Mobile Networking

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1393

PLCP format, Data Rates, OFDM, Modulations, …

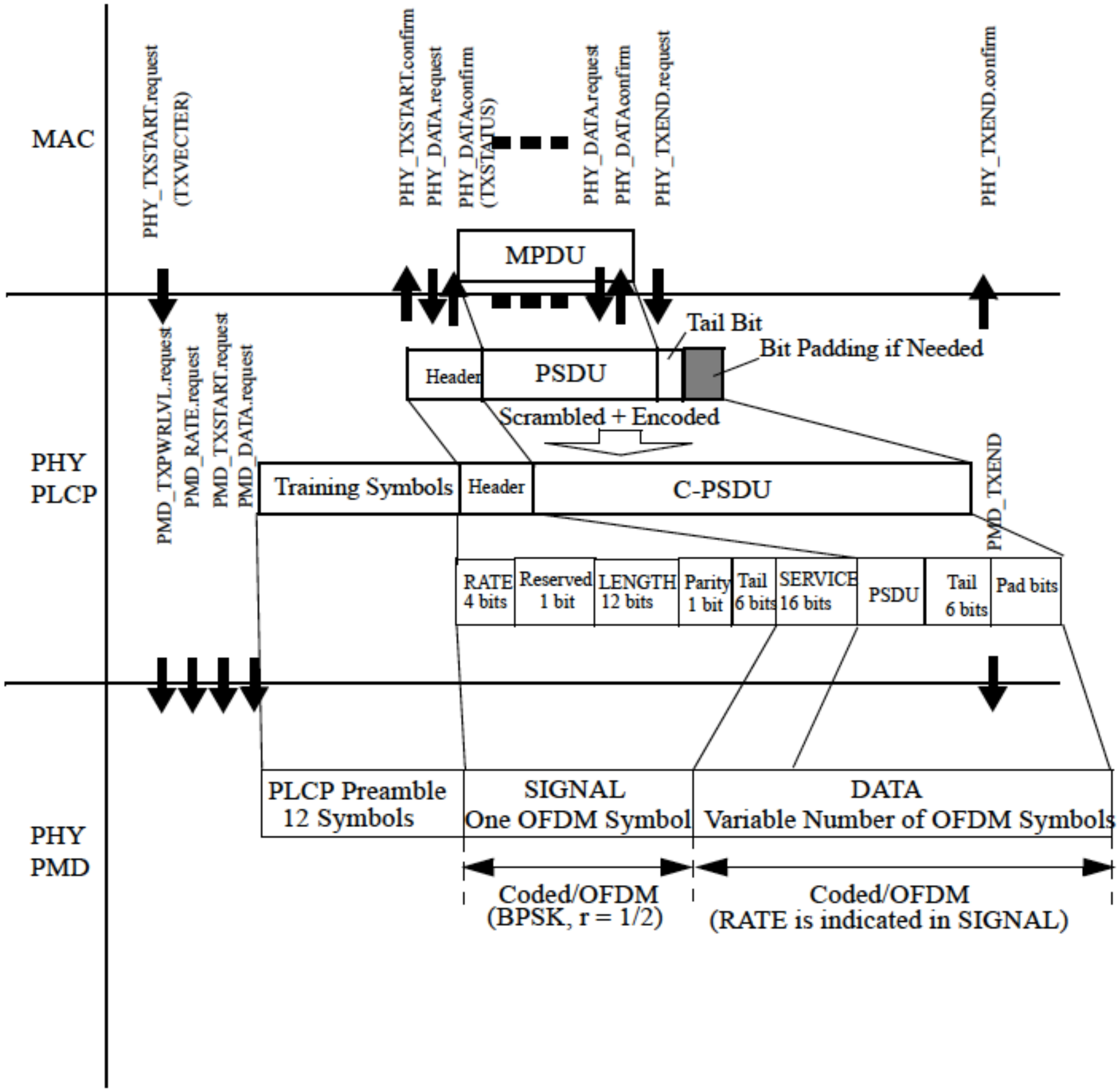
802.11A PHYSICAL LAYER

Contents

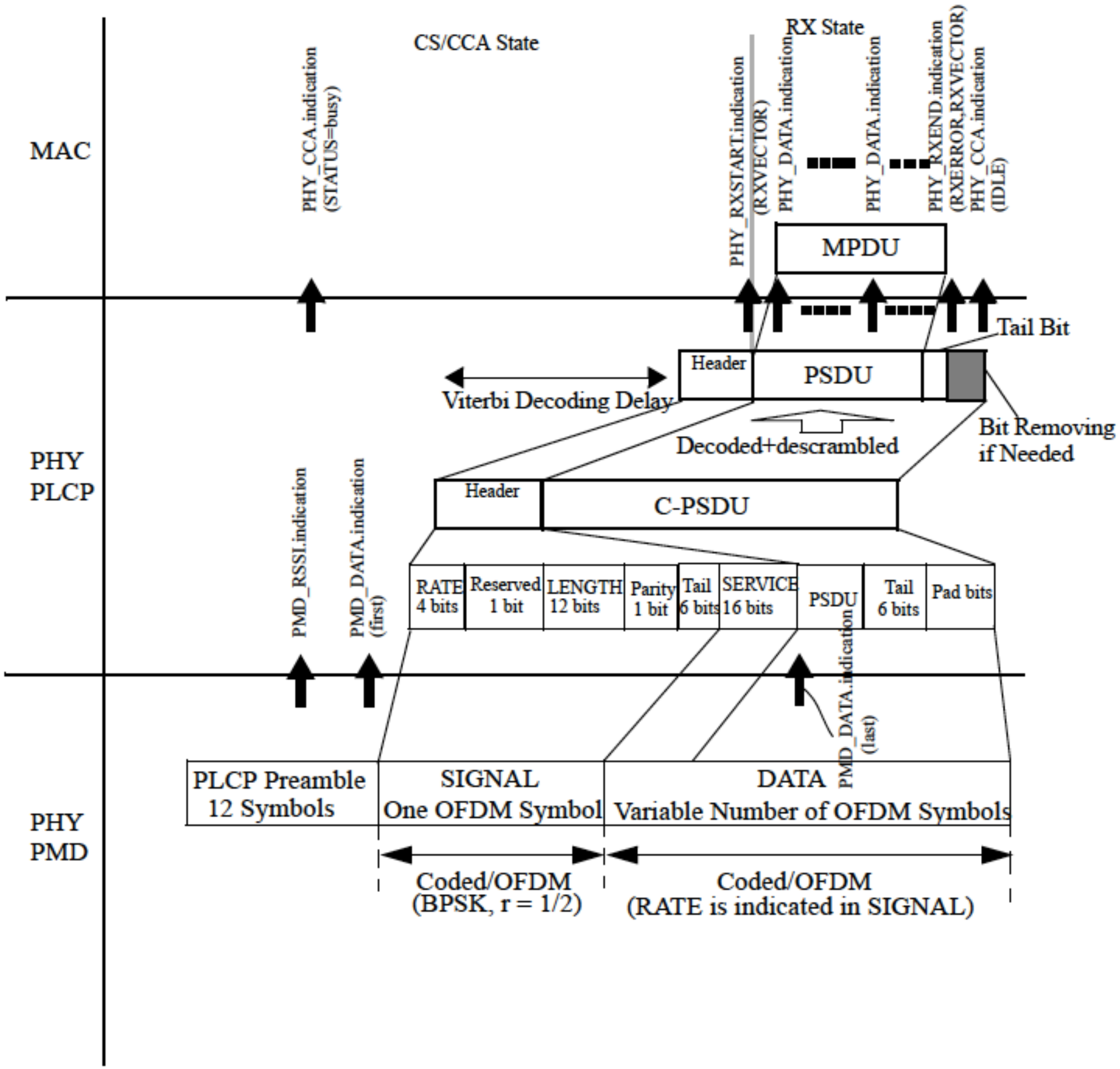
IEEE 802.11a

- IEEE Standard 802.11a-1999--High-speed Physical Layer Extension in the 5 GHz Band:
- Frequency range: 5.15-5.25, 5.25-5.35, and 5.725-5.825 GHz.
- Orthogonal Frequency Division Multiplexing (OFDM).
- Data payload communication capability: 6, 9, 12, 18, 24, 36, 48, and 54 Mbps.

PLCP Transmit Procedure



PLCP Receive Procedure

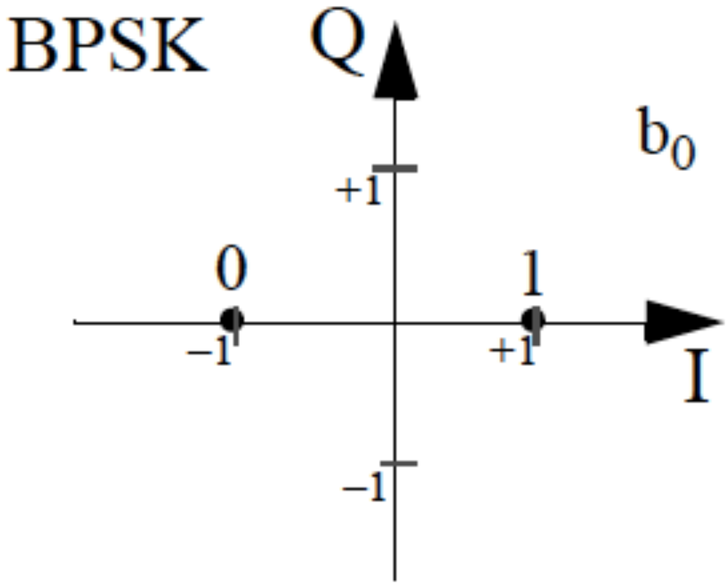


Contents

Rate-Dependent Parameters in IEEE 802.11a

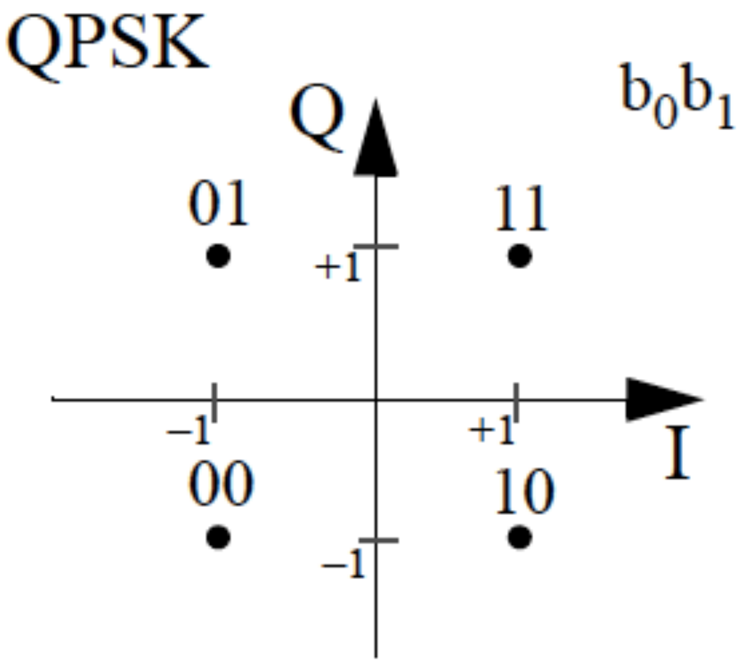
Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})	Data rate (Mb/s) (20 MHz channel spacing)	Data rate (Mb/s) (10 MHz channel spacing)	Data rate (Mb/s) (5 MHz channel spacing)
BPSK	1/2	1	48	24	6	3	1.5
BPSK	3/4	1	48	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

BPSK Modulation Table



Input bit (b_0)	I-out	Q-out
0	–1	0
1	1	0

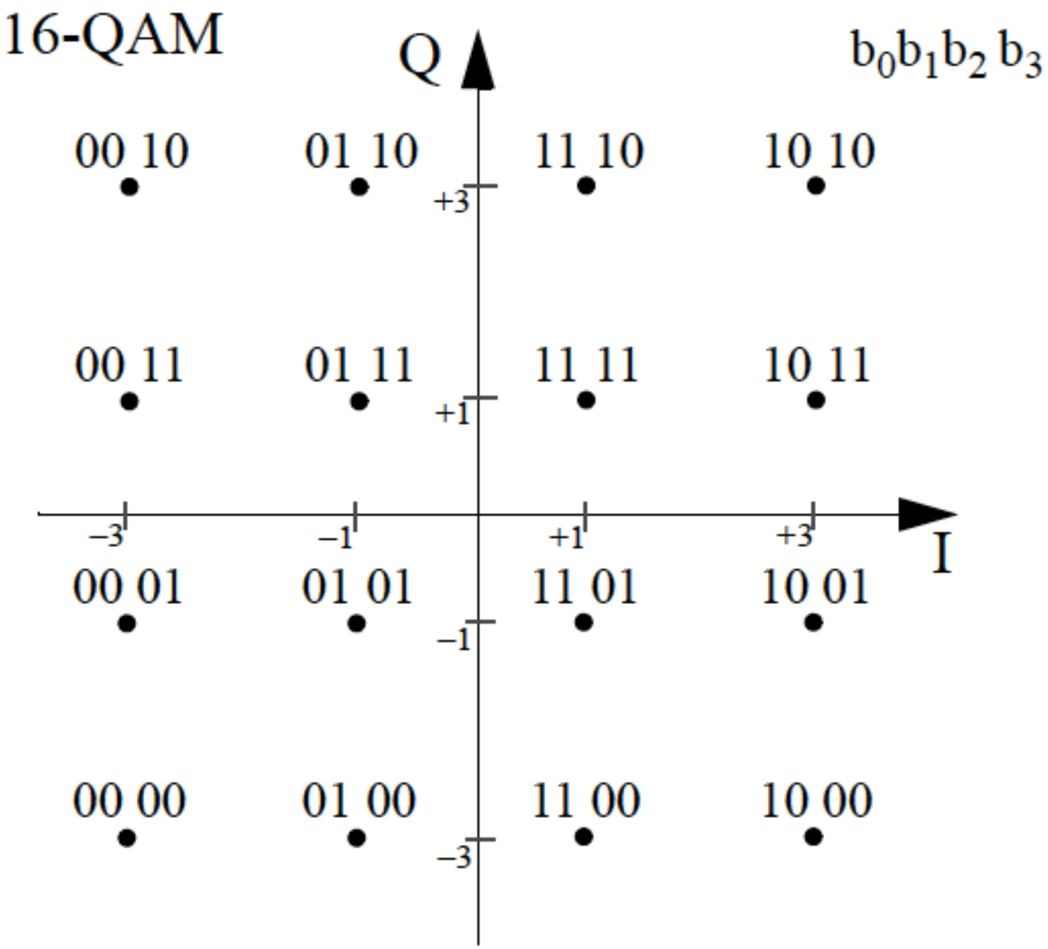
QPSK Modulation Table



Input bit (b_0)	I-out
0	–1
1	1

Input bit (b_1)	Q-out
0	–1
1	1

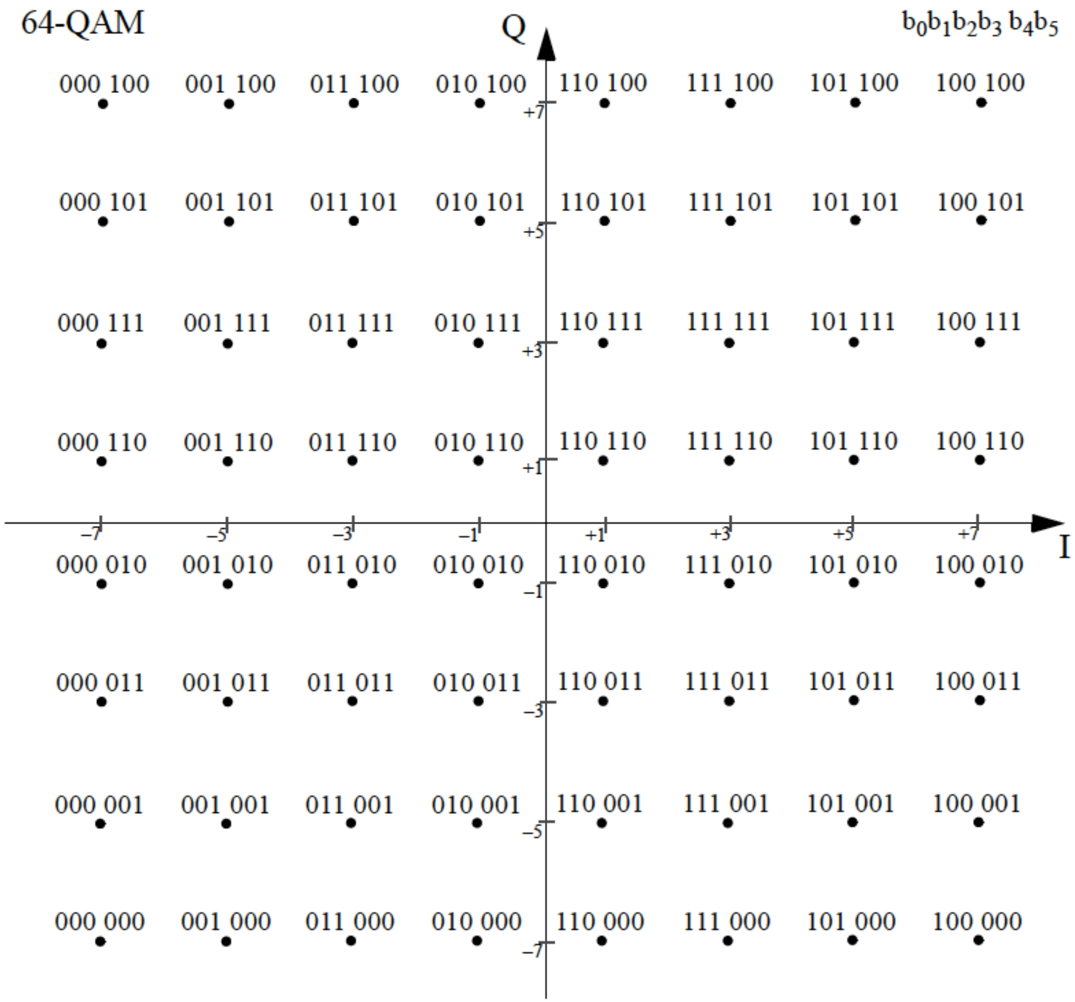
16-QAM Modulation Table



Input bits (b_0 b_1)	I-out
00	−3
01	−1
11	1
10	3

Input bits (b_2 b_3)	Q-out
00	−3
01	−1
11	1
10	3

64-QAM Modulation Table



Input bits ($b_0\ b_1\ b_2$)	I-out
000	–7
001	–5
011	–3
010	–1
110	1
111	3
101	5
100	7

Input bits ($b_3\ b_4\ b_5$)	Q-out
000	–7
001	–5
011	–3
010	–1
110	1
111	3
101	5
100	7

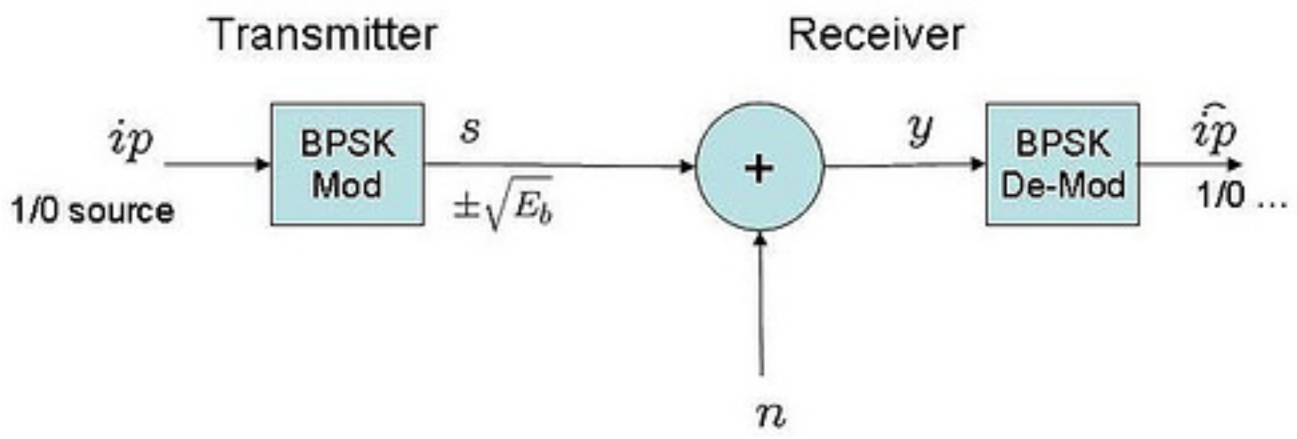
Constellation Mapping

- $d_m = I + Q\,j$
- The output value is also normalized:

$$d_m = (I + Q\,j) \,/\, K_{MOD}$$

Modulation	K_{MOD}
BPSK	1
QPSK	$1/\sqrt{2}$
16-QAM	$1/\sqrt{10}$
64-QAM	$1/\sqrt{42}$

BPSK Performance Analysis



Channel Model: AWGN

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-(x-\mu)^2}{2\sigma^2}}$$

$$\mu = 0$$

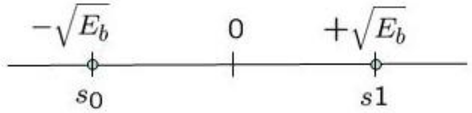
$$\sigma^2 = \frac{N_0}{2}$$

BPSK Performance Analysis

- Received Signal (y):
  - $y=s_1+n$ when bit 1 transmitted
  - $y=s_0+n$ when bit 0 is transmitted
- The conditional probability distribution function (PDF) of y for the two cases are

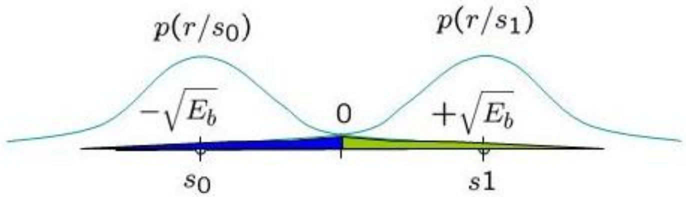
Correct Detection:

$$p(y|s_0)=\frac{1}{\sqrt{\pi N_0}}e^{\frac{-(y+\sqrt{E_b})^2}{N_0}}$$



$$y > 0 \rightarrow s_1$$

$$p(y|s_1)=\frac{1}{\sqrt{\pi N_0}}e^{\frac{-(y-\sqrt{E_b})^2}{N_0}}$$



$$y< 0 \rightarrow s_0$$

BPSK BER Calculation

- The probability of error if "*1*" is transmitted

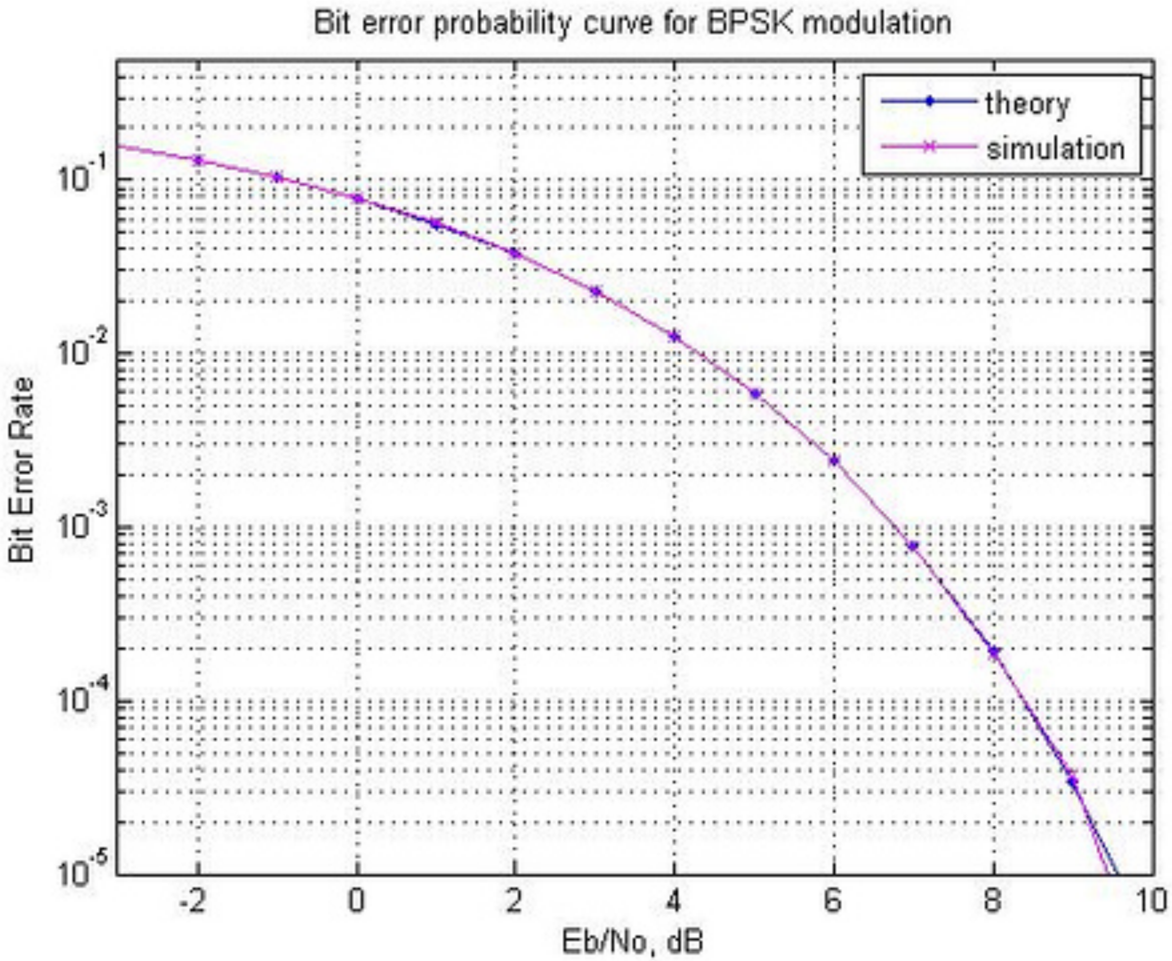
$$p(e|s_1) = \frac{1}{\sqrt{\pi N_0}} \int_{-\infty}^{0} e^{\frac{-(y-\sqrt{E_b})^2}{N_0}} dy = \frac{1}{\sqrt{\pi}} \int_{\sqrt{\frac{E_b}{N_0}}}^{\infty} e^{-z^2} dz = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right)$$

$$erfc(x) = \frac{2}{\sqrt{\pi}} \int_{x}^{\infty} e^{-x^2} dx$$

- Probability of bit error $P_b = p(s_1)p(e|s_1) + p(s_0)p(e|s_0)$

$$P_b = \frac{1}{2} erfc\left(\sqrt{\frac{E_b}{N_0}}\right)$$

BER for BPSK Modulation



802.11a Modulation Performance in AWGN

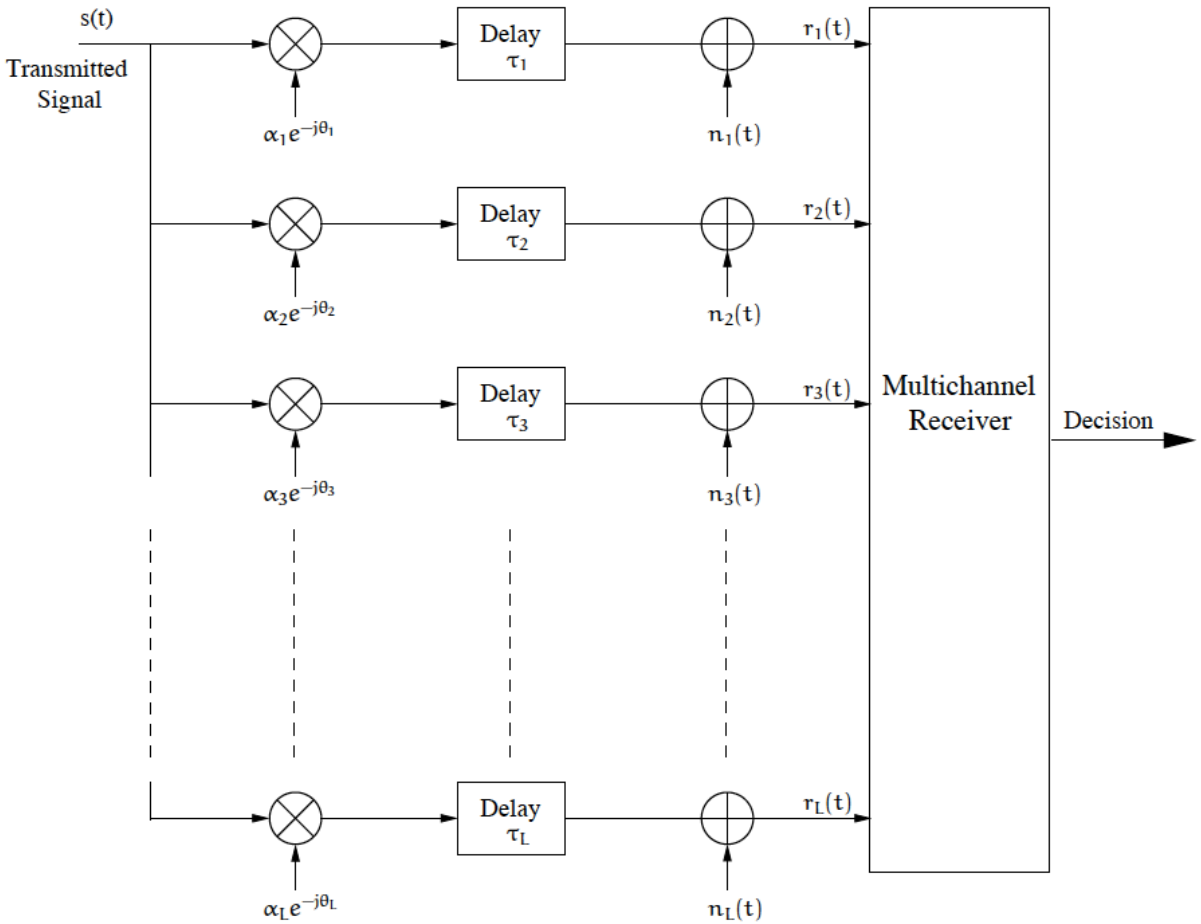
Modulation	*Symbol error*	*Bit error*
BPSK	$Q\left(\sqrt{2 \cdot \frac{\mathcal{E}_s}{N_o}}\right)$	$Q\left(\sqrt{2 \cdot \frac{\mathcal{E}_b}{N_o}}\right)$
4-QAM	$2Q\left(\sqrt{\frac{\mathcal{E}_s}{N_o}}\right) - Q^2\left(\sqrt{\frac{\mathcal{E}_s}{N_o}}\right)$	$Q\left(\sqrt{2 \cdot \frac{\mathcal{E}_b}{N_o}}\right)$
16-QAM	$3Q\left(\sqrt{\frac{\mathcal{E}_s}{5N_o}}\right) - \frac{9}{4}Q^2\left(\sqrt{\frac{\mathcal{E}_s}{5N_o}}\right)$	$\frac{3}{4}Q\left(\sqrt{\frac{4\mathcal{E}_b}{5N_o}}\right) + \frac{1}{2}Q\left(3\sqrt{\frac{4\mathcal{E}_b}{5N_o}}\right)$
64-QAM	$\frac{7}{2}Q\left(\sqrt{\frac{\mathcal{E}_s}{21N_o}}\right) - \frac{49}{16}Q^2\left(\sqrt{\frac{\mathcal{E}_s}{21N_o}}\right)$	$\frac{7}{12}Q\left(\sqrt{\frac{2\mathcal{E}_b}{7N_o}}\right) + \frac{1}{2}Q\left(3\sqrt{\frac{2\mathcal{E}_b}{7N_o}}\right)$

802.11a Modulation Performance in Rayleigh Fading Channel

Modulation	*Symbol error*	*Bit error*
BPSK	$\frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma_b}}{1+\bar{\gamma_b}}}\right)$	$\frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma_b}}{1+\bar{\gamma_b}}}\right)$
4-QAM	$\left(1-\sqrt{\frac{\bar{\gamma_b}}{1+\bar{\gamma_b}}}\right)-\frac{1}{4}\left(1-\sqrt{\frac{\bar{\gamma_b}}{1+\bar{\gamma_b}}}\times\frac{4}{\pi}\tan^{-1}\left(\sqrt{\frac{1+\bar{\gamma_b}}{\bar{\gamma_b}}}\right)\right)$	$\frac{1}{2}\left(1-\sqrt{\frac{\bar{\gamma_b}}{1+\bar{\gamma_b}}}\right)$
16-QAM	$\frac{3}{2}\left(1-\sqrt{\frac{2\bar{\gamma_b}/5}{1+2\bar{\gamma_b}/5}}\right)-\frac{9}{16}\left(1-\sqrt{\frac{2\bar{\gamma_b}/5}{1+2\bar{\gamma_b}/5}}\times\frac{4}{\pi}\tan^{-1}\left(\sqrt{\frac{1+2\bar{\gamma_b}/5}{2\bar{\gamma_b}/5}}\right)\right)$	$\frac{5}{8}-\frac{3}{8}\sqrt{\frac{2\bar{\gamma_b}}{5+2\bar{\gamma_b}}}-\frac{1}{4}\sqrt{\frac{18\bar{\gamma_b}}{5+18\bar{\gamma_b}}}$
64-QAM	$\frac{7}{4}\left(1-\sqrt{\frac{\bar{\gamma_b}/7}{1+\bar{\gamma_b}/7}}\right)-\frac{49}{64}\left(1-\sqrt{\frac{\bar{\gamma_b}/7}{1+\bar{\gamma_b}/7}}\times\frac{4}{\pi}\tan^{-1}\left(\sqrt{\frac{1+\bar{\gamma_b}/7}{\bar{\gamma_b}/7}}\right)\right)$	$\frac{13}{24}-\frac{7}{24}\sqrt{\frac{\bar{\gamma_b}}{7+\bar{\gamma_b}}}-\frac{1}{4}\sqrt{\frac{9\bar{\gamma_b}}{7+9\bar{\gamma_b}}}$

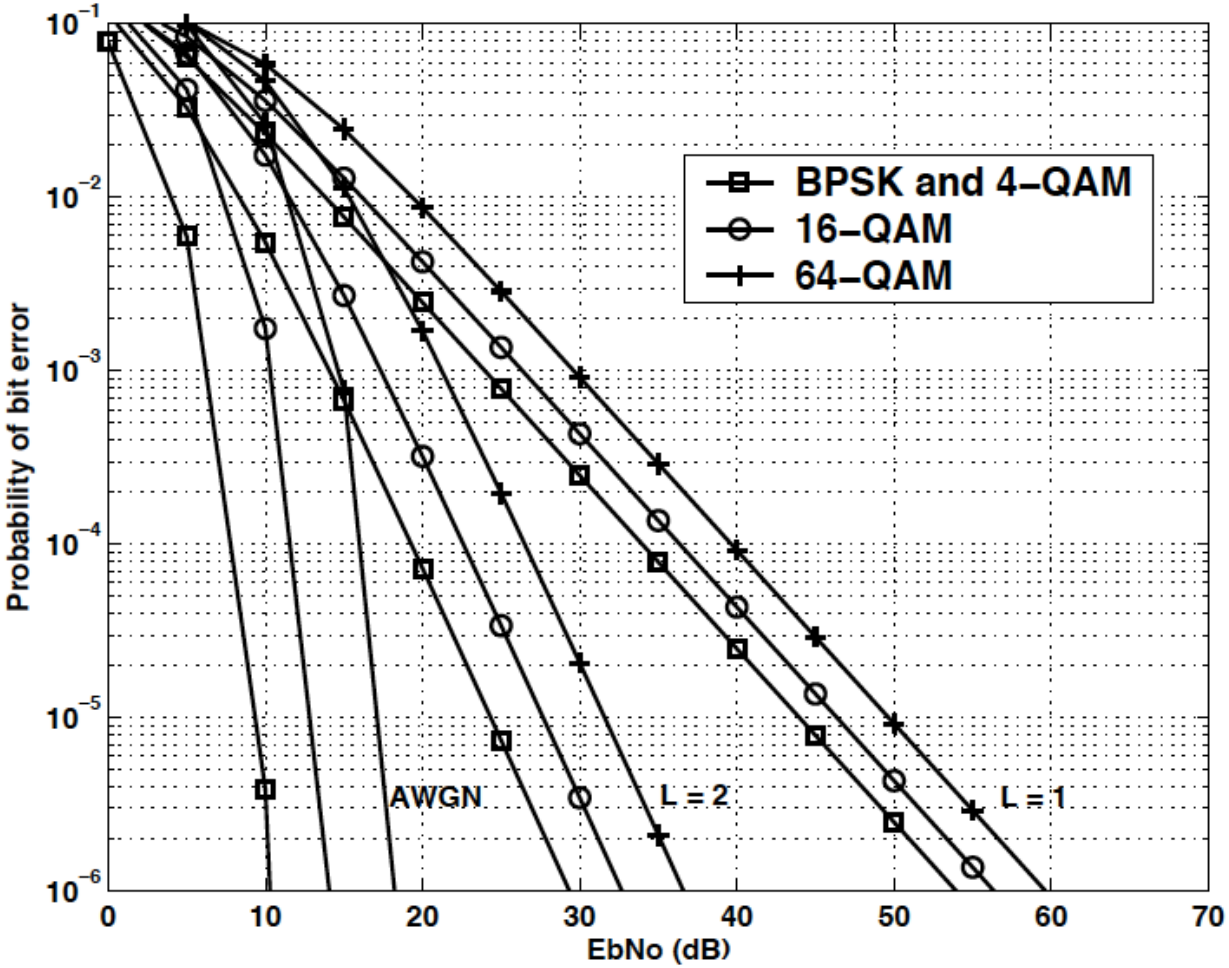
$\bar{\gamma_b}$ is the average signal to noise ratio per bit

802.11a Modulation Performance with Multichannel Receiver

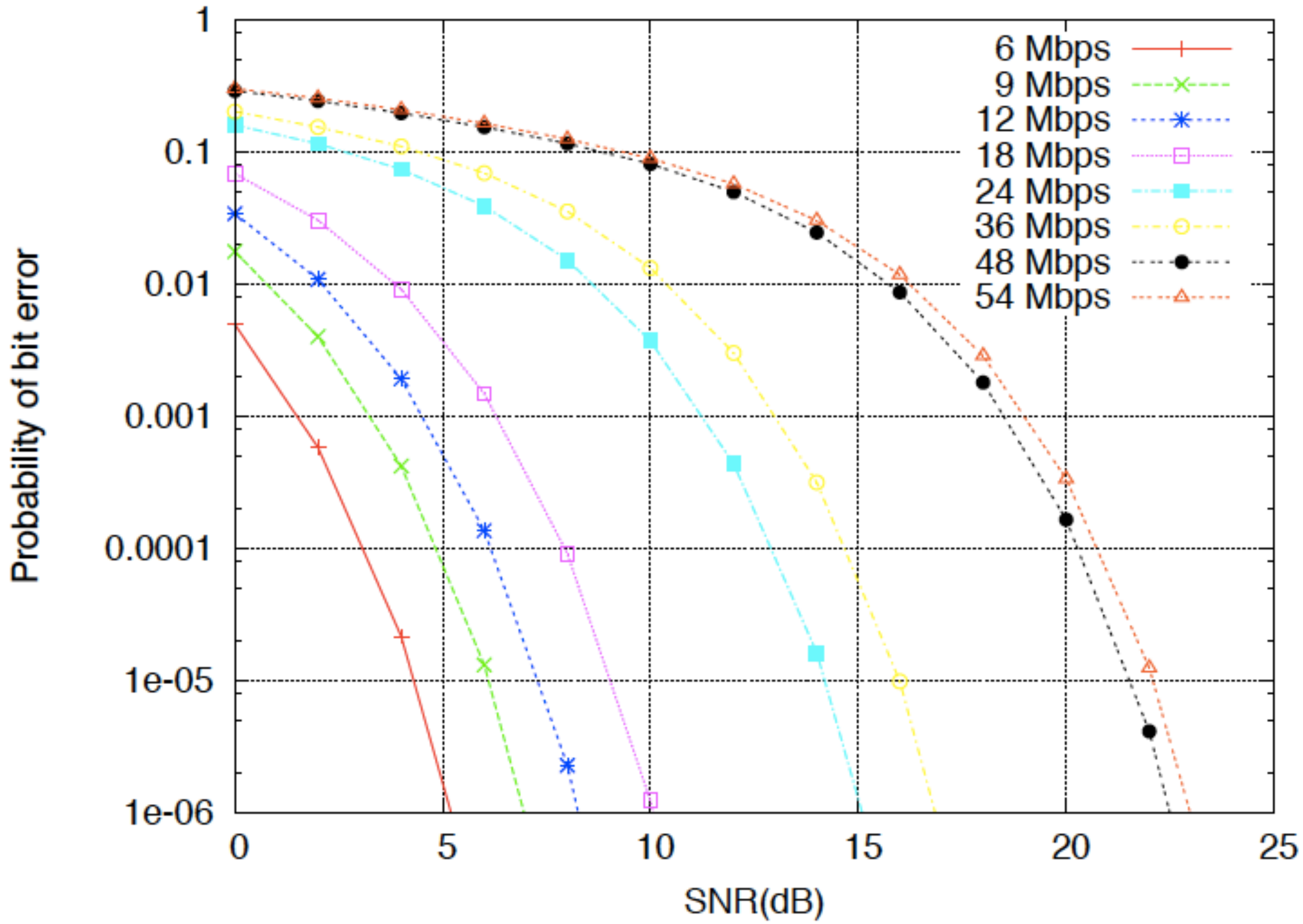


$\{\alpha_\ell\}_{\ell=1}^L$, $\{\theta_\ell\}_{\ell=1}^L$, and $\{\tau_\ell\}_{\ell=1}^L$ are the random channel amplitudes, phases, and delay respectively, where ℓ is the channel index

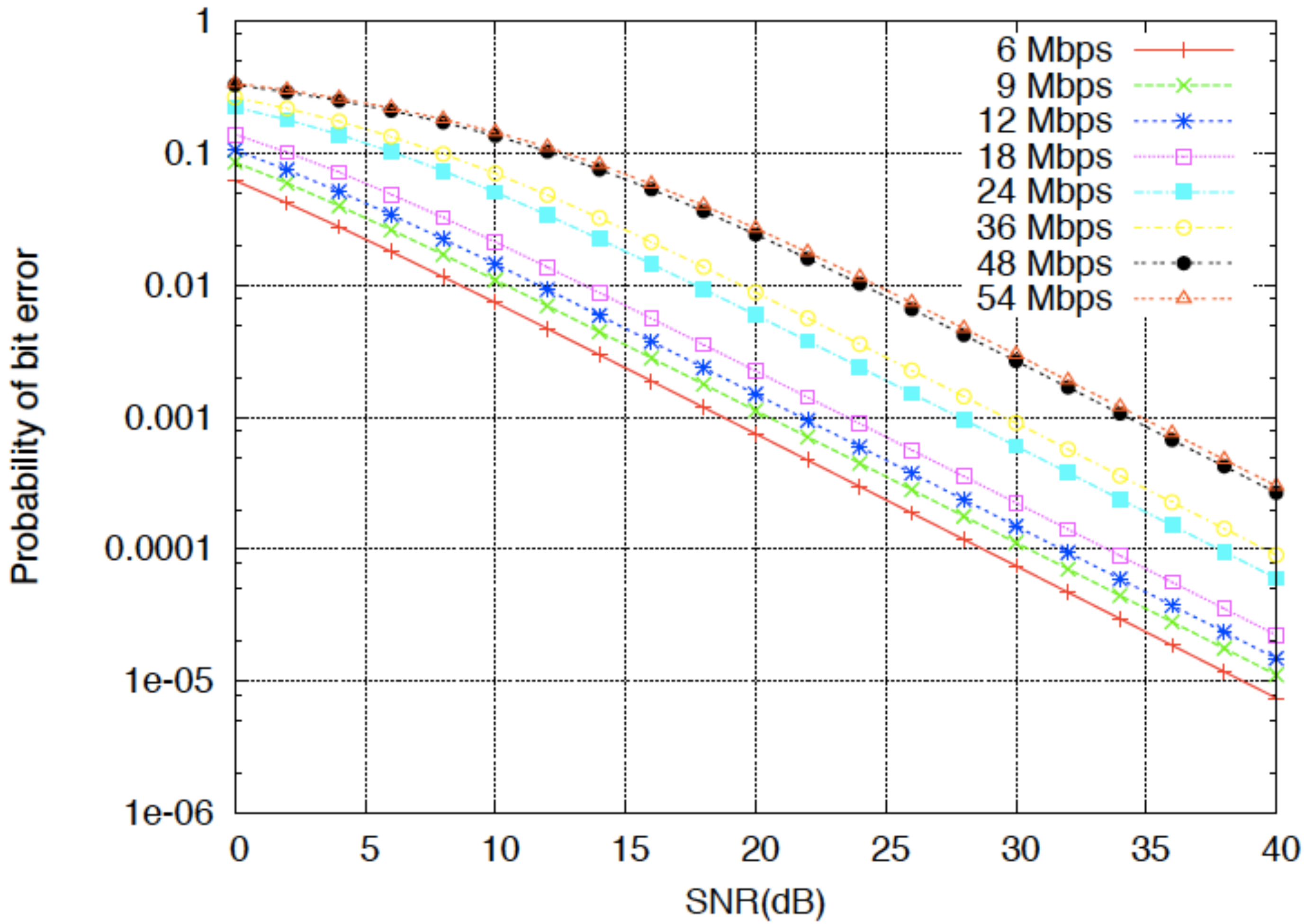
BER for Available Modulations in 802.11a



BER for Available Data Rates in 802.11a for AWGN



BER for Available Data Rates in 802.11a for Rayleigh Fading (L=1)



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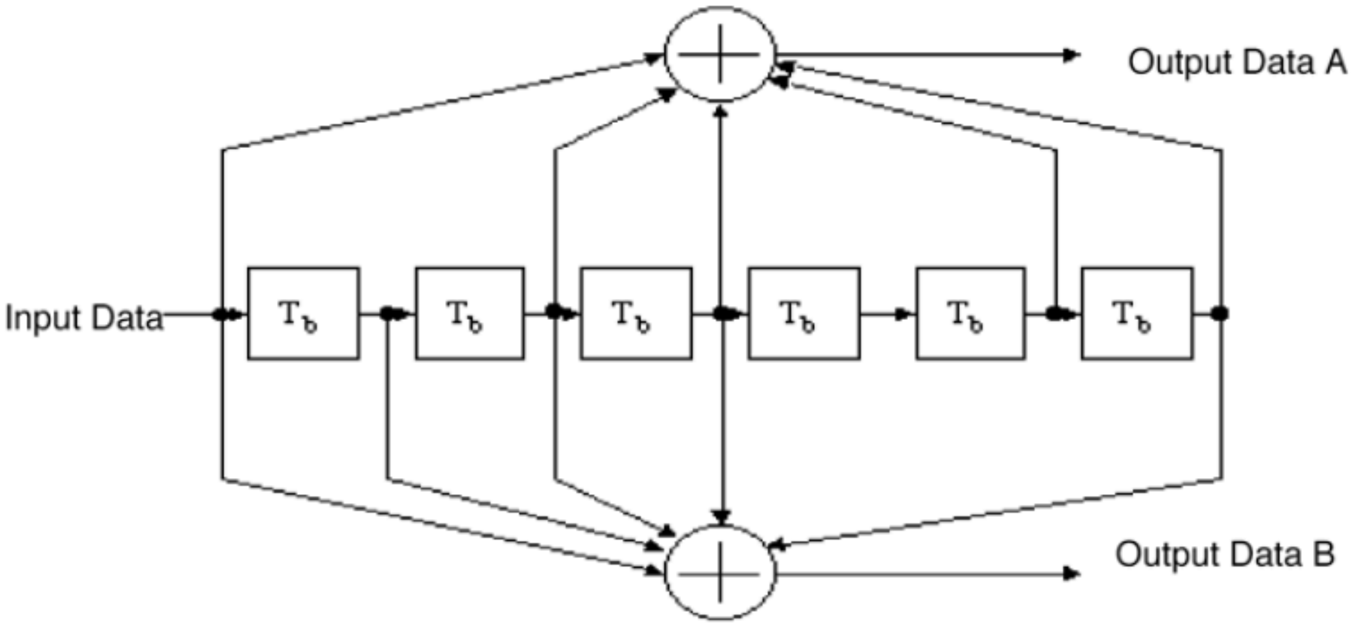
BPSK	1/2	1	48	24	6	3	1.5
BPSK	3/4	1	48	36	9	4.5	2.25
QPSK	1/2	2	96	48	12	6	3
QPSK	3/4	2	96	72	18	9	4.5
16-QAM	1/2	4	192	96	24	12	6
16-QAM	3/4	4	192	144	36	18	9
64-QAM	2/3	6	288	192	48	24	12
64-QAM	3/4	6	288	216	54	27	13.5

Convolutional Encoder

- Use the industry-standard generator polynomials,
  - $g_0 = 133_8$ and $g_1 = 171_8$, of rate $R = 1/2$,

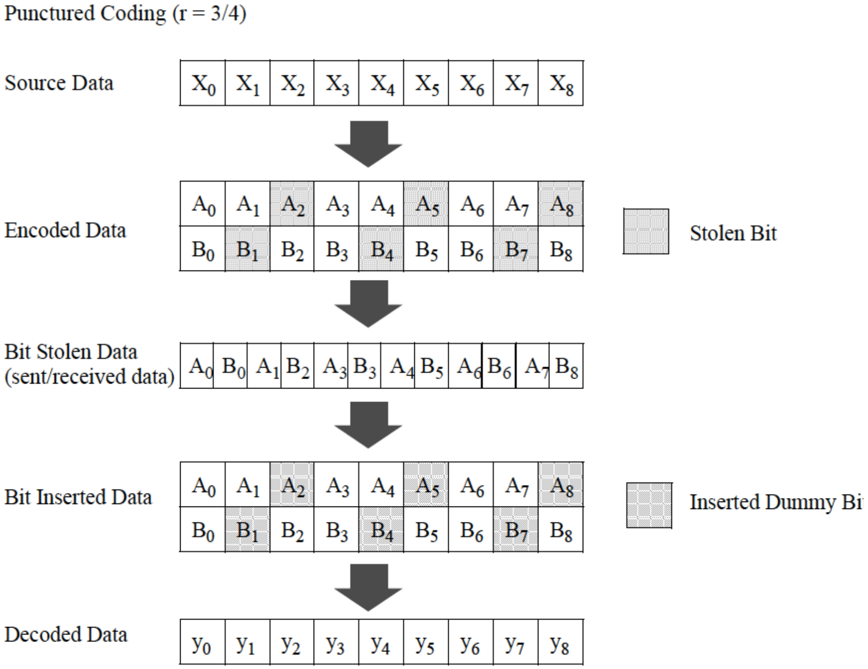


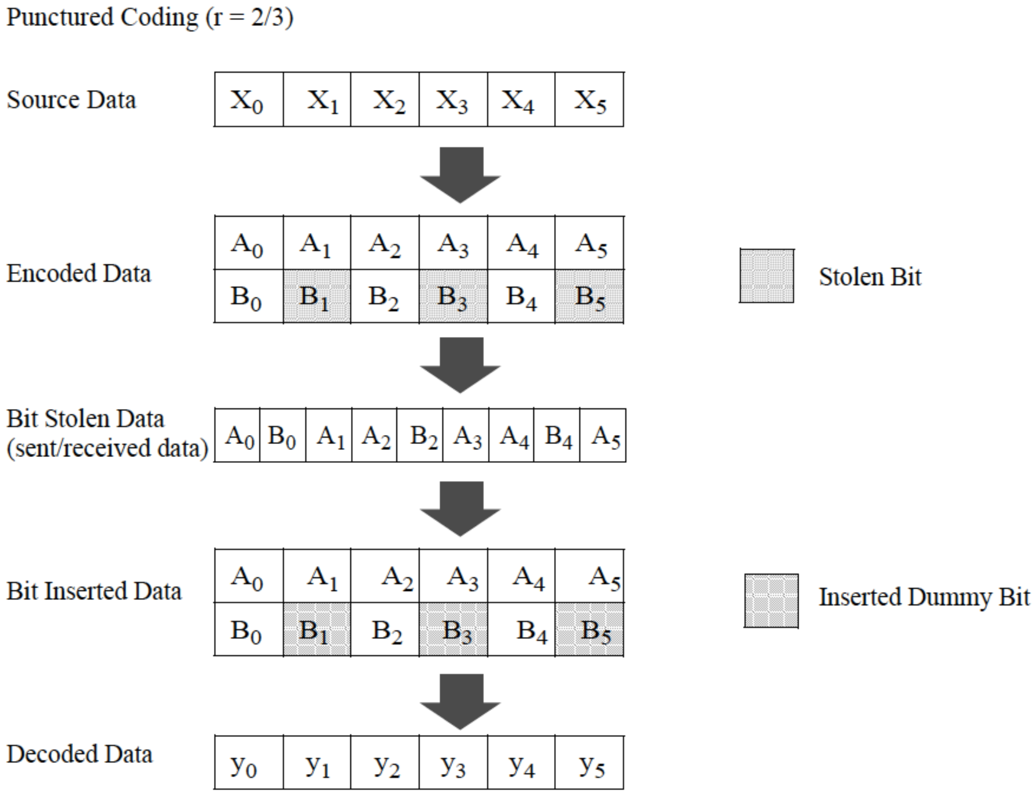
(first output)

(second output)

Punctured Coding

- To omit some of the encoded bits in the transmitter
  - Thus reducing the number of transmitted bits and **increasing the coding rate**
  - Inserting a dummy "zero" metric into the convolutional decoder on the receive side
  - Decoding by the Viterbi algorithm is recommended.





Performance of Viterbi Decoder

The upper bound probability of error: $P_e(L) \leq 1 - (1 - P_u)^{8L}$

The union bound P_u of the first-event error probability is given by:

$$P_u = \sum_{d=d_{free}}^{\infty} a_d \times P_d$$

FEC rate	d_f	$(a_{d_f}, a_{d_f+1}, a_{d_f+2}, \cdots)$
1/2	10	(11, 0, 38, 0, 193, 0, 1331, 0, 7275, 0, 40406, 0, 234969, 0, 1337714, 0, 7594819, 0, 433775588, 0, $\cdots$)
2/3	6	(1, 16, 48, 158, 642, 2435, 9174, 34701, 131533, 499312, $\cdots$)
3/4	5	(8, 31, 160, 892, 4512, 23297, 120976, 624304, 3229885, 16721329, $\cdots$)

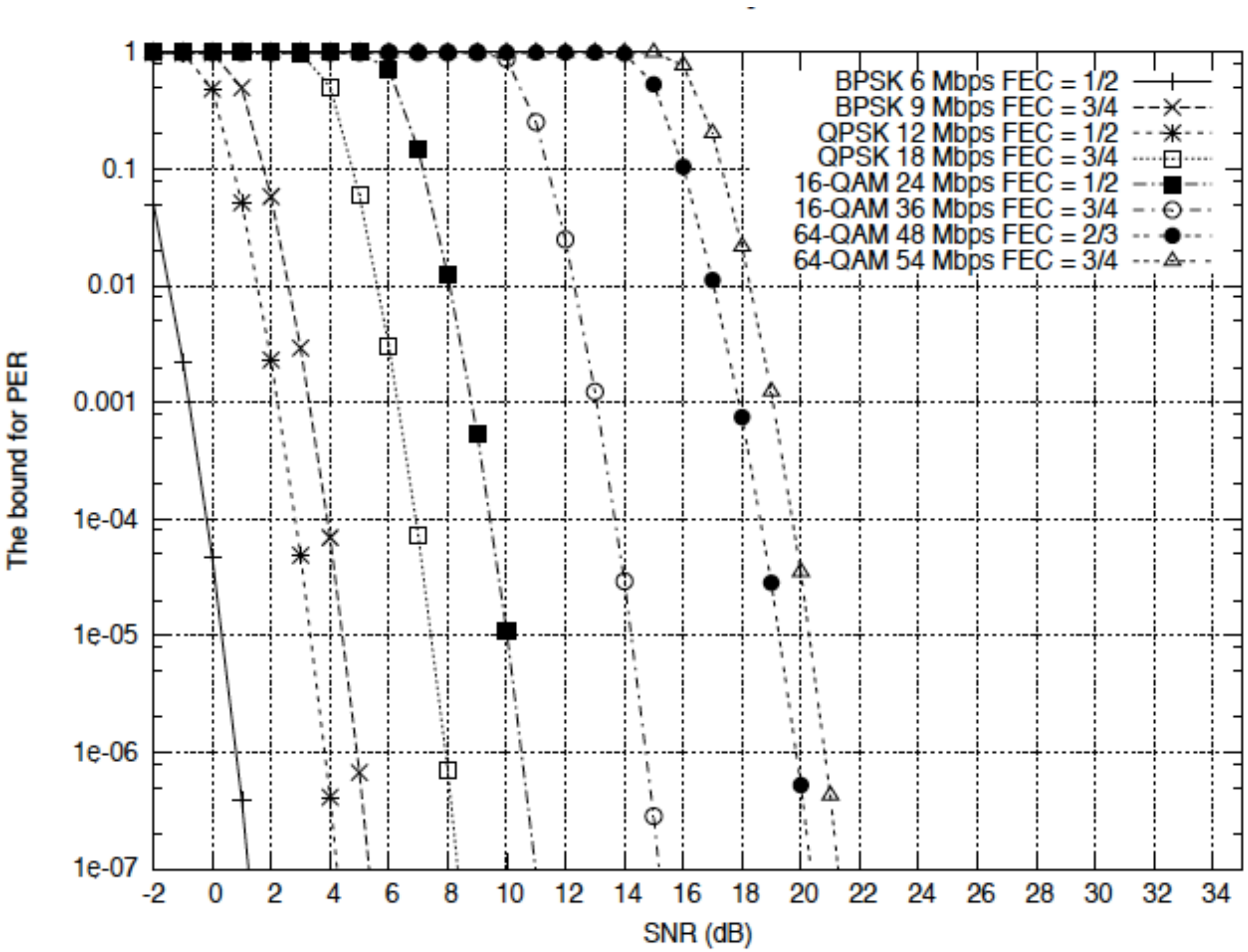
Performance of Viterbi Decoder

P_d is the probability that an incorrect path at distance d from the correct path is chosen by the Viterbi decoder:

$$P_d = \begin{cases} \sum_{k=(d+1)/2}^{d} \binom{d}{k} \rho^k (1-\rho)^{d-k} & \text{d is odd} \\ \frac{1}{2}\binom{d}{d/2} \rho^{d/2}(1-\rho)^{d/2} + \sum_{k=d/2+1}^{d} \binom{d}{k} \rho^k (1-\rho)^{d-k} & \text{d is even} \end{cases}$$

ρ: the bit error probability for the physical modulation

Upper Bound for the PER in 802.11a (Length=1500Bytes)



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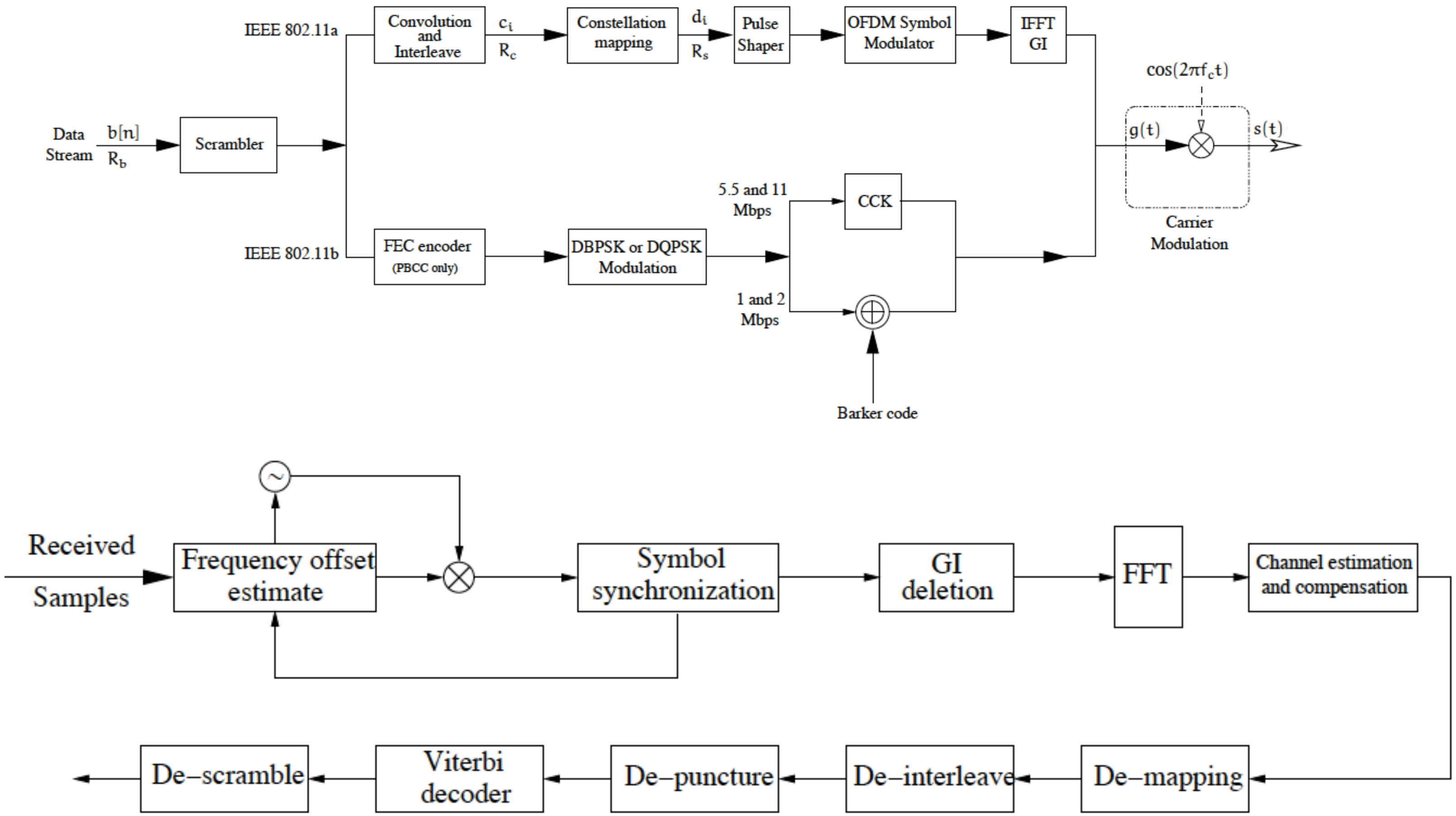
802.11 Transmission and Reception: A Complete Picture



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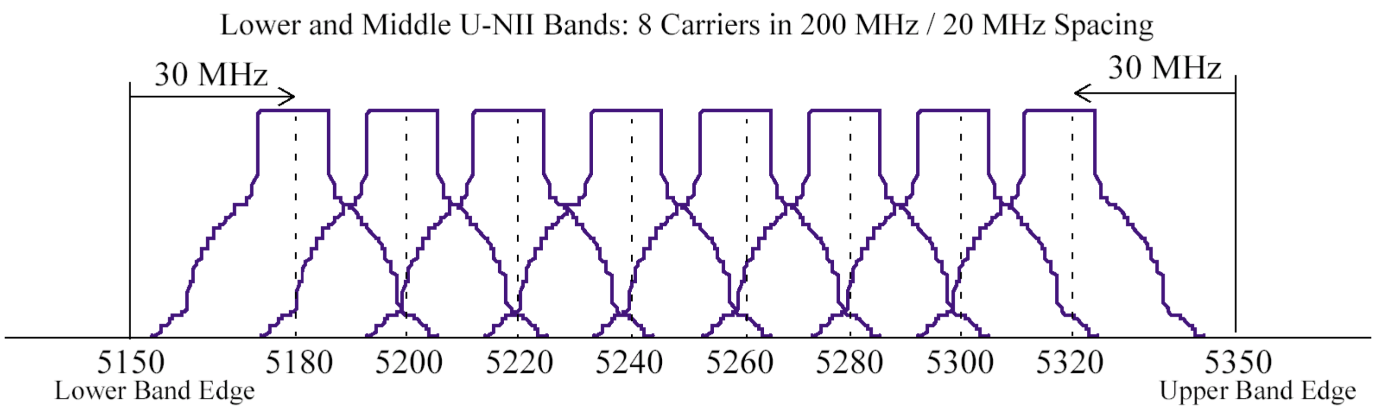
BPSK	3/4	1	48	36	9	4.5	2.25
QPSK	1/2	2	96	48	12	6	3
QPSK	3/4	2	96	72	18	9	4.5
16-QAM	1/2	4	192	96	24	12	6
16-QAM	3/4	4	192	144	36	18	9
64-QAM	2/3	6	288	192	48	24	12
64-QAM	3/4	6	288	216	54	27	13.5

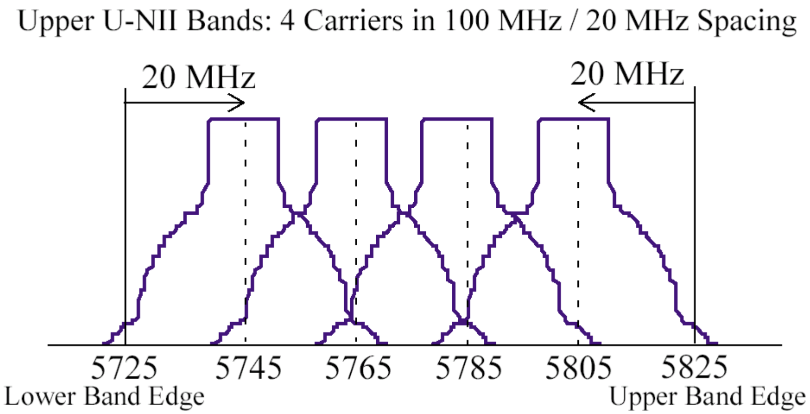
OFDM: A Brief Review

- Orthogonal frequency division multiplexing (OFDM) has very good ISI mitigation property
- Splits the high bit rate stream into many lower bit rate streams
- Each stream being sent using an independent carrier frequency

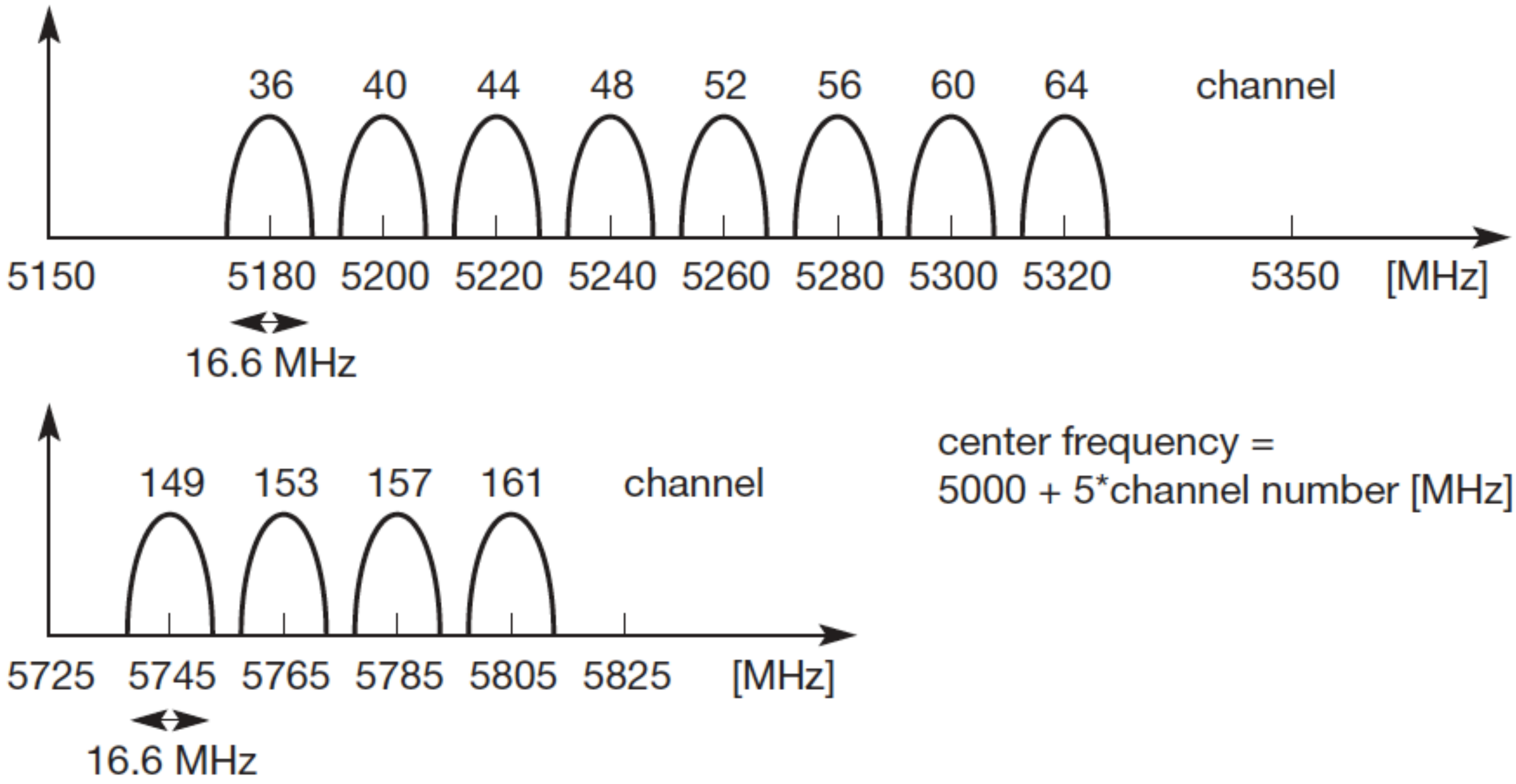
802.11a Channels

- 8 independent channels in 5.15GHz-5.35GHz
- 4 independent channels in 5.725-5.825GHz



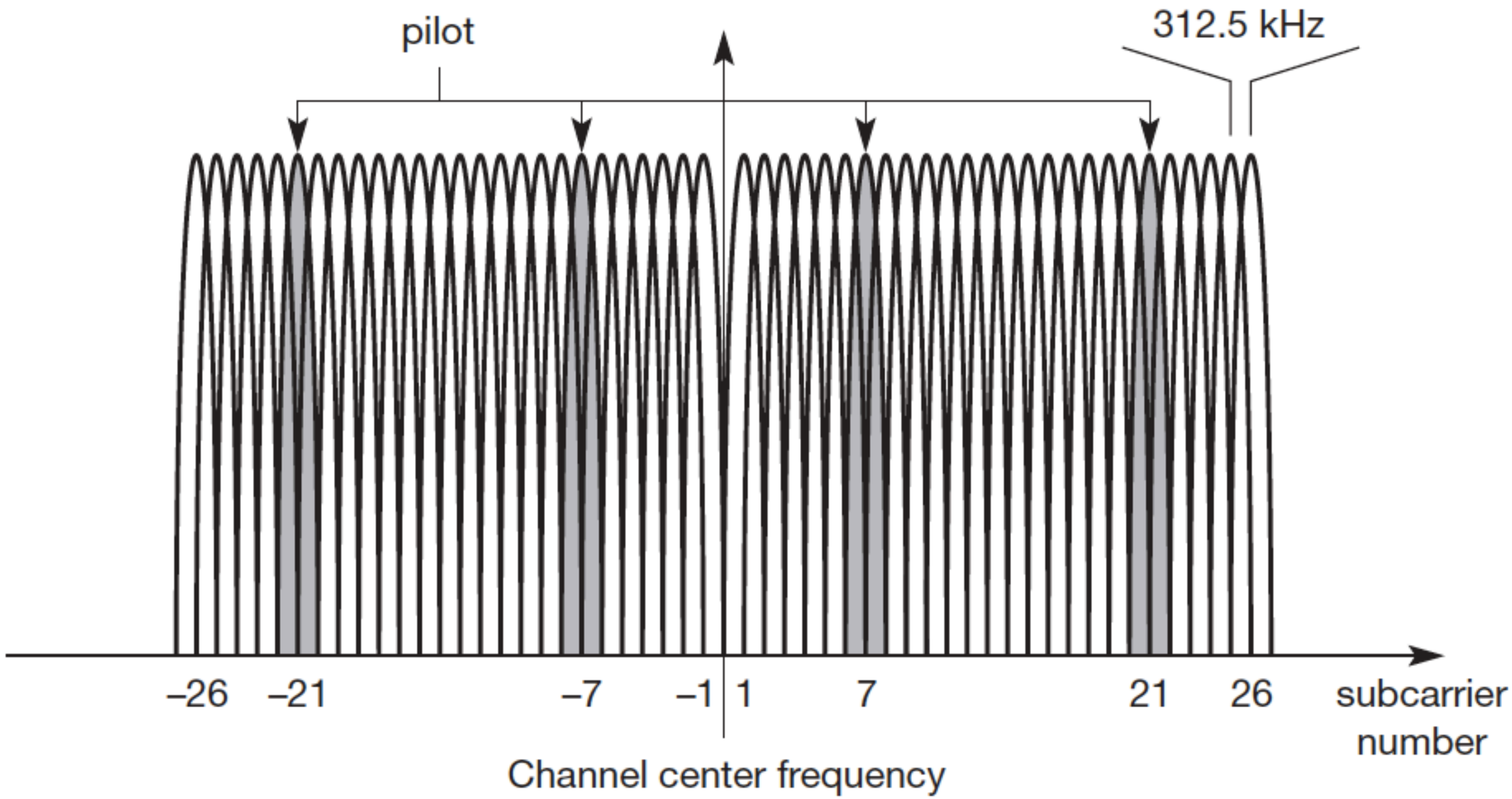


802.11a Channel Numbering

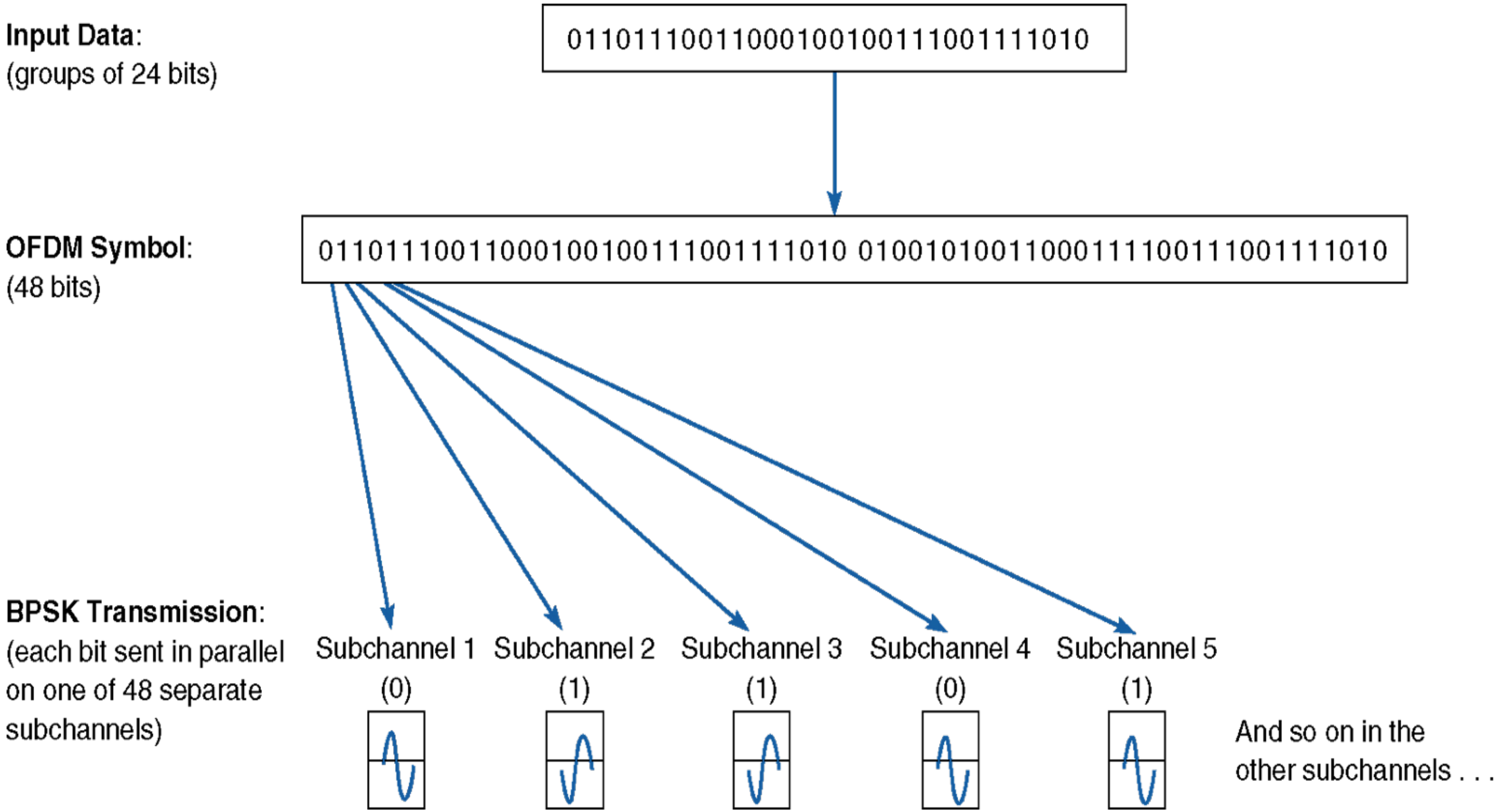


center frequency =
5000 + 5*channel number [MHz]

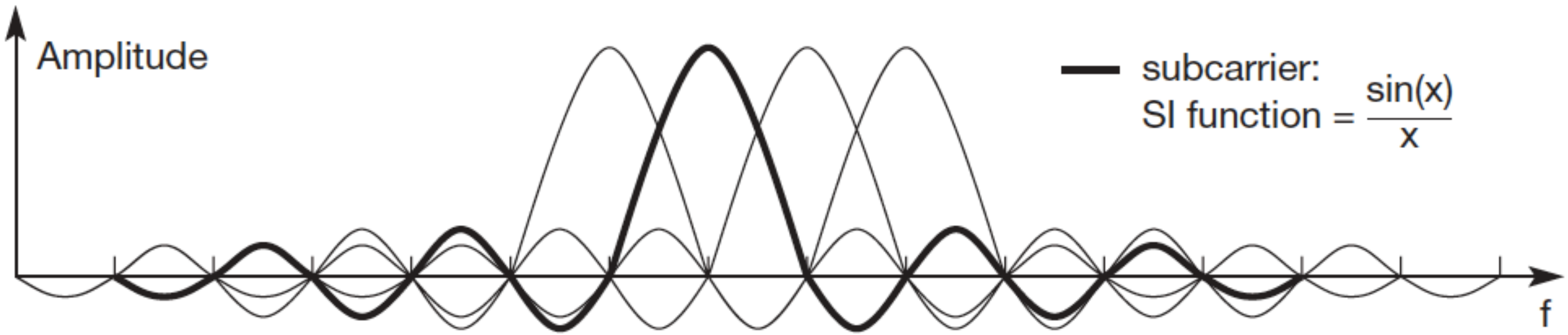
OFDM Sub-channels in 802.11a



802.11a: Use of OFDM and BPSK



Superposition of Orthogonal Frequencies



The maximum of one subcarrier frequency appears exactly at a frequency where all other subcarriers equal zero.

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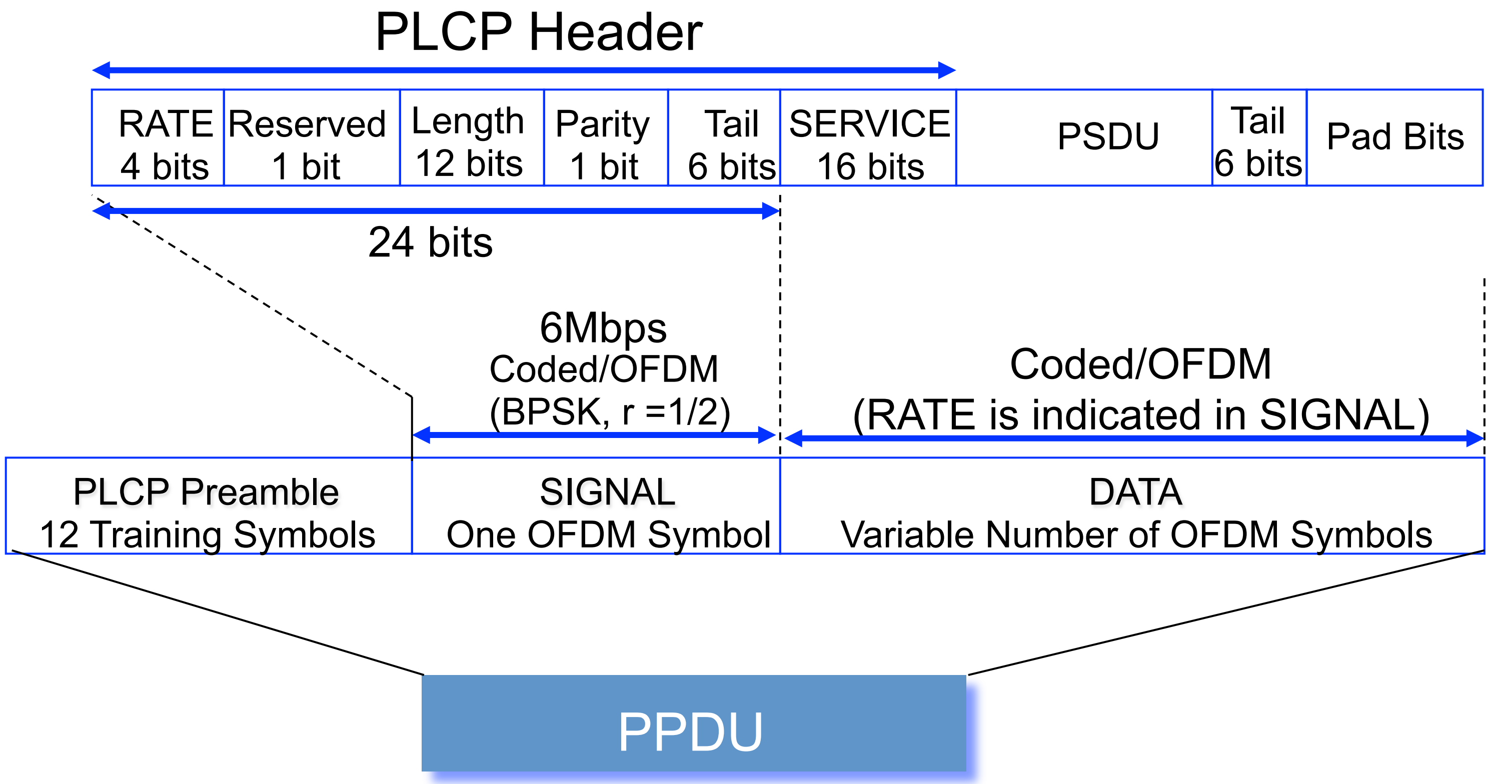
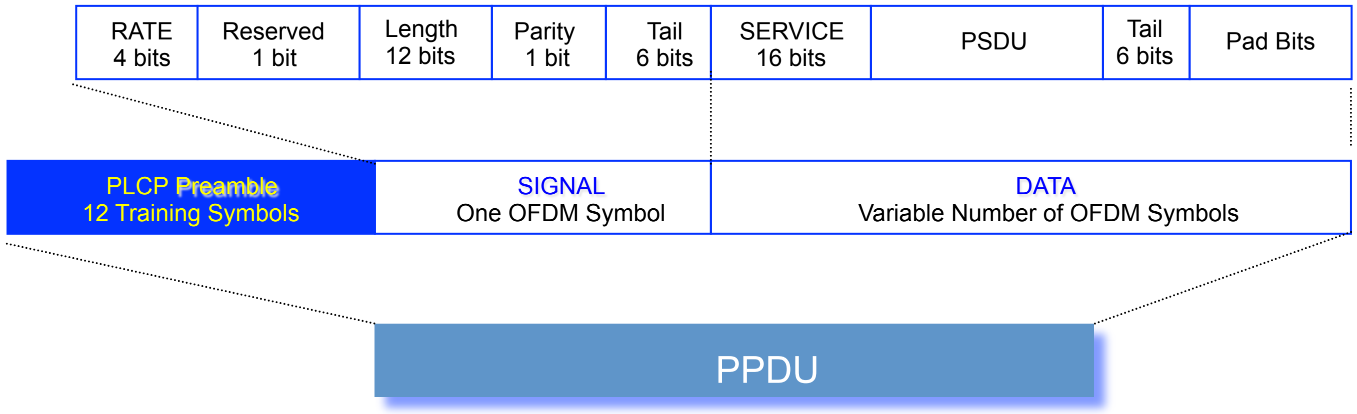
IEEE 802.11a PLCP frame format



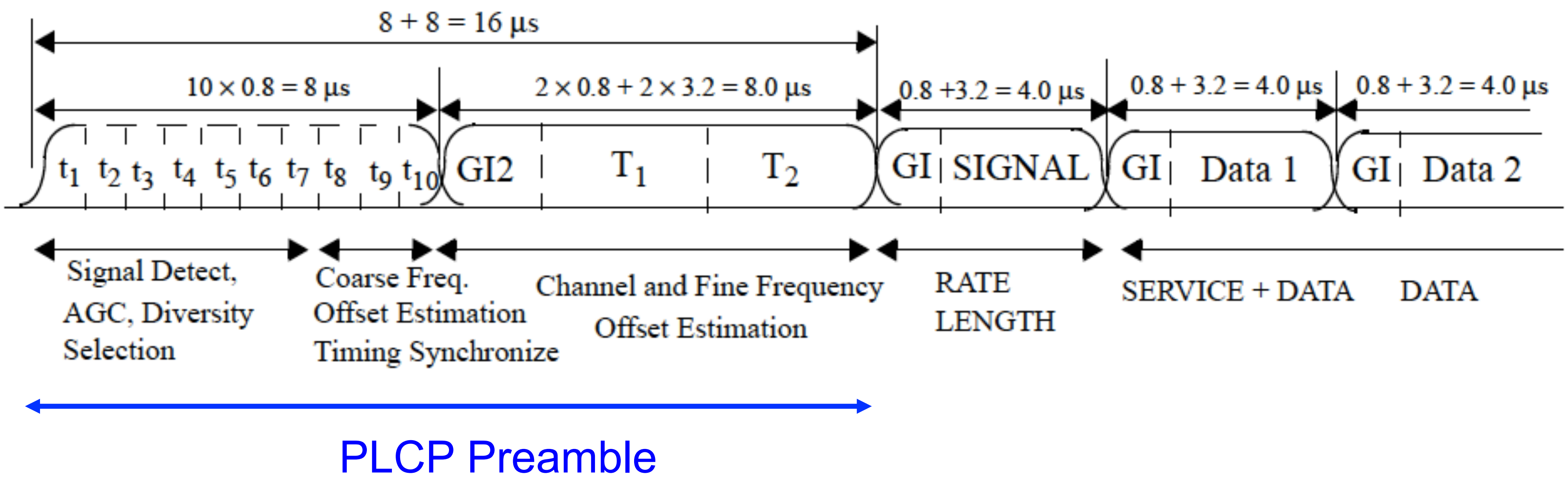
PLCP Preamble



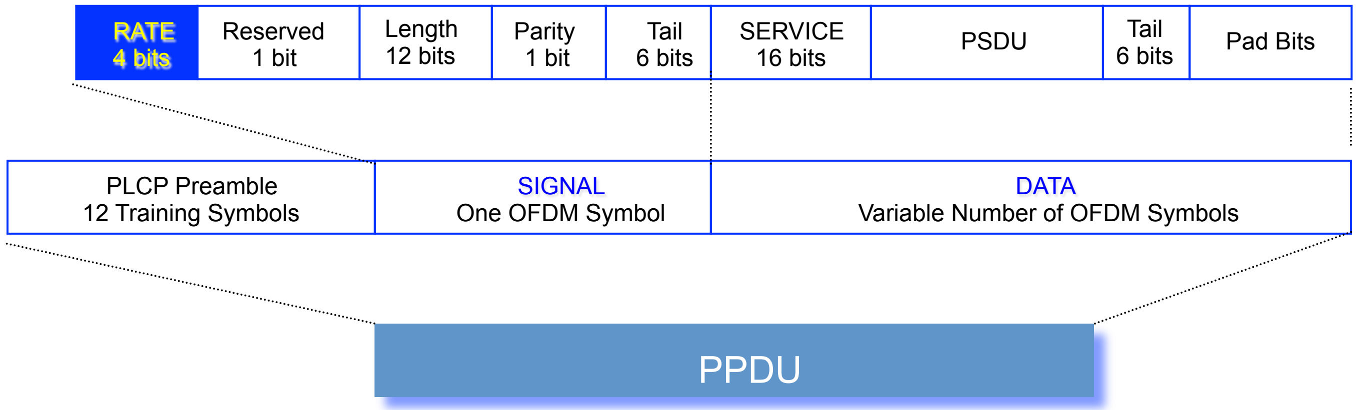
Preamble field contains

- <u>10 short training sequence</u>
  - used for AGC convergence, diversity selection, timing acquisition, and coarse frequency acquisition in the receiver
- <u>2 long training sequence</u>
  - used for channel estimation and fine frequency acquisition in the receiver
- And a guard interval (GI)

PLCP Preamble

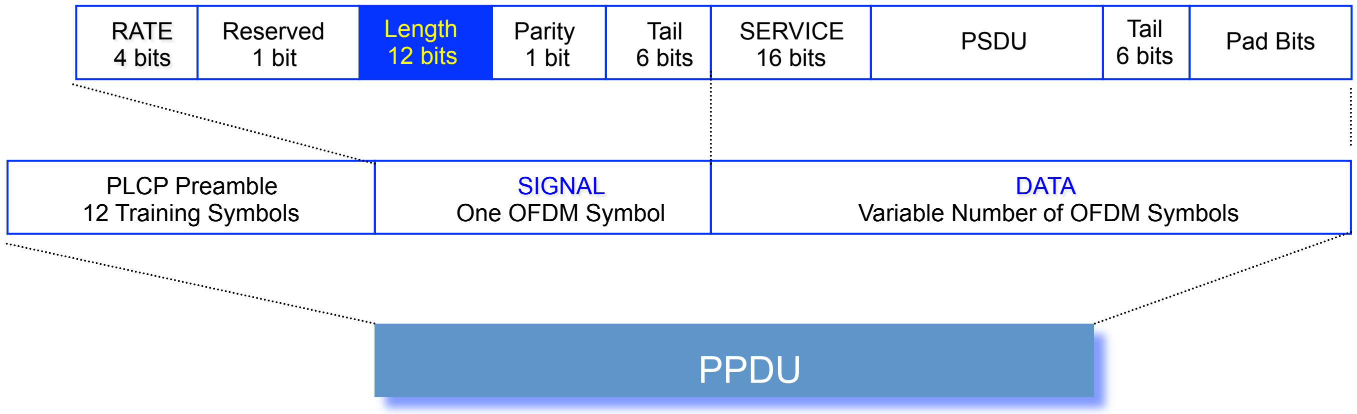


PLCP Rate/Length



- Data Rates (<u>determined from TXVECTOR</u>)
  - 1101 : 6Mbps (M)
  - 1111 : 9Mbps
  - 0101 : 12Mbps (M)
  - 0111 : 18Mbps
  - 1001 : 24Mbps (M)
  - 1011 : 36Mbps
  - 0001 : 48Mbps
  - 0011 : 54Mbps

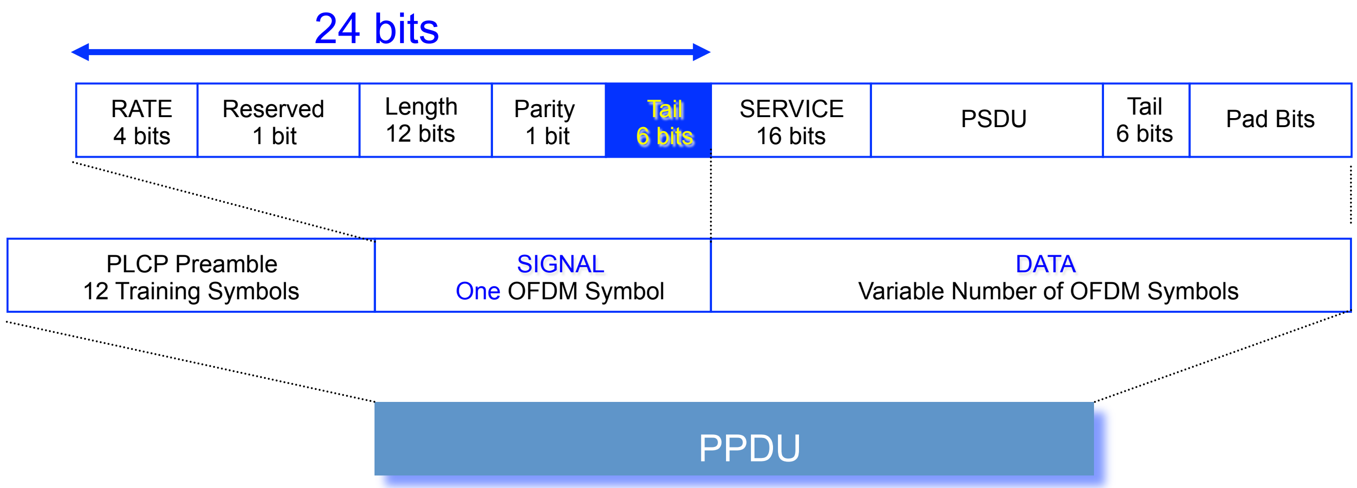
PLCP Rate/Length



- The PLCP LENGTH field shall be an unsigned 12-bit integer that indicates the number of **octets** in the PSDU that the MAC is currently requesting the PHY to transmit

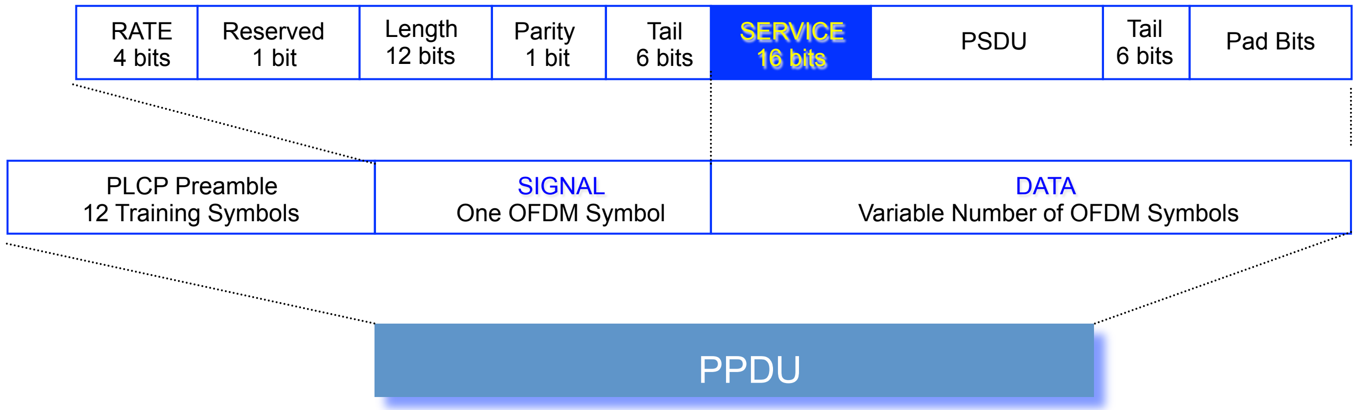
- Used by the PHY to determine the number of octet transfers that will occur between the MAC and the PHY after receiving a request to start transmission

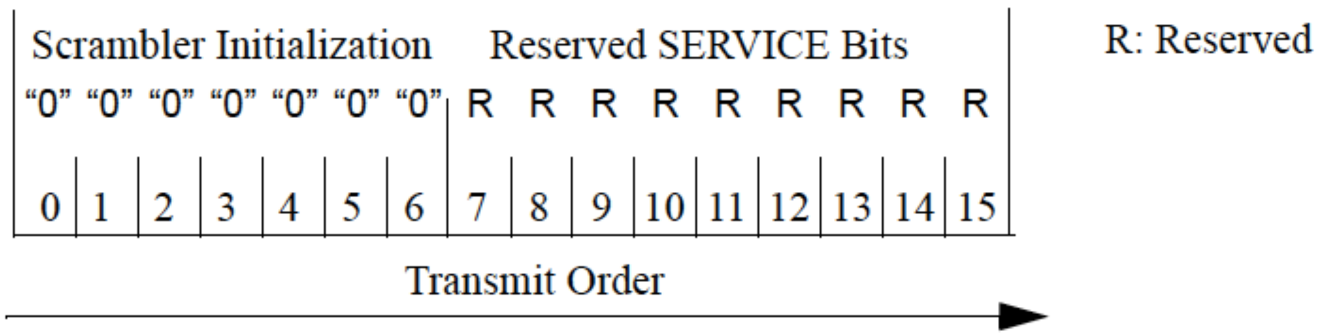
PLCP Tail Subfield



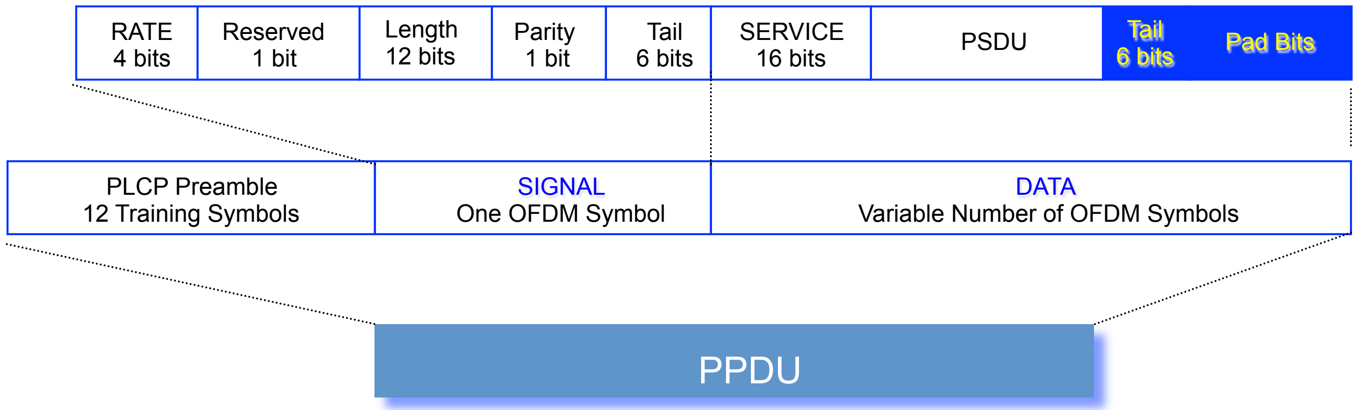
- 6 'zero' bit
- To make the length of SIGNAL field to be 24 bits (for the N_{DBPS}=24 in 6Mbps mode)
- To facilitate a reliable and timely detection of the RATE and LENGTH fields

PLCP Service



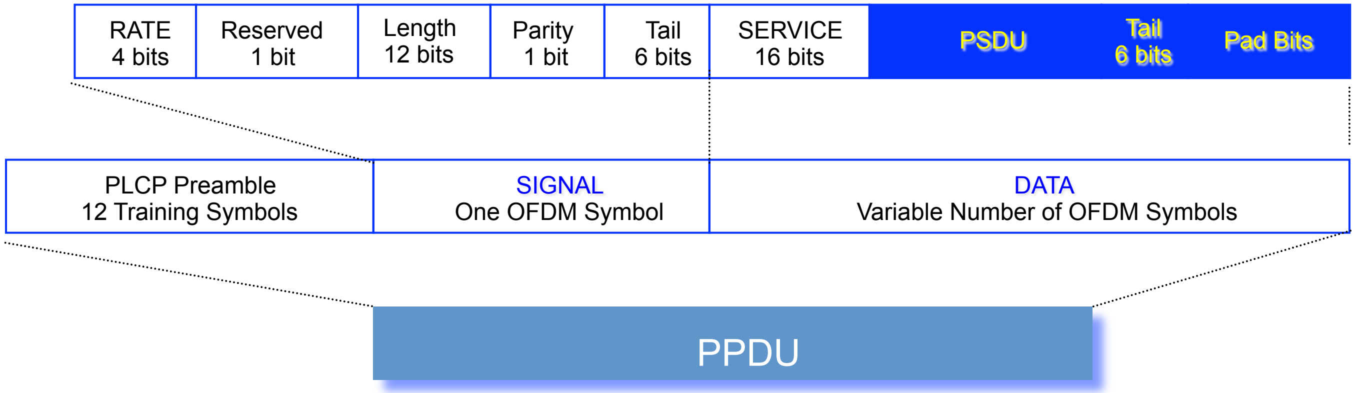


PSDU Tail



- Append 6 non-scrambled tail bits for PSDU to return the convolutional code to the "zero state"
- Add pad bits (with "zero" and at least 6 bits) such that the length of DATA field is a multiple of N_{DBPS}

PLCP DATA Encoding



1. **Encode** data string with convolutional encoder (include punctured coding)
2. **Divide** encoded bit string into groups of N_{CBPS} bits
3. Within each group, perform data **interleaving**
4. For each of the groups, **convert** bit string group into a **complex number** according to the modulation tables (see slides 7-10)
5. Divide the complex number string into groups of 48 complex numbers, each such group will be associated with one OFDM symbol
   - map to subcarriers –26~-22, -20~-8, -6~-1, 1~6, 8~20, 22~26
   - 4 subcarriers –21, -7, 7, 21 are used for pilot
   - subcarrier 0 is useless
6. Convert subcarriers to time domain using inverse Fast Fourier transform (IFFT)
7. Append OFDM symbols after SINGNAL and un-convert to RF freq.

IEEE 802.11a TxVector

Parameter	Associated primitive	Value
LENGTH	PHY-TXSTART.request (TXVECTOR)	1–4095
DATATRATE	PHY-TXSTART.request (TXVECTOR)	6, 9, 12, 18, 24, 36, 48, and 54 Mb/s for 20 MHz channel spacing (Support of 6, 12, and 24 Mb/s data rates is mandatory.) 3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s for 10 MHz channel spacing (Support of 3, 6, and 12 Mb/s data rates is mandatory.) 1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s for 5 MHz channel spacing (Support of 1.5, 3, and 6 Mb/s data rates is mandatory.)
SERVICE	PHY-TXSTART.request (TXVECTOR)	Scrambler initialization; 7 null bits + 9 reserved null bits
TXPWR_LEVEL	PHY-TXSTART.request (TXVECTOR)	1–8
TIME_OF_ DEPARTURE_ REQUESTED	PHY-TXSTART.request (TXVECTOR)	False, true. When true, the MAC entity requests that the PHY PLCP entity measures and reports time of departure parameters corresponding to the time when the first frame energy is sent by the transmitting port; when false, the MAC entity requests that the PHY PLCP entity neither measures nor reports time of departure parameters.

IEEE 802.11a RxVector

Parameter	Associated primitive	Value
LENGTH	PHY-RXSTART.indication	1–4095
RSSI	PHY-RXSTART.indication (RXVECTOR)	0–RSSI maximum
DATARATE	PHY-RXSTART.request (RXVECTOR)	6, 9, 12, 18, 24, 36, 48, and 54 Mb/s for 20 MHz channel spacing (Support of 6, 12, and 24 Mb/s data rates is mandatory.) 3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s for 10 MHz channel spacing (Support of 3, 6, and 12 Mb/s data rates is mandatory.) 1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s for 5 MHz channel spacing (Support of 1.5, 3, and 6 Mb/s data rates is mandatory.)
SERVICE	PHY-RXSTART.request (RXVECTOR)	Null
RCPI (see NOTE)	PHY-RXSTART.indication (RXVECTOR) PHY-RXEND.indication (RXVECTOR)	0–255
ANT_STATE (see NOTE)	PHY-RXSTART.indication (RXVECTOR) PHY-RXEND.indication (RXVECTOR)	0–255
RX_START_OF_FRAME_OFFSET	PHY-RXSTART.indication (RXVECTOR)	0 to $2^{32}-1$. An estimate of the offset (in 10 ns units) from the point in time at which the start of the preamble corresponding to the incoming frame arrived at the receive antenna port to the point in time at which this primitive is issued to the MAC.
NOTE—Parameter is present only when dot11RadioMeasurementActivated is true.		

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 ($T_{GI} + T_{FFT}$)
T_{SHORT}: Short training sequence duration	8 μs ($10 \times T_{FFT}/4$)	16 μs ($10 \times T_{FFT}/4$)	32 μs ($10 \times T_{FFT}/4$)
T_{LONG}: Long training sequence duration	8 μs ($T_{GI2} + 2 \times T_{FFT}$)	16 μs ($T_{GI2} + 2 \times T_{FFT}$)	32 μs ($T_{GI2} + 2 \times T_{FFT}$)