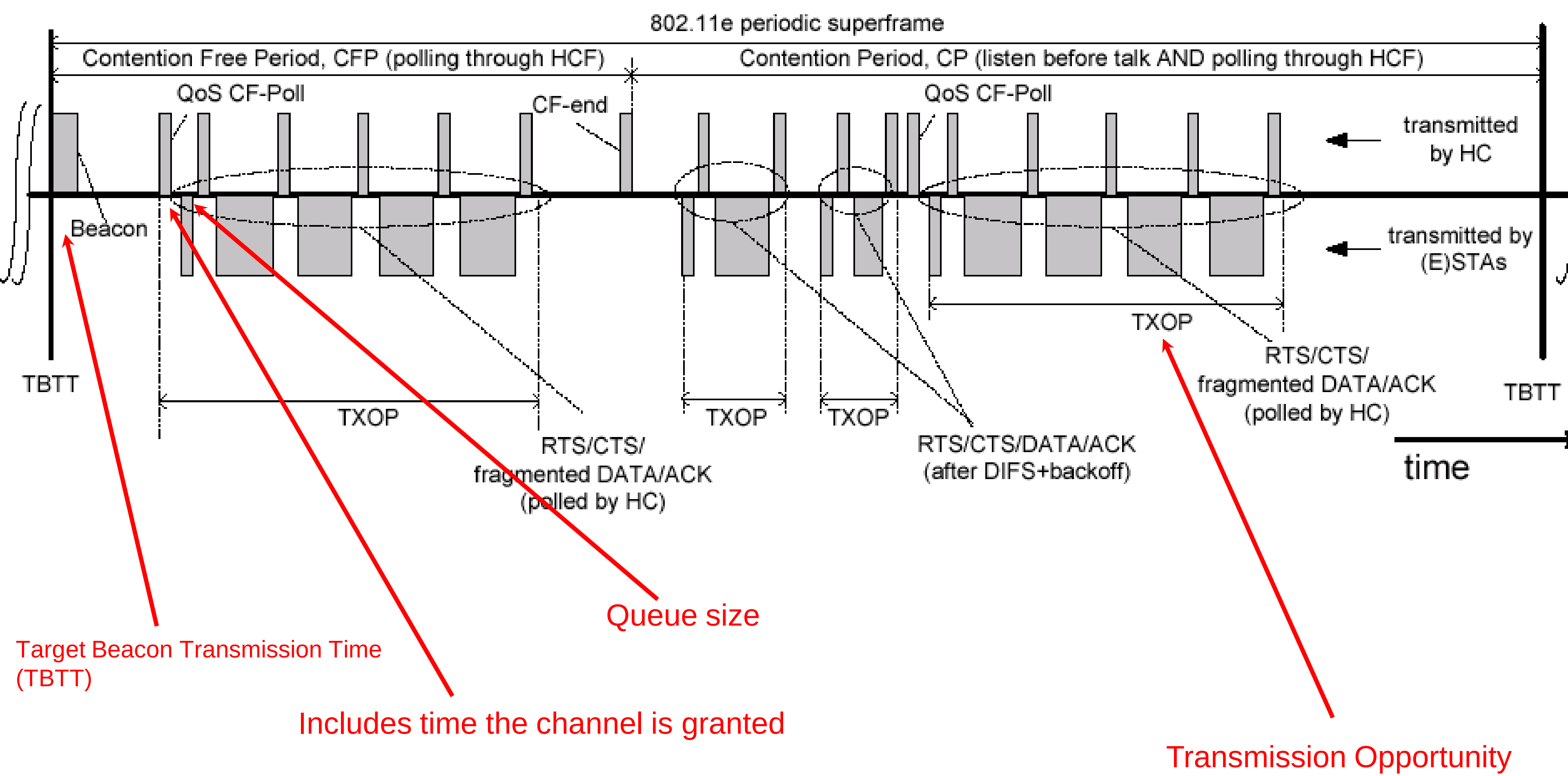


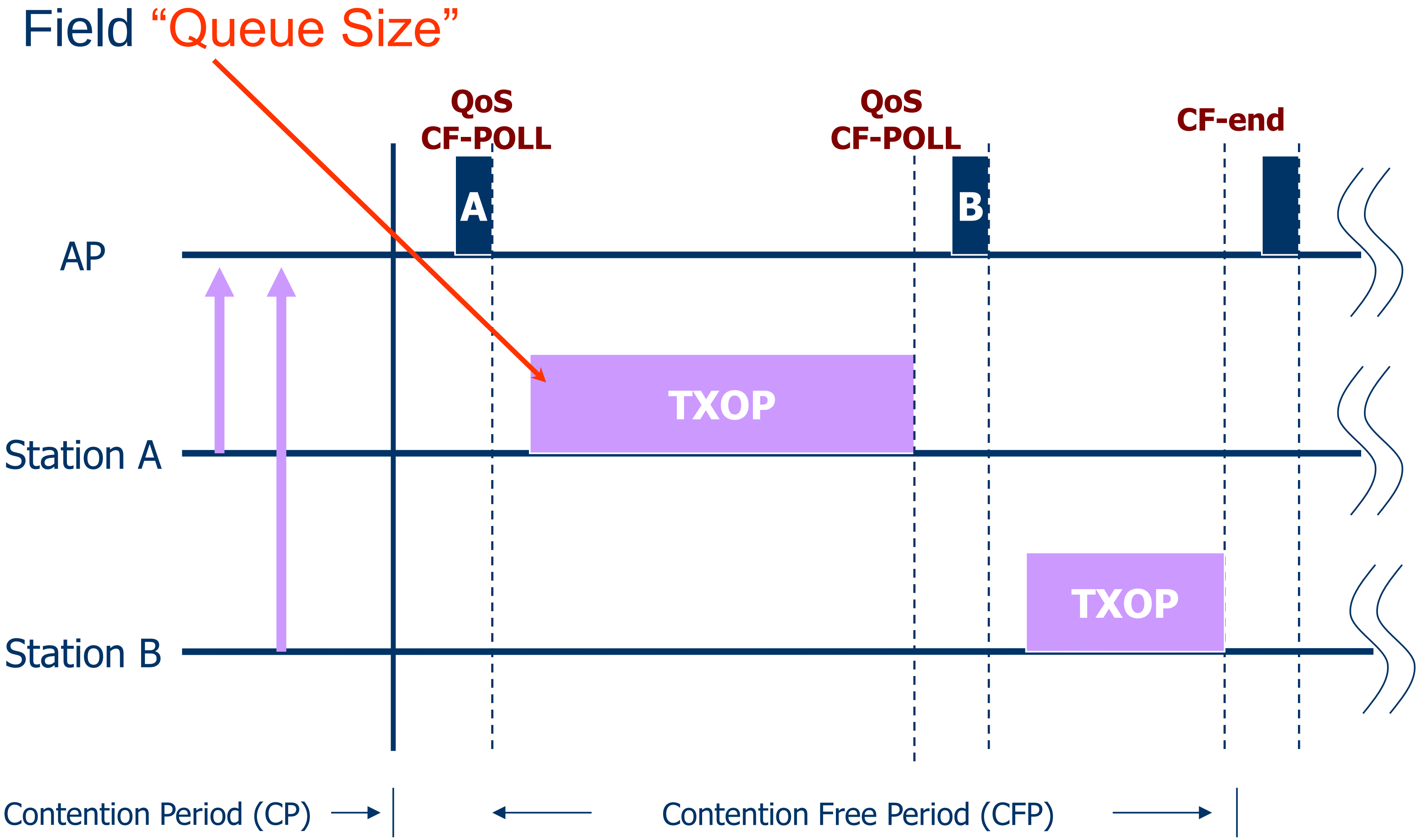
Figure 62c—CAP/CFP/CP periods



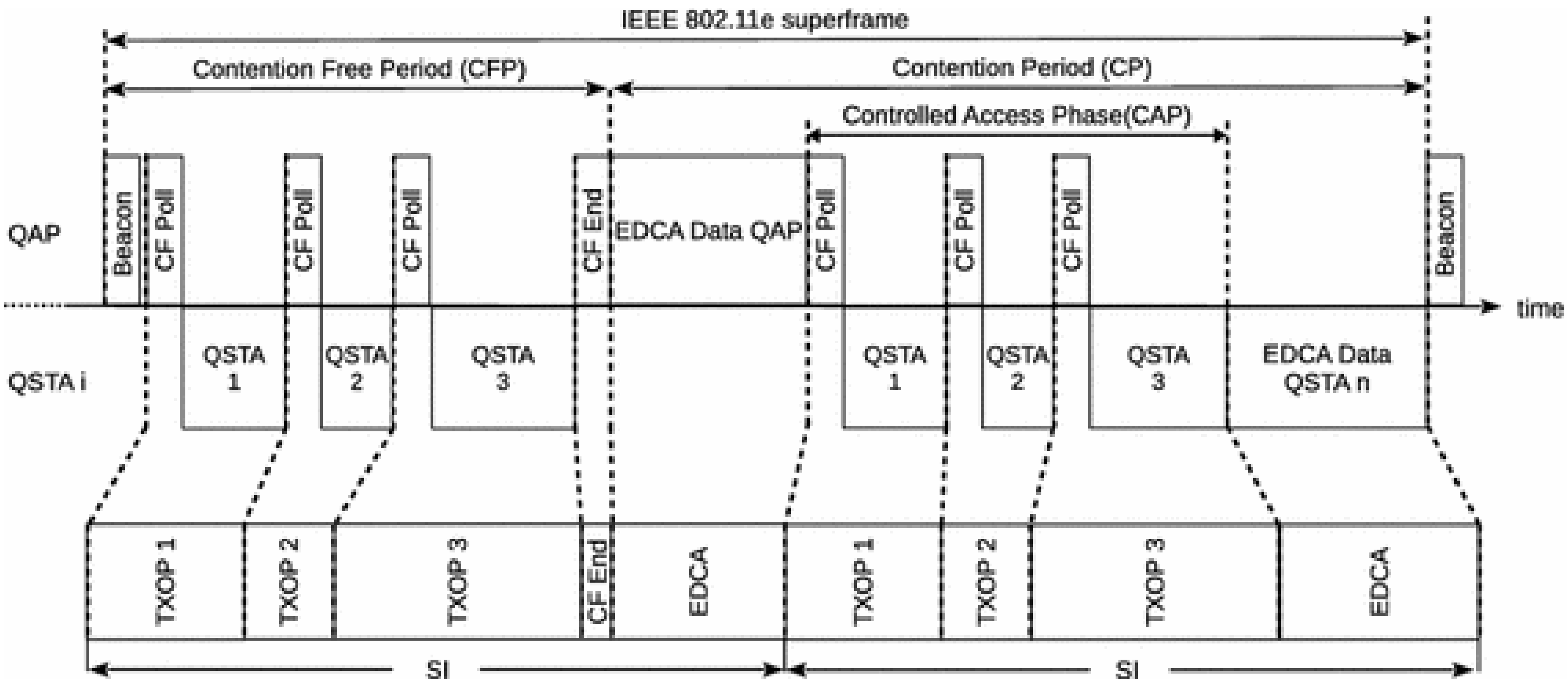
HCCA
(HCF Control Channel Access)



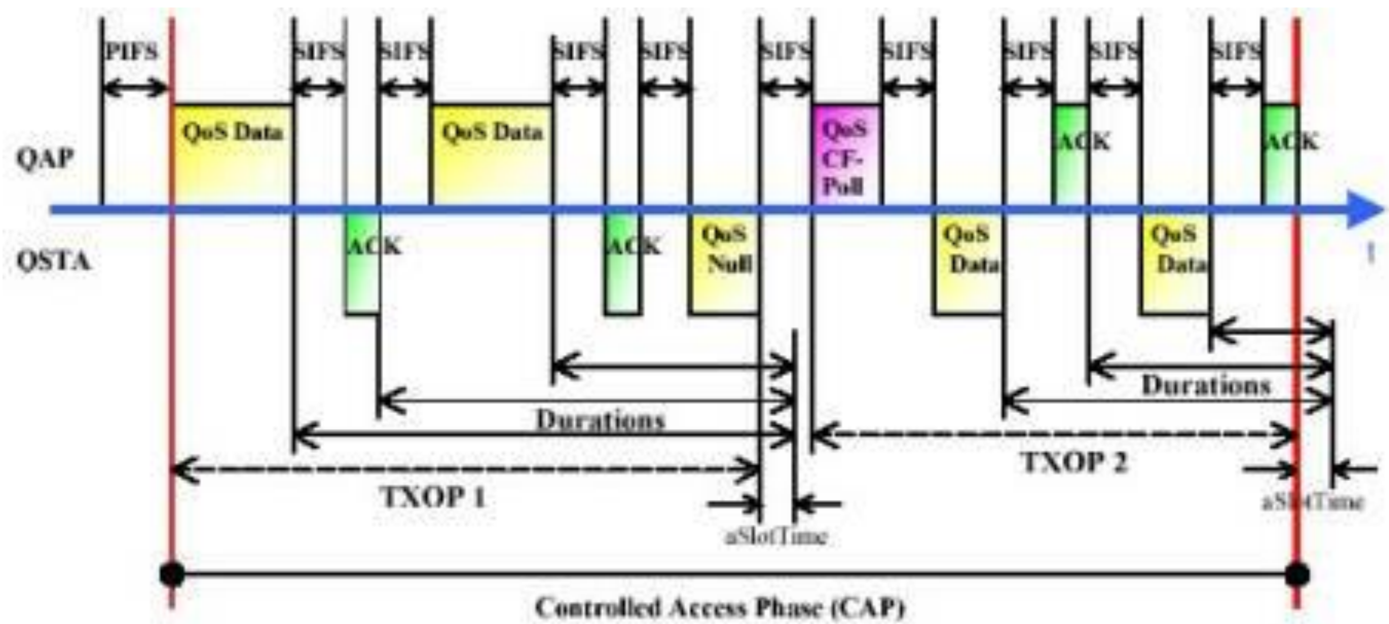
Reservation with HCCA



Reservation with HCCA



Reservation with HCCA



QoS CF-Poll	Transmitted by QAP to grant a HCCA-TXOP, no data.
QoS-Data+CF-Poll	Transmitted by QAP to grant a HCCA-TXOP, with data.
QoS-Null	Transmitted by QSTA when it has no more data, or it is the last frame of the TXOP.
QoS-Data	QoS data transfer between QAP and QSTA. Used by EDCA as well as HCCA.
QoS CF-Ack	Transmitted by QAP in response to QoS-Null requesting a TXOP, no data.
QoS-Data+CF-Ack	Transmitted by QAP in response to QoS-Null requesting a TXOP, with data.
QoS CF-Ack+CF-Poll, QoS-Data+CF-Ack+CF-Poll	Generally not used.

Factors Affecting Wireless QoS

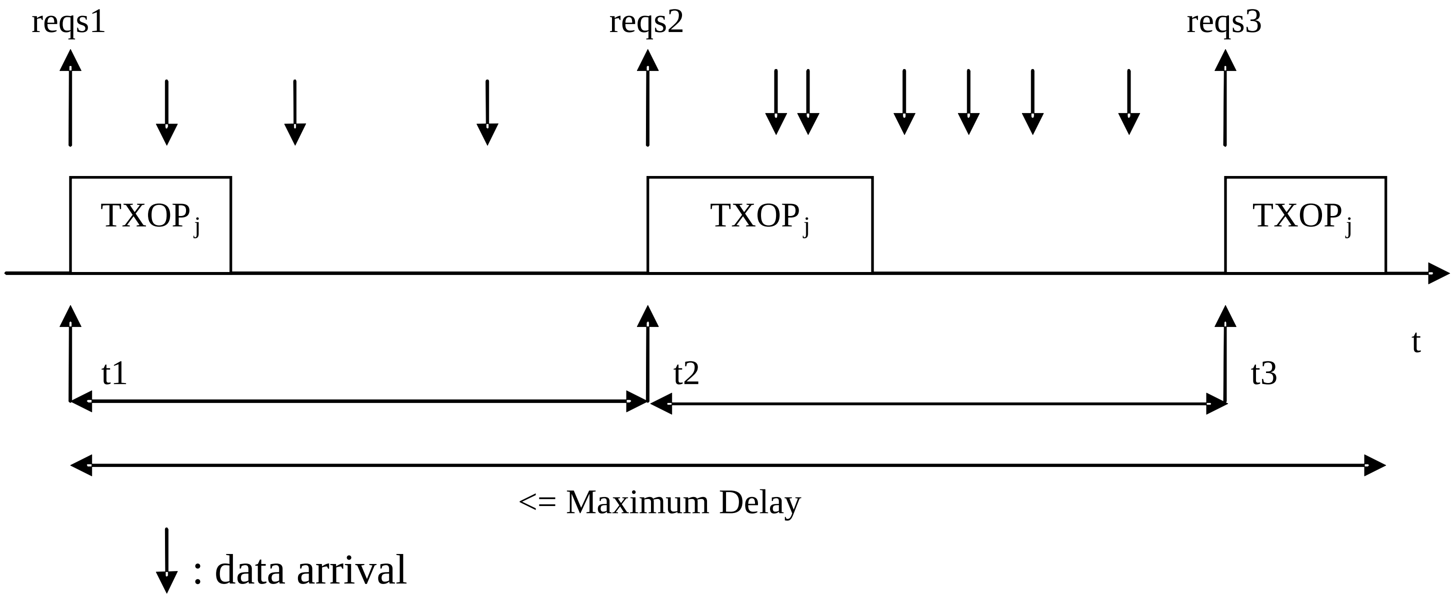
- QoS of wireless network is affected by the following:
  - Attenuation,
  - Multi-path interference,
  - Spectrum interference: for example interferences from neighboring cells,
  - Noise: Noise sources can be natural and man-made such as radio, TV and other radio-frequency transmission,
  - Mobility: affects hand-over and resource utilization, management,
  - Limited capacity: resources are costly.
- Higher error rates are typical

Core Network QoS Components

- **Admission Control**: Limits number of flows admitted into the network so that each individual flow obtains its desired QoS.

- **Scheduling**:
  - Scheduling affects delay, jitter and loss rate.
  - Allows protection against misbehaving flows.
  - Takes into account traffic and channel conditions

Traffic Scheduling in 802.11e

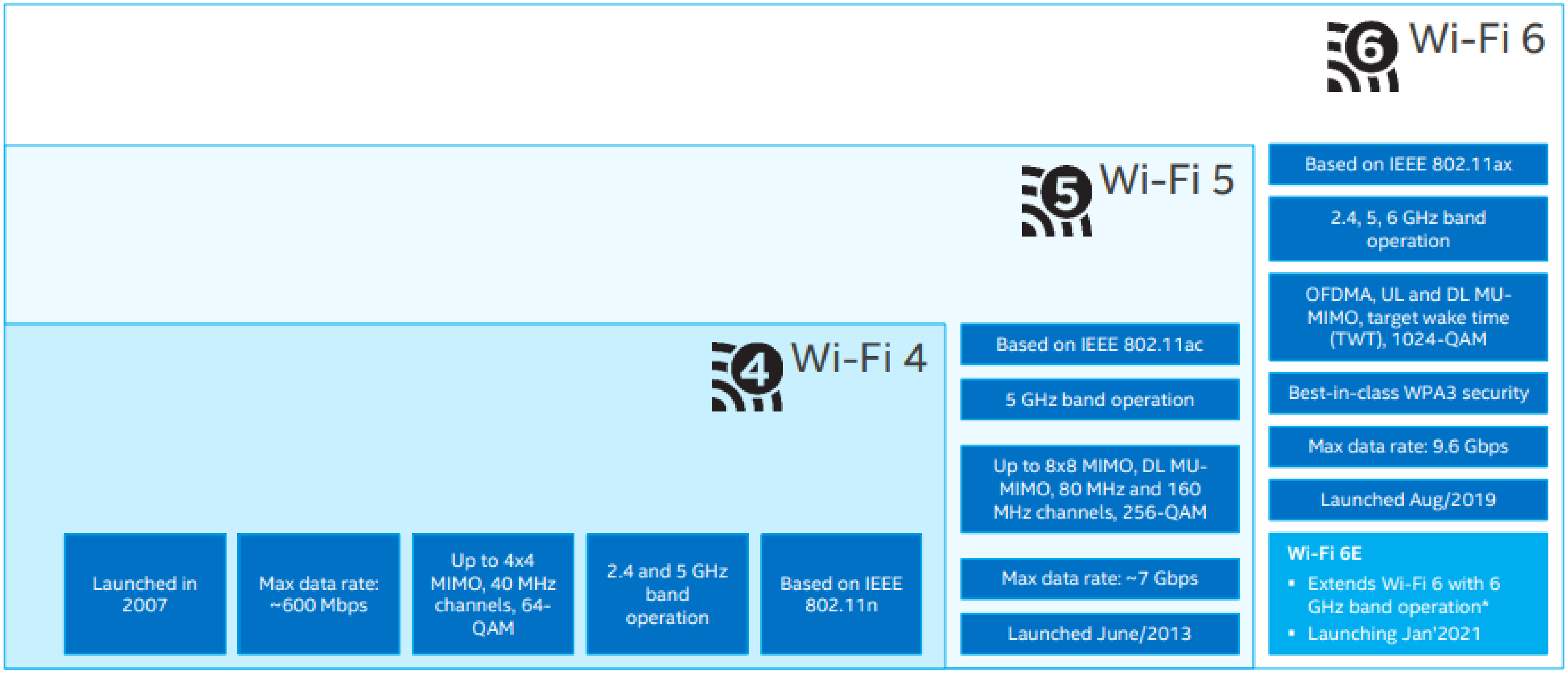


IEEE 802.11
Physical Layer Enhancements

802.11 PHY enhancements

	Wi-Fi 4	Wi-Fi 5	Wi-Fi 6	Wi-Fi 6E	Wi-Fi 7
Launch date	2007	2013	2019	2021	2024 (expected)
IEEE standard	802.11n	802.11ac	802.11ax		802.11be
Max data rate	1.2 Gbps	3.5 Gbps	9.6 Gbps		46 Gbps
Bands	2.4 GHz, 5 GHz	5 GHz	2.4 GHz, 5 GHz	6 GHz	2.4 GHz, 5 GHz, 6 Hz
Channel size	20, 40 MHz	20, 40, 80 80+80, 160 MHz	20, 40, 80 80+80, 160 MHz		Up to 320 MHz
Modulation	64-QAM	256-QAM	1024-QAM		4096-QAM
MIMO	4×4 MIMO	4×4 MIMO, DL MU-MIMO	8×8 UL/DL MU-MIMO		16×16 UL/DL MU-MIMO

802.11 PHY enhancements



802.11 PHY and MAC

	802.11b	802.11a	802.11g	802.11n	802.11ac
Frequency	2.4 GHz	5 GHz	2.4 GHz	2.4/5 GHz	5 GHz
Channel width	20 MHz	20 MHz	20 MHz	20/40 MHz	20/40/80/ 160 MHz
PHY	DSSS	OFDM	OFDM, DSSS	OFDM	OFDM
MIMO & beamforming	No	No	No	Yes	Yes
Max. data rate	**11 Mbps**	**54 Mbps**	**54 Mbps**	**600 Mbps**	**~6933 Mbps**

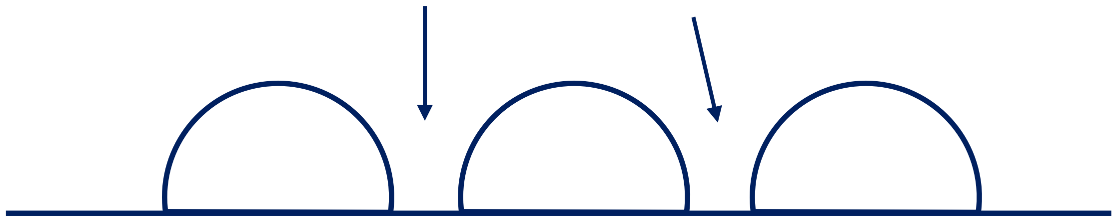
MAC:
CSMA/CA and wideband medium access

PHY-I:
OFDM and modulation

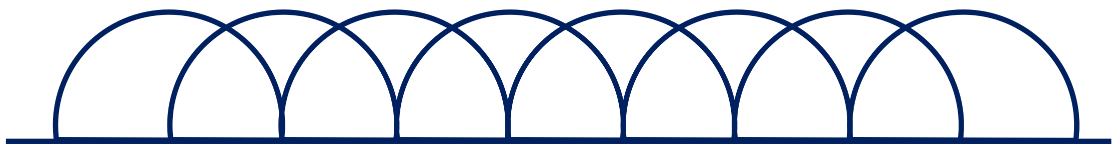
PHY-II:
MIMO and beamforming

OFDM vs FDM

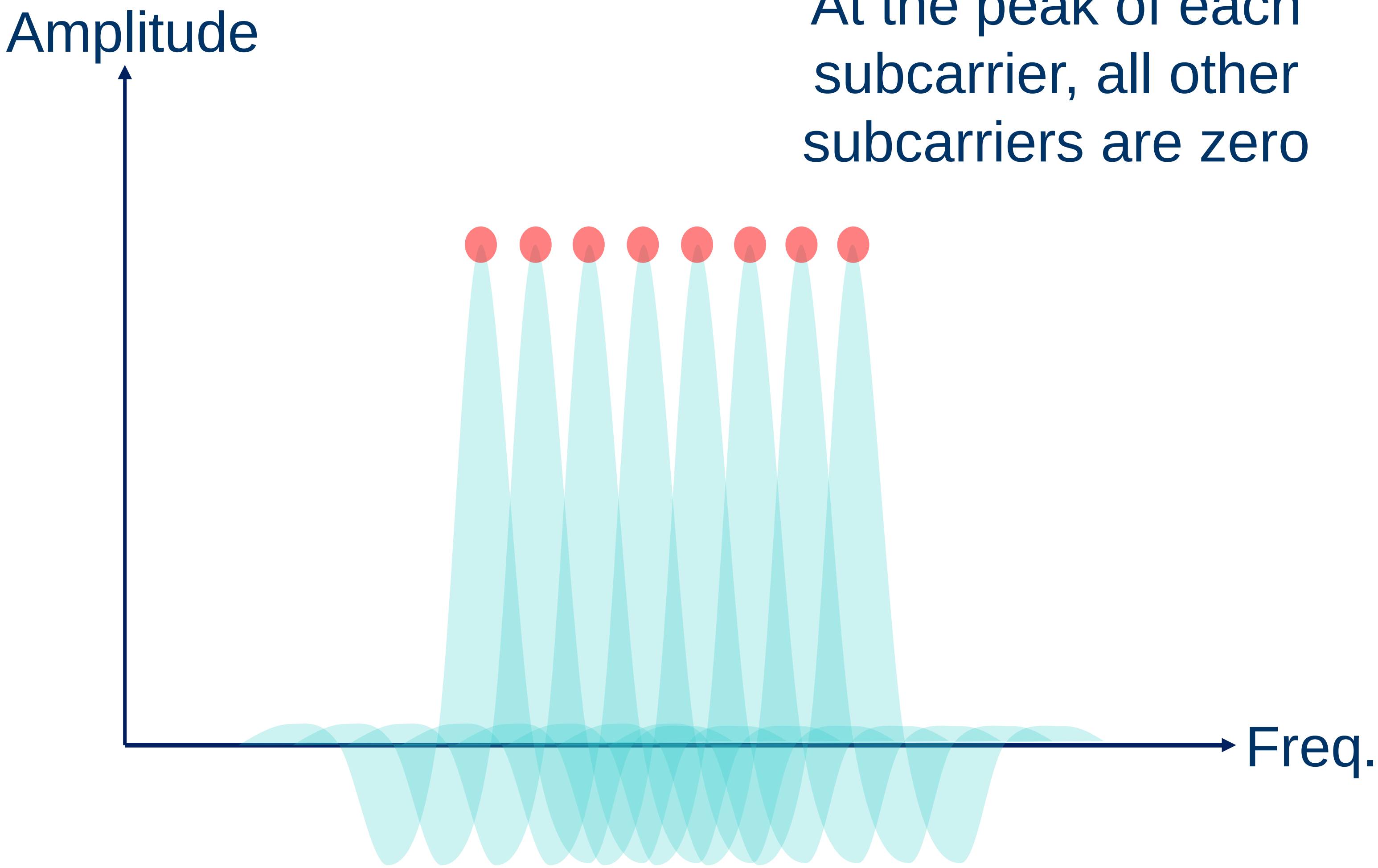
- FDM
  - Non-overlapping subchannels
  - Wastage of bandwidth necessary to separate subchannels



- OFDM
  - Overlapping but orthogonal subchannels
  - Carefully chosen subchannels – at the peak of each subcarrier, all other subcarriers are zero



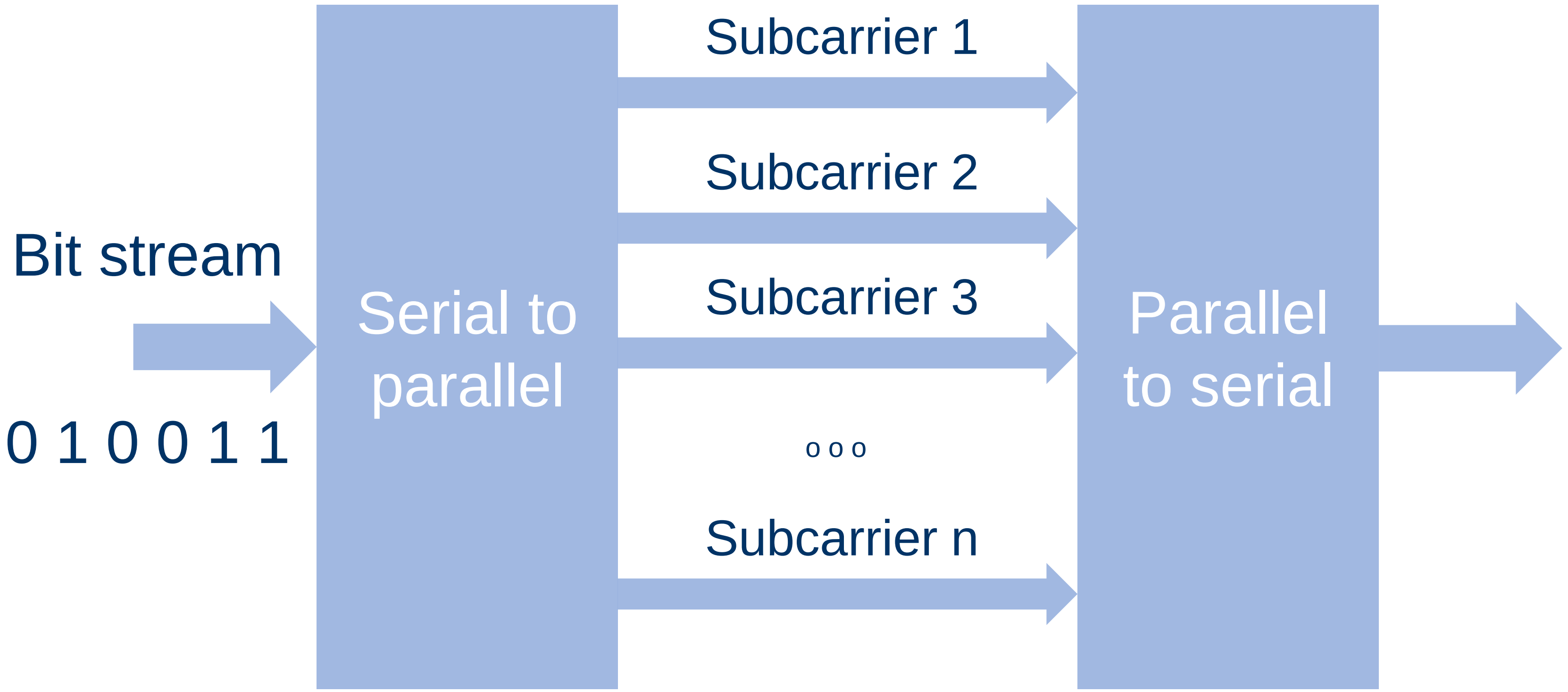
OFDM subcarriers



At the peak of each subcarrier, all other subcarriers are zero

OFDM

- How to spread information over the subcarriers?

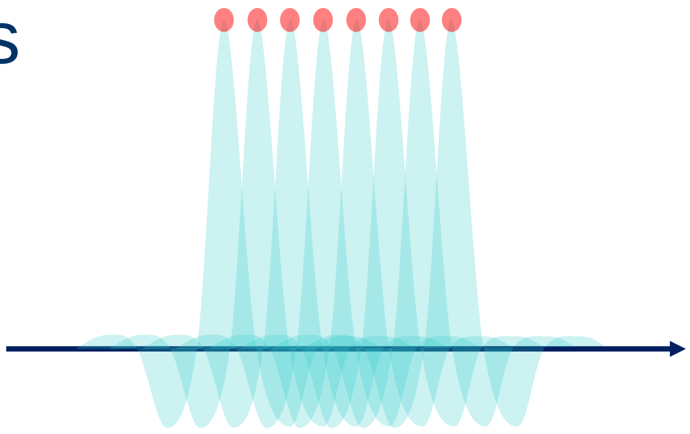


OFDM

- Example with 8 subcarriers

0 1 0 0 1 1 0 1 1 0 0 1 0 1 0 1

Sub 1	0	1
Sub 2	1	0
Sub 3	0	0
Sub 4	0	1
Sub 5	1	0
Sub 6	1	1
Sub 7	0	0
Sub 8	1	1

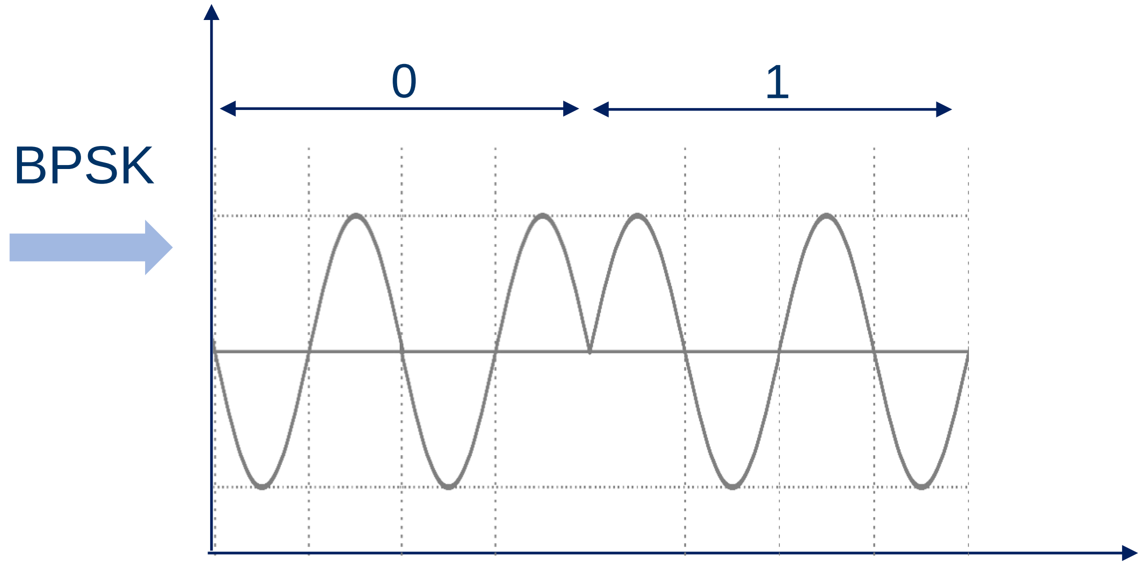


Step 1: Serial to parallel

OFDM

- Step 2: Modulate bits on each subcarrier

Sub 1	0	1
Sub 2	1	0
Sub 3	0	0
Sub 4	0	1
Sub 5	1	0
Sub 6	1	1
Sub 7	0	0
Sub 8	1	1

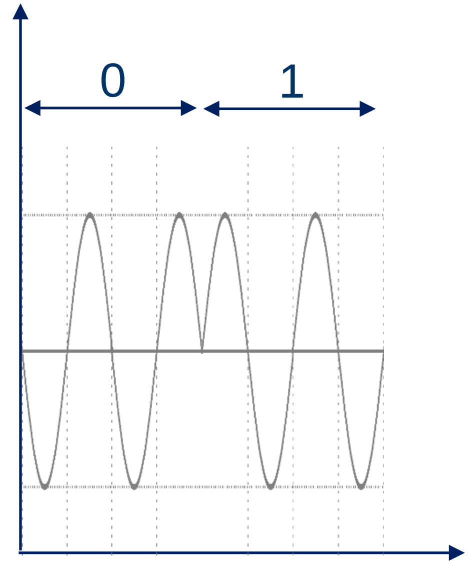


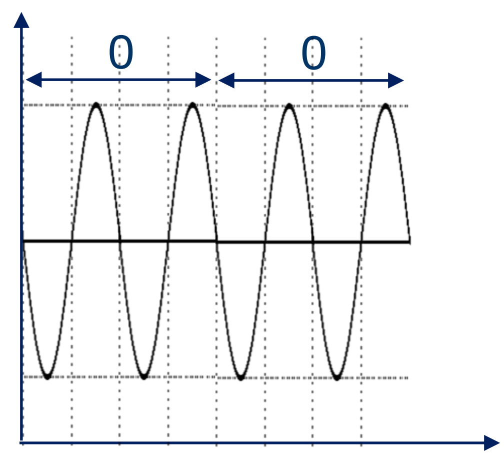
OFDM

- Step 2: Modulate bits on each subcarrier

Sub 1	0	1
Sub 2	1	0
Sub 3	0	0
Sub 4	0	1
Sub 5	1	0
Sub 6	1	1
Sub 7	0	0
Sub 8	1	1

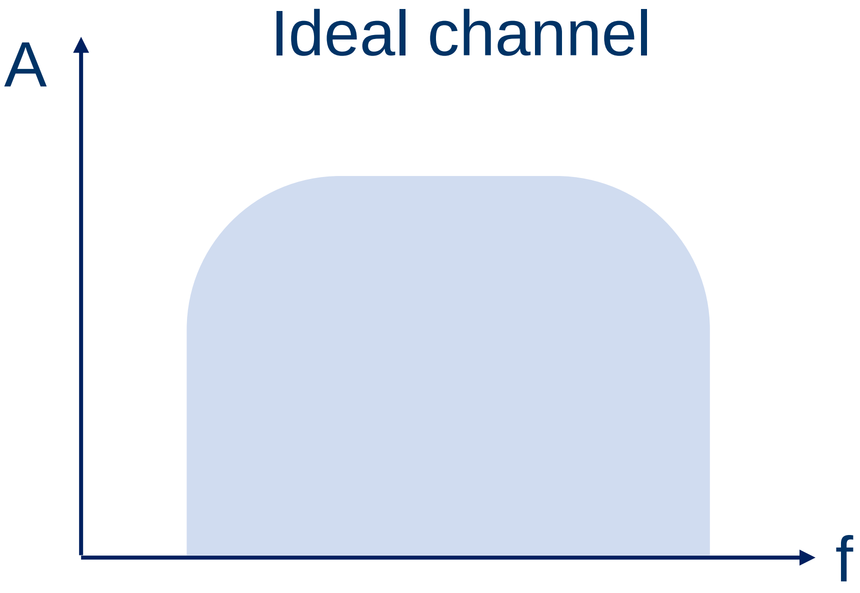
BPSK

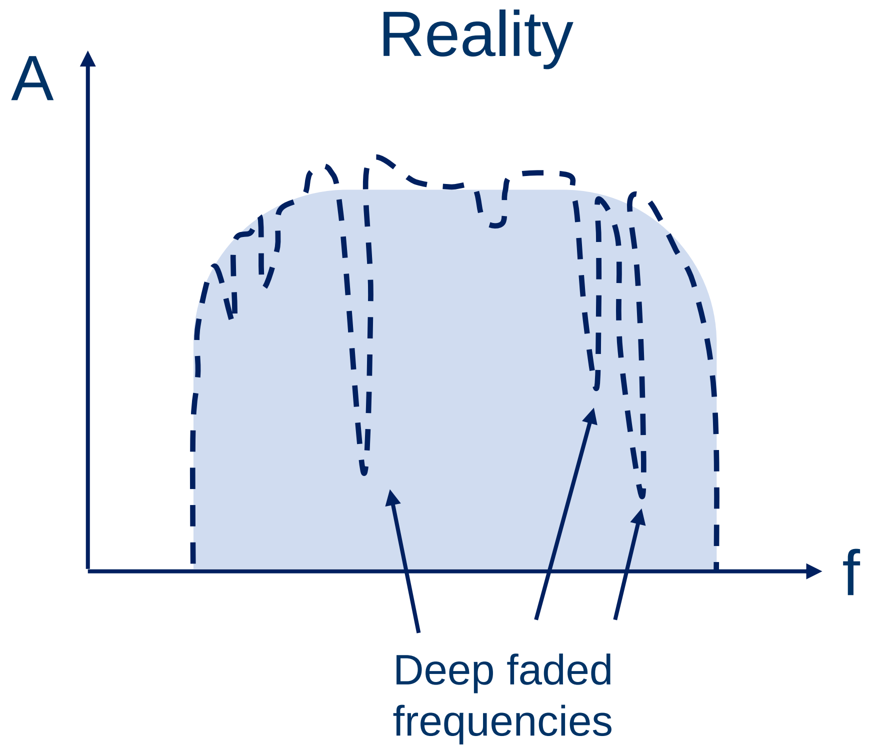




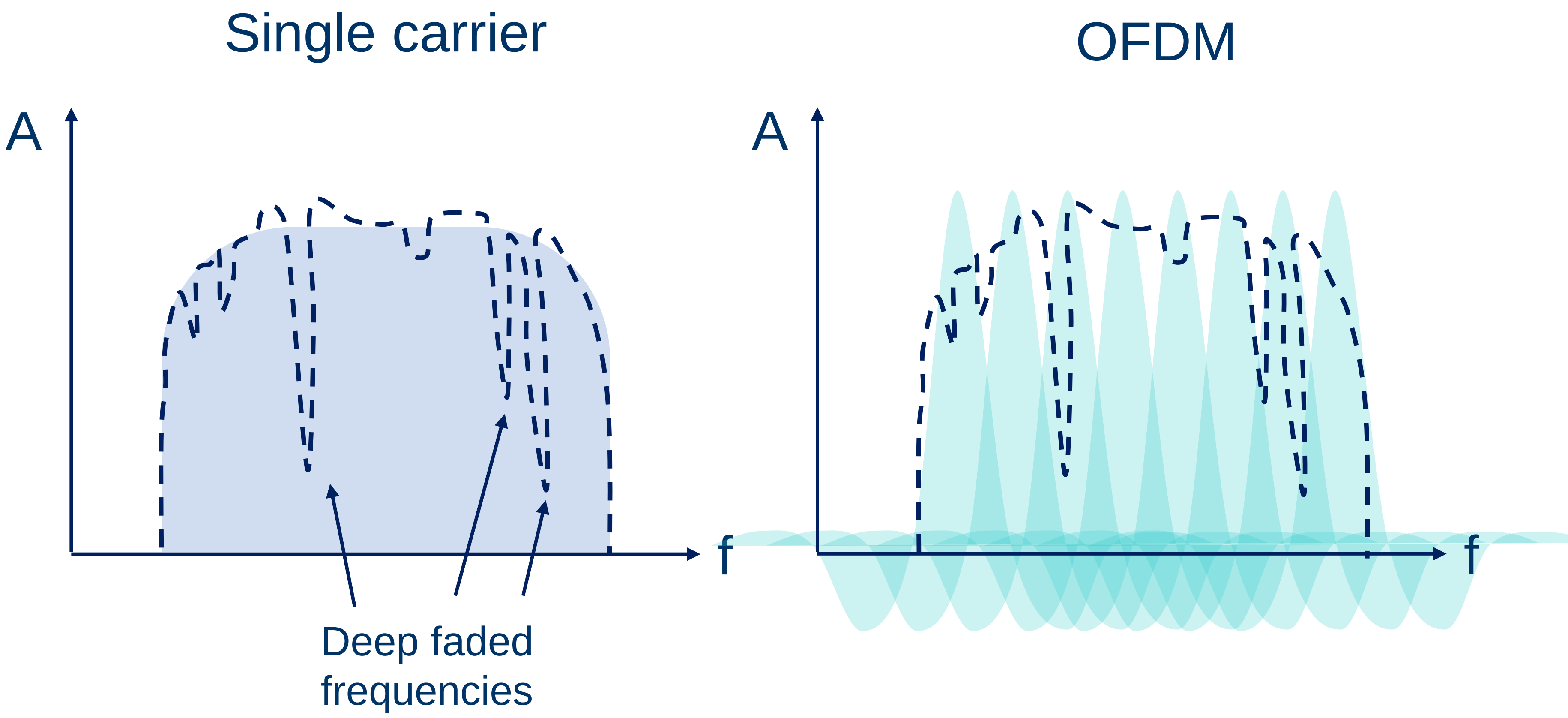
Why OFDM?

- Frequency selective fading
  - Some frequencies within the channel fade severely
  - These frequencies are uncorrelated



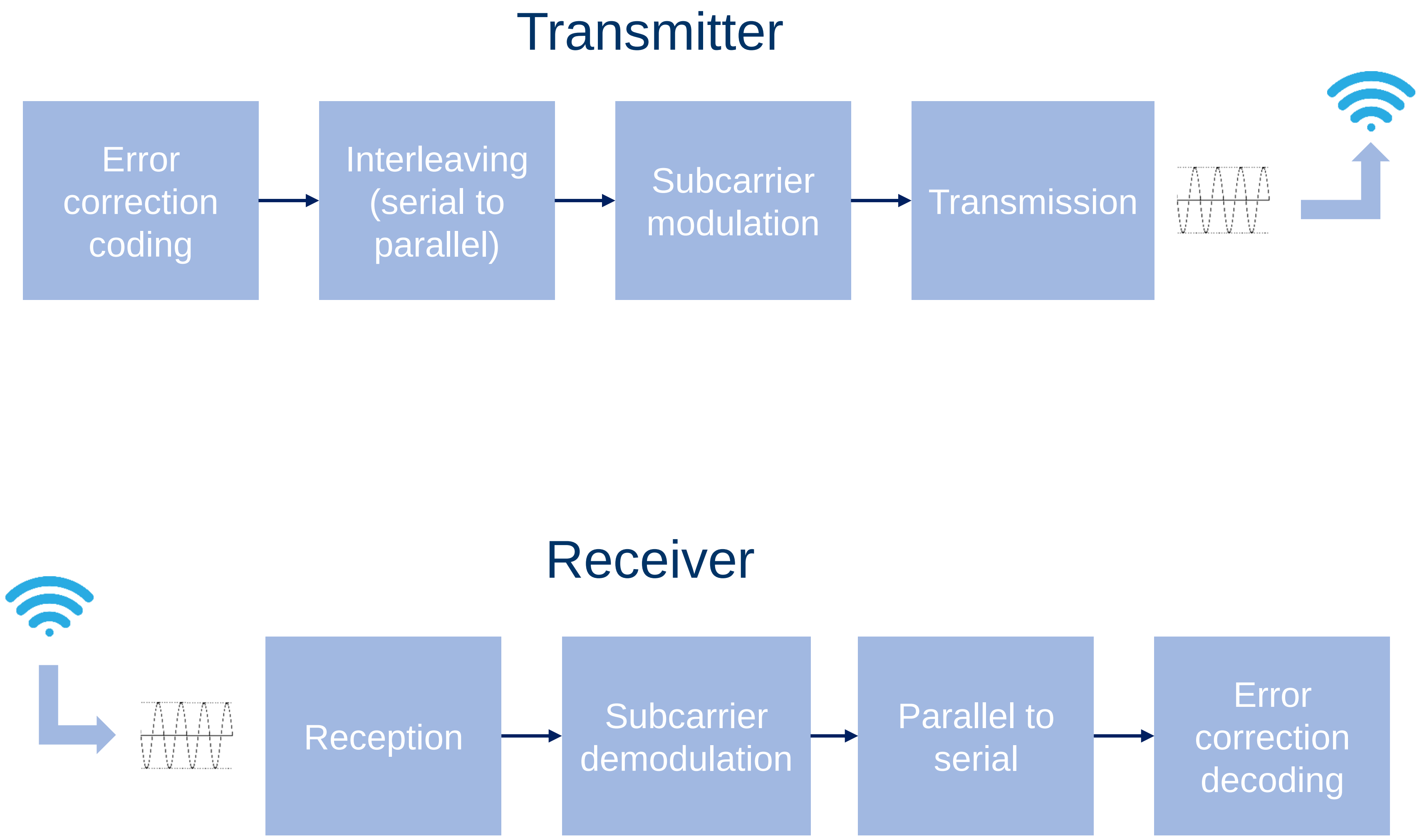


Why OFDM?



- Frequency selective affects only some subcarriers in OFDM
  - Lower bit error rate

OFDM Block Diagram

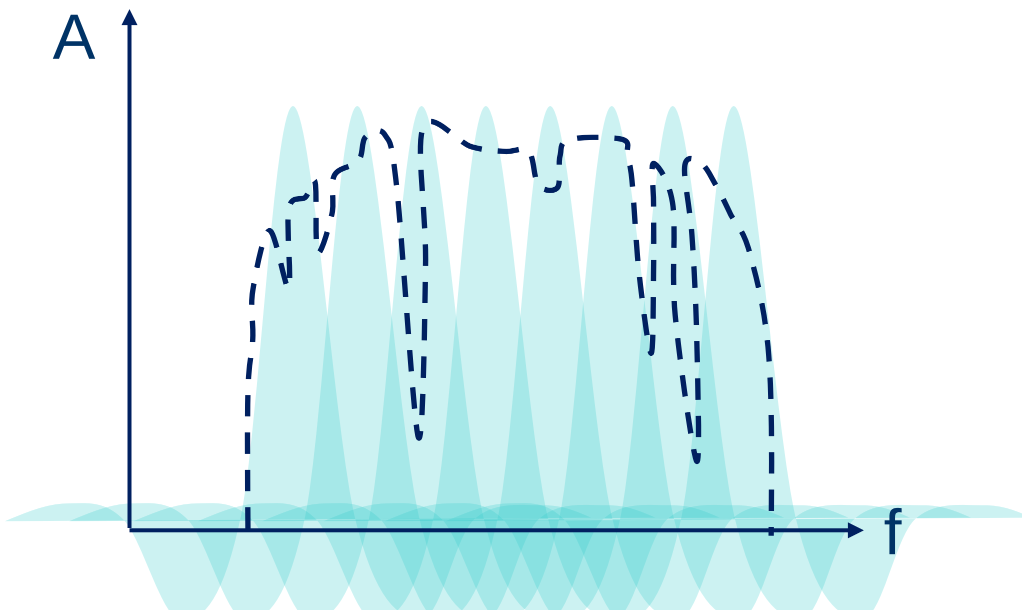


Interleaving

- Process of mapping the incoming data bits to subcarriers
  - In practice, serial to parallel interleaving is not round-robin

- General rule
  - Map the consecutive bits to subcarriers far away from each other
  - Reduces the probability of consecutive bits being dropped due to fading in nearby subcarriers – improves FEC performance

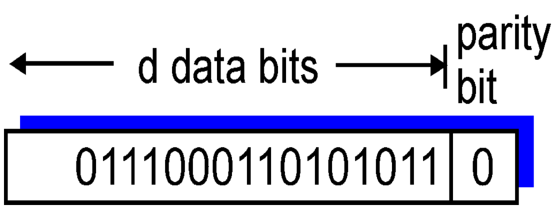
0 1 0 0 1 1 0



Error control - Parity checking

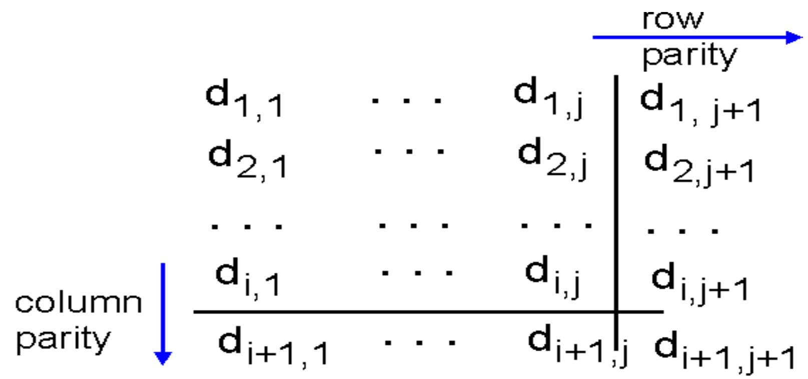
single bit parity:

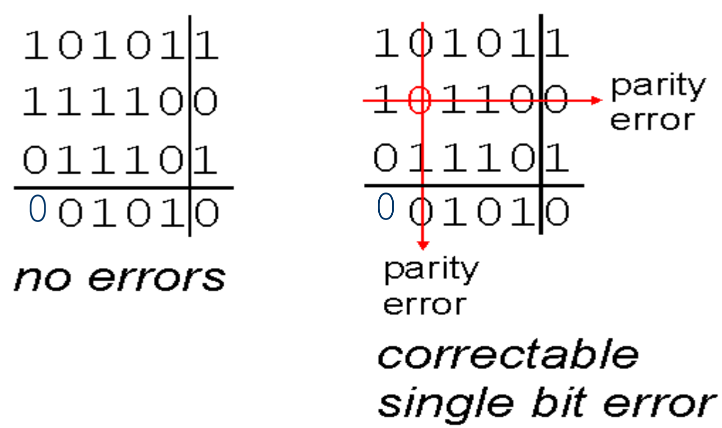
- *d*etect single bit errors



two-dimensional bit parity:

- detect and correct single bit errors





Modulation

- 802.11a supports following modulation schemes

Modulation	Bits per symbol
BPSK	1
QPSK	2
16-QAM	4
64-QAM	6

- More bits per symbol = More delay before transmission of a single symbol

Block Interleaving

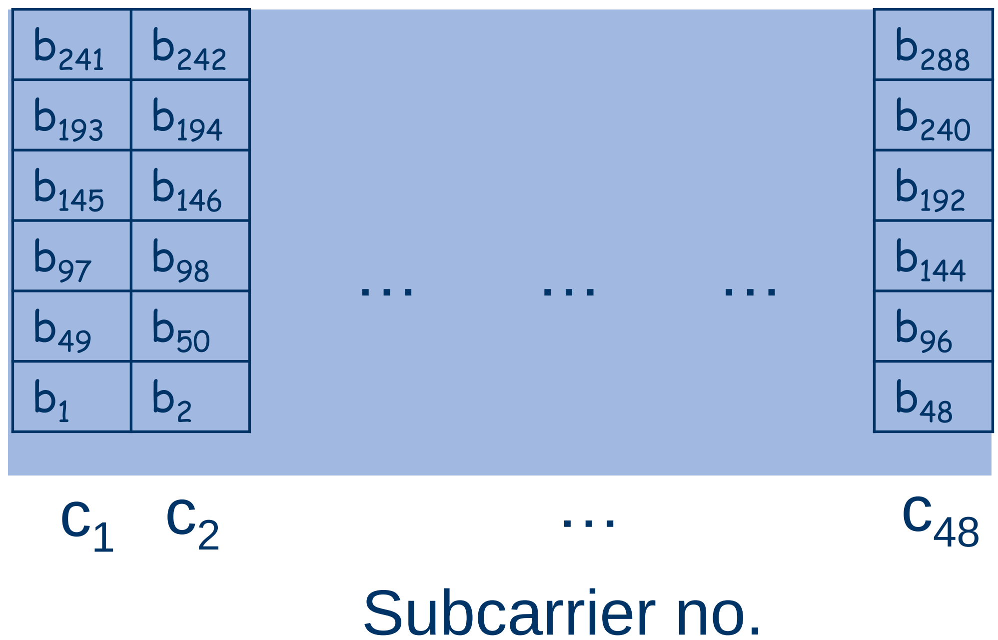
- 802.11a example
  - 48 subcarriers
  - Modulation chosen - 64 QAM (6 bits per symbol)

More complex versions of block interleavers can be used

- Interleaver buffer size = 48 x 6 = 288 bits

0, 1, 0, … , 1

$b_1, b_2, b_3, \ldots, b_{288}$

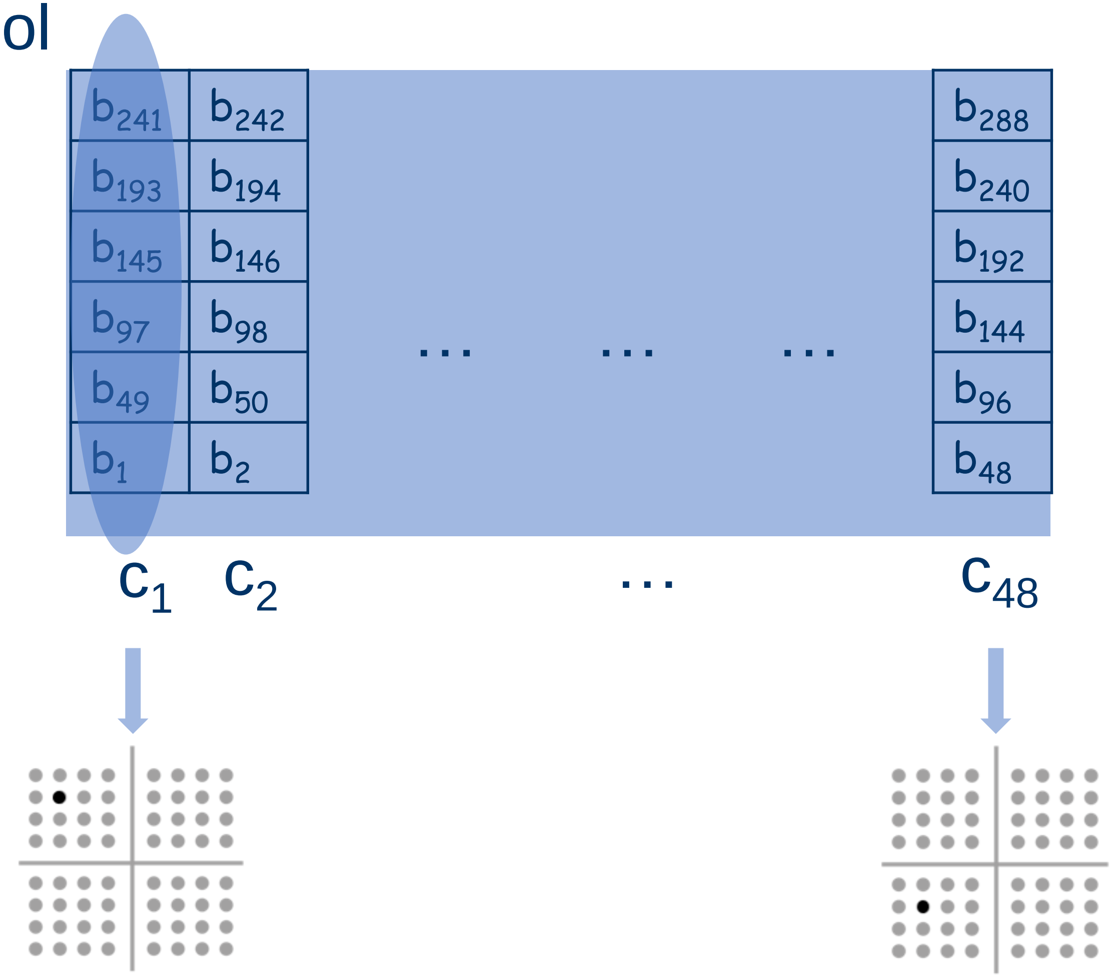


Subcarrier Modulation

- Subcarrier symbol

0, 1, 0, … , 1

$b_1, b_2, b_3, \ldots, b_{288}$

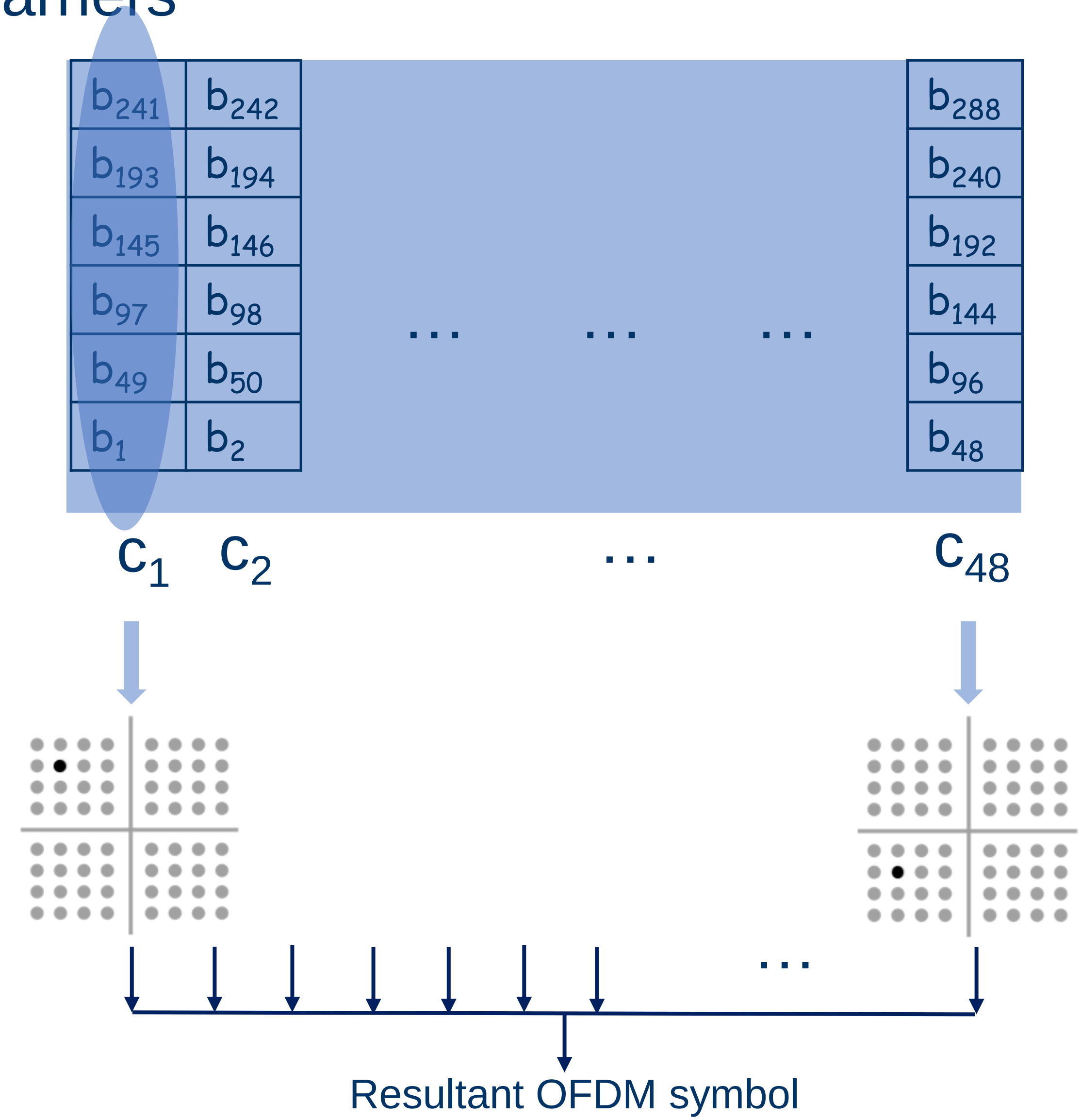


Final transmission

- Combine subcarriers

0, 1, 0, … , 1

$b_1, b_2, b_3, \ldots, b_{288}$



802.11a OFDM PHY

Modulation	Coding rate	Coded bits per subcarrier symbol	Coded bits per OFDM symbol	Data bits per OFDM symbol	Data rate (Mbps)
BPSK	1/2				
BPSK	3/4				
QPSK	1/2				
QPSK	3/4				
16-QAM	1/2				
16-QAM	3/4				
64-QAM	2/3				
64-QAM	3/4				

802.11a OFDM PHY

Modulation	Coding rate	Coded bits per subcarrier symbol	Coded bits per OFDM symbol	Data bits per OFDM symbol	Data rate (Mbps)
BPSK	1/2	1			
BPSK	3/4	1			
QPSK	1/2	2			
QPSK	3/4	2			
16-QAM	1/2	4			
16-QAM	3/4	4			
64-QAM	2/3	6			
64-QAM	3/4	6			

802.11a OFDM PHY

Modulation	Coding rate	Coded bits per subcarrier symbol	Coded bits per OFDM symbol	Data bits per OFDM symbol	Data rate (Mbps)
BPSK	1/2	1	48		
BPSK	3/4	1	48		
QPSK	1/2	2	96		
QPSK	3/4	2	96		
16-QAM	1/2	4	192		
16-QAM	3/4	4	192		
64-QAM	2/3	6	288		
64-QAM	3/4	6	288		

802.11a OFDM PHY

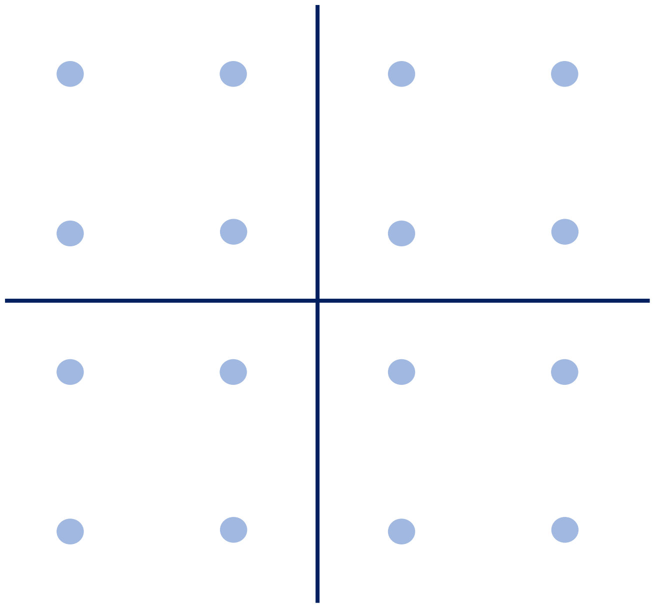
Modulation	Coding rate	Coded bits per subcarrier symbol	Coded bits per OFDM symbol	Data bits per OFDM symbol	Data rate (Mbps)
BPSK	1/2	1	48	24	
BPSK	3/4	1	48	36	
QPSK	1/2	2	96	48	
QPSK	3/4	2	96	72	
16-QAM	1/2	4	192	96	
16-QAM	3/4	4	192	144	
64-QAM	2/3	6	288	192	
64-QAM	3/4	6	288	216	

802.11a OFDM PHY

Modulation	Coding rate	Coded bits per subcarrier symbol	Coded bits per OFDM symbol	Data bits per OFDM symbol	Data rate (Mbps)
BPSK	1/2	1	48	24	6
BPSK	3/4	1	48	36	9
QPSK	1/2	2	96	48	12
QPSK	3/4	2	96	72	18
16-QAM	1/2	4	192	96	24
16-QAM	3/4	4	192	144	36
64-QAM	2/3	6	288	192	48
64-QAM	3/4	6	288	216	54

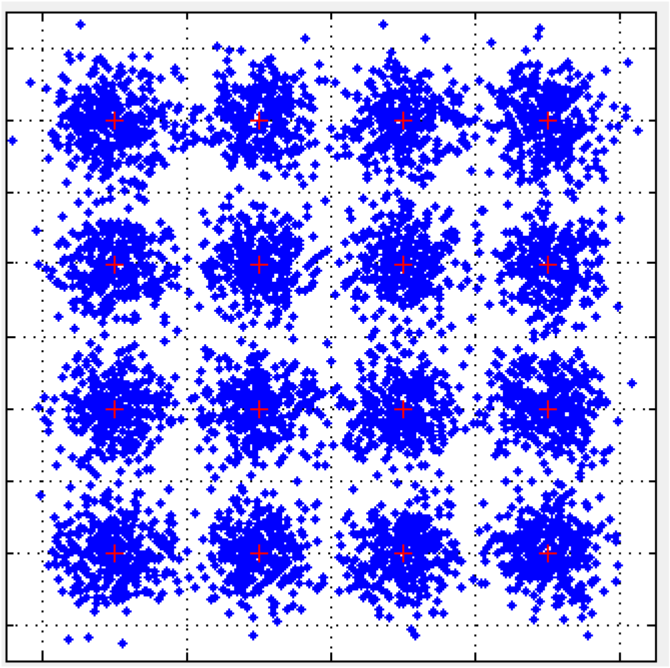
Demodulation

- Received symbols depend on channel variations
  - Multi-path – common reason behind amplitude and phase changes



Transmitter

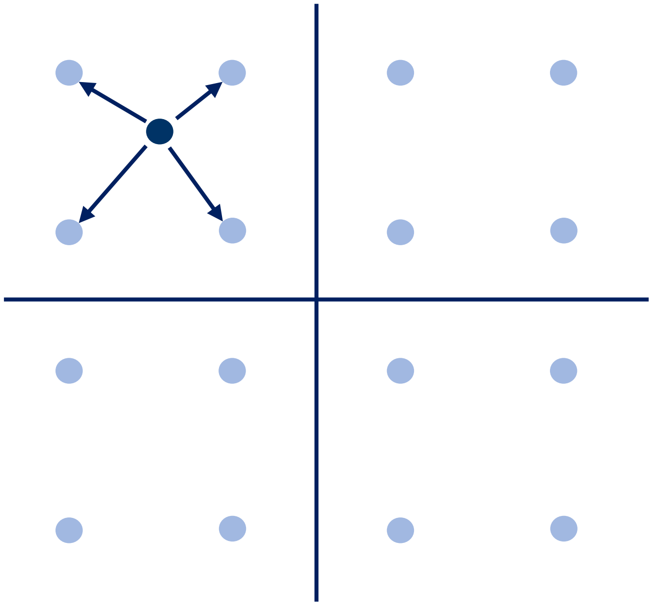
Inter-symbol interference



Receiver

Demodulation

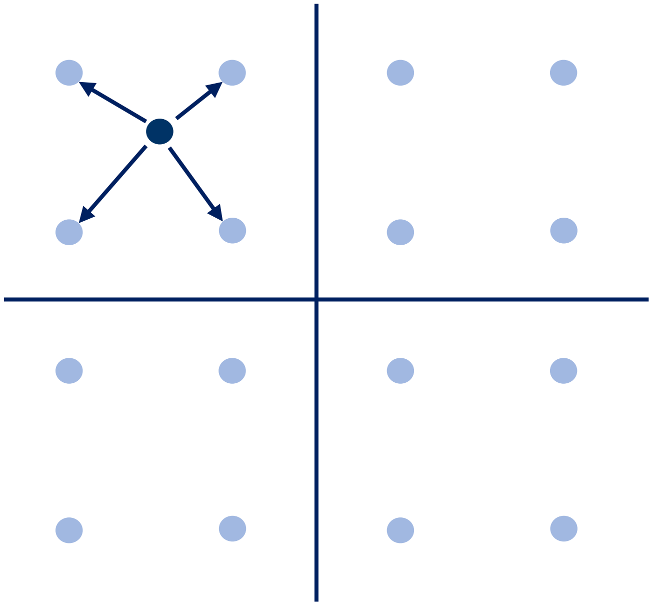
- Hard decision
  - Calculate the distance to the constellation points, pick the one with the lowest distance
  - Can be overly conservative



Receiver

Demodulation

- Soft decision
  - For the received symbol, calculate its distance to the nearby constellation points
  - Use the distance to associate a probability to the constellation point
  - Combine the probabilities with FEC decoding to minimize errors



Receiver

RSS, SNR and SINR

- Commonly used measures of channel quality

- RSS – Received Signal Strength
  - Measured in dBm
  - Often available through RSSI register on WiFi chipsets

- SNR – Signal to Noise Ratio (S/N)
  - Measured in dB
  - Ratio of RSS and measured noise, available or can be derived

- SINR – Signal to Noise and Interference Ratio (S/I+N)
  - Measured in dB
  - Considers how much interference is caused by other transmissions
  - Very useful metric but difficult to measure

Receiver sensitivity

- Better signal strength (higher SNR) ensures lower inter-symbol interference (ISI)
- 802.11 standards associate a receiver sensitivity with each modulation and data rate

802.11a

Modulation	Data rate (Mbps)	Receiver sensitivity (dBm)
BPSK	6	-82
BPSK	9	-81
QPSK	12	-79
QPSK	18	-77
16-QAM	24	-74
16-QAM	36	-70
64-QAM	48	-66
64-QAM	54	-65

OFDM in 802.11ac

- 802.11ac introduces the use of 256 QAM
  - 256 QAM – 8 bits per symbol

Modulation	Coding rate	Receiver sensitivity (dBm)
BPSK	1/2	-82
QPSK	1/2	-79
QPSK	3/4	-77
16-QAM	1/2	-74
16-QAM	3/4	-70
64-QAM	2/3	-66
64-QAM	3/4	-65
64-QAM	5/6	-64
256-QAM	3/4	-59
256-QAM	5/6	-57

OFDM in 802.11ac

- 802.11ac uses wider channel widths
  - 20, 40, 80 and 160 MHz
  - More subcarriers for OFDM

Channel width (MHz)	OFDM subcarriers
20	52
40	108
80	234
160	468

- For higher data rates, 160 MHz channel width and 256 QAM modulation can be used