Modern Wireless Networks

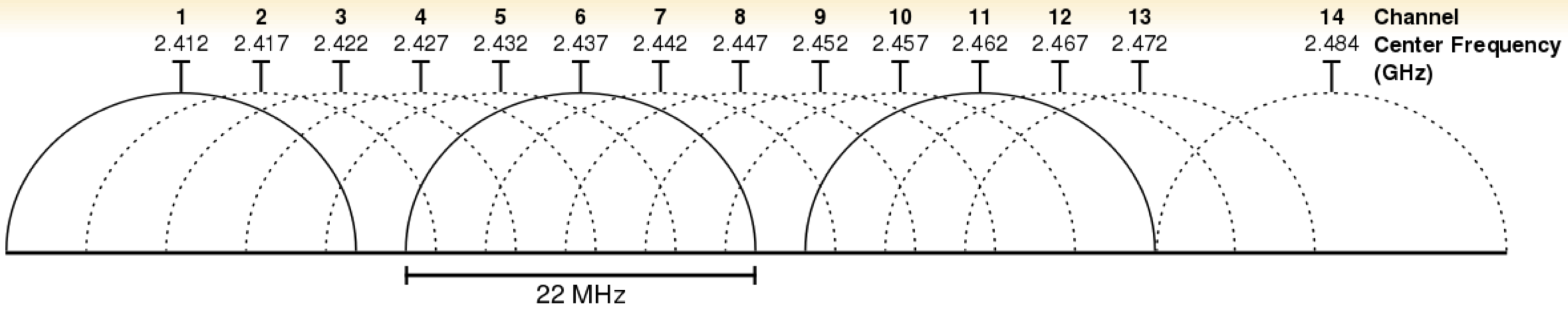
Wireless LANs

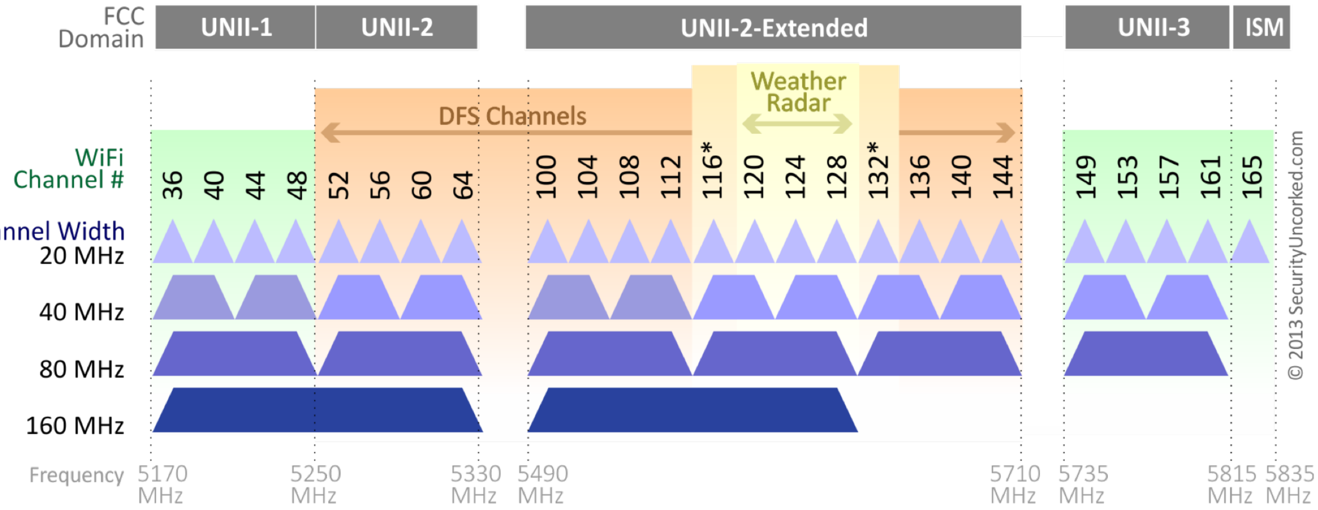
UNIVERSITY AT ALBANY
State University of New York

ICEN 574– Spring 2019

Prof. Dola Saha

Channels (Frequency)

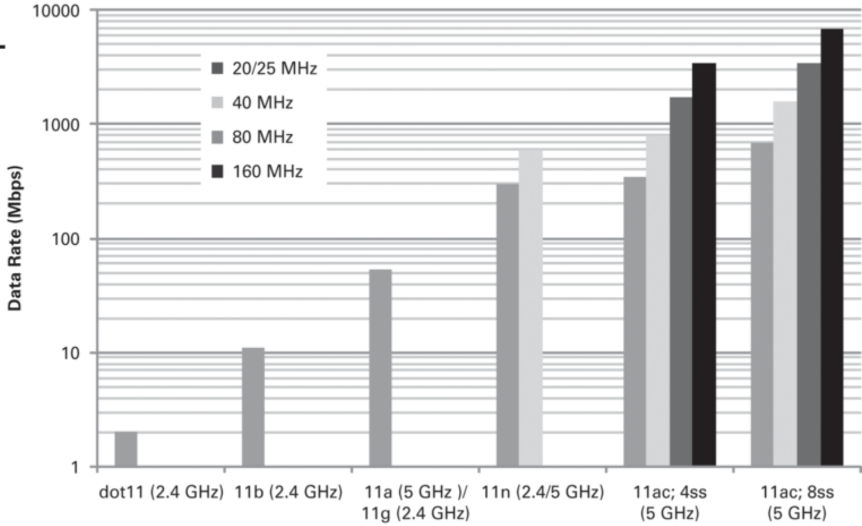




IEEE 802.11 Wireless LANs

➢ MAC and PHY Standard http://www.ieee802.org/11/

	802.11	802.11b	802.11a	802.11g	802.11n	802.11ac
PHY technology	DSSS	DSSS/ CCK	OFDM	OFDM DSSS/ CCK	SDM/OFDM	SDM/OFDM MU-MIMO
Data rates (Mbps)	1, 2	5.5, 11	6–54	1–54	6.5–600	6.5–6933.3
Frequency band (GHz)	2.4	2.4	5	2.4	2.4 and 5	5
Channel spacing (MHz)	25	25	20	25 MHz	20 and 40	20, 40, 80, and 160

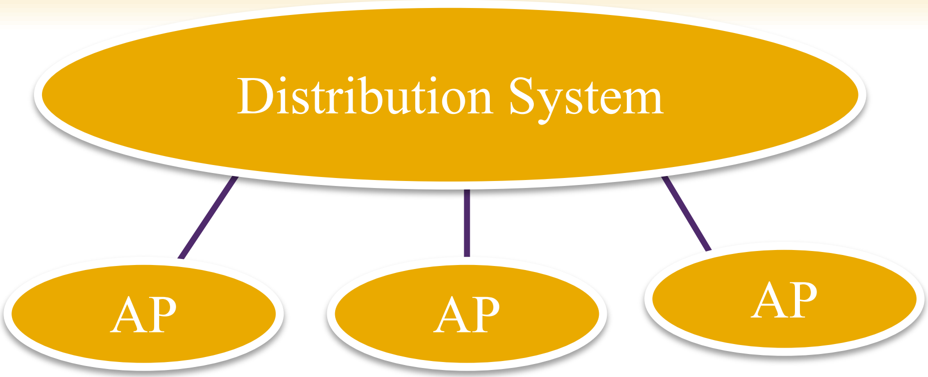


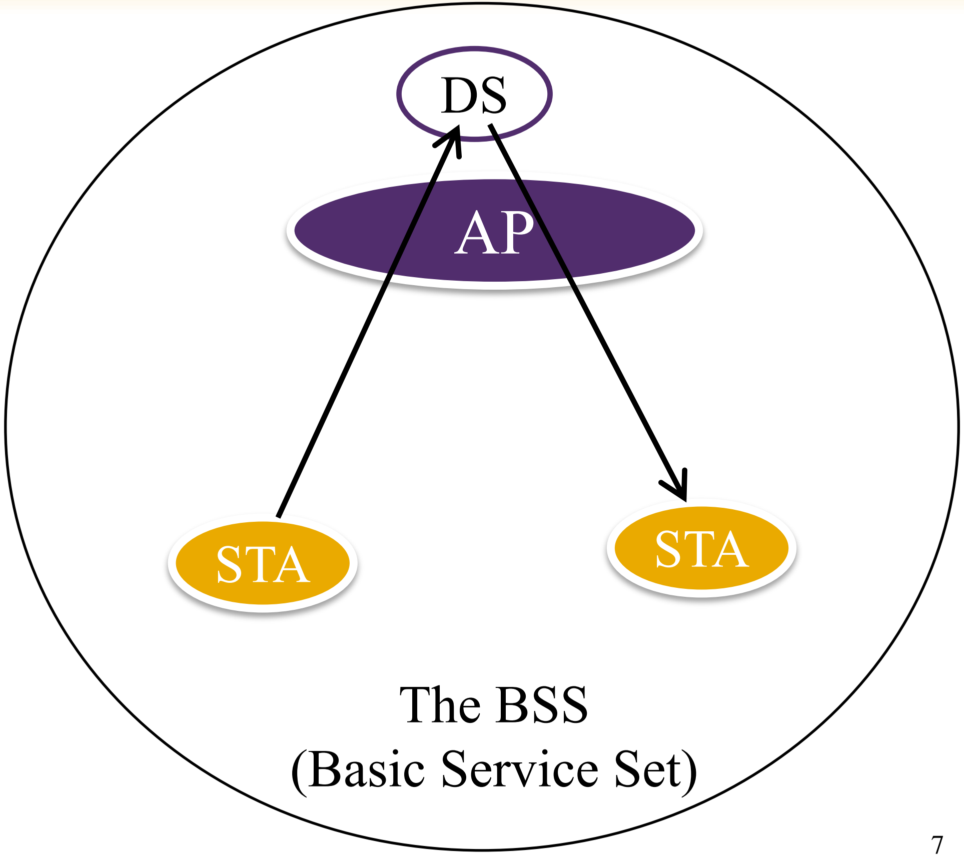
CSMA/CA

Hidden Terminal

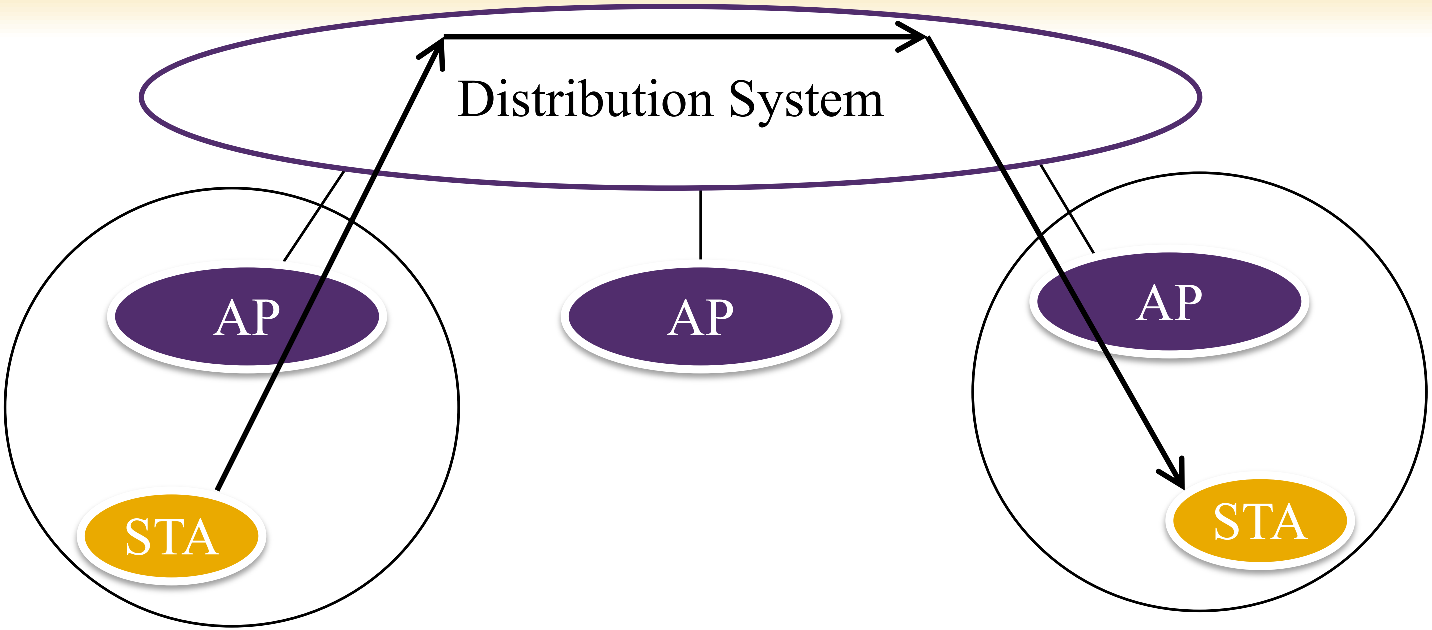
Exposed Terminal

Network Architecture



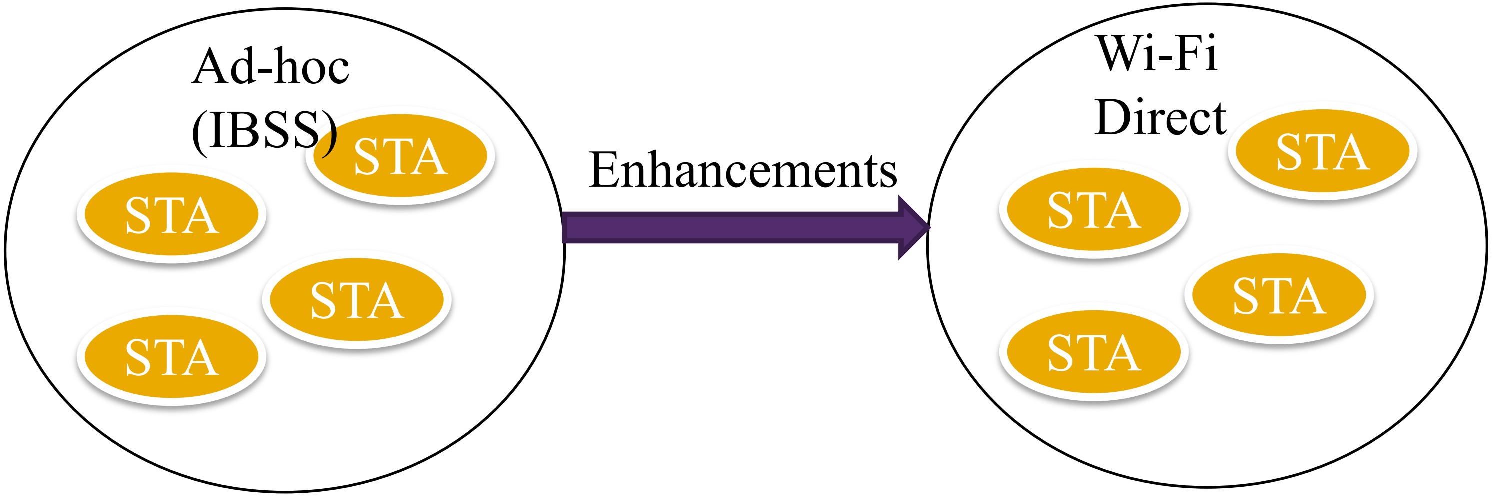


Network Architecture



- A set of one or more interconnected basic service sets (BSSs) and integrated local area networks (LANs) that appears as a single BSS to the logical link control layer at any station associated with one of those BSSs.

Infrastructure-less



PHY

- DSSS (Chapter 15 of standard)
- High rate DSSS (Chapter 16)
- OFDM PHY (Chapter 17)
- Extended Rate PHY (Chapter 18)
- High Throughput PHY (Chapter 19)
- Directional multi-gigabit (DMG) PHY (Chapter 20)
- Very high throughput (VHT) PHY (Chapter 21)
- Television very high throughput (TVHT) PHY (Chapter 22)

OFDM-PHY Timing

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)	0.156 25 MHz (= 10 MHz/64)	0.078 125 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 ($1/\Delta_F$)
$T_{PREAMBLE}$: PHY preamble duration	16 μs ($T_{SHORT} + T_{LONG}$)	32 μs ($T_{SHORT} + T_{LONG}$)	64 μs ($T_{SHORT} + T_{LONG}$)

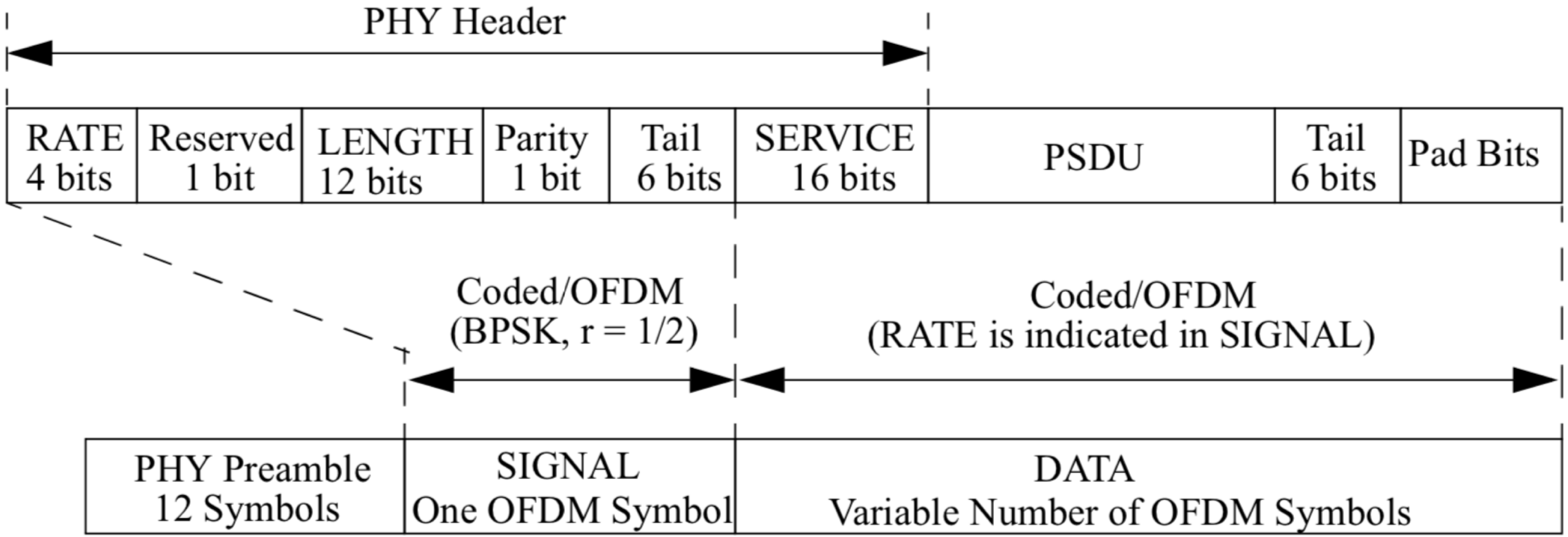
OFDM-PHY Timing

Parameter	Value (20 MHz channel spacing)	Value (10 MHz channel spacing)	Value (5 MHz channel spacing)
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 ($T_{GI2} + 2 \times T_{FFT}$)

Modulation & Coding

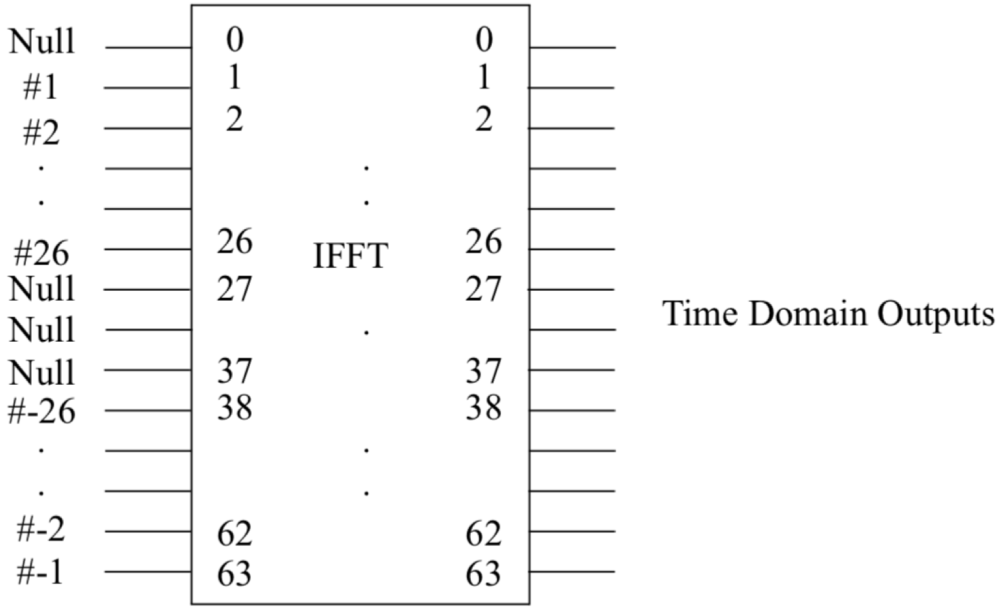
Modulation	Coding rate (R)	Coded bits per subcarrier (N_{BPSC})	Coded bits per OFDM symbol (N_{CBPS})	Data bits per OFDM symbol (N_{DBPS})	Data rate (Mb/s) (20 MHz channel spacing)	Data rate (Mb/s) (10 MHz channel spacing)	Data rate (Mb/s) (5 MHz channel spacing)
BPSK	1/2	1	48	24	6	3	1.5
BPSK	3/4	1	48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

OFDM PHY

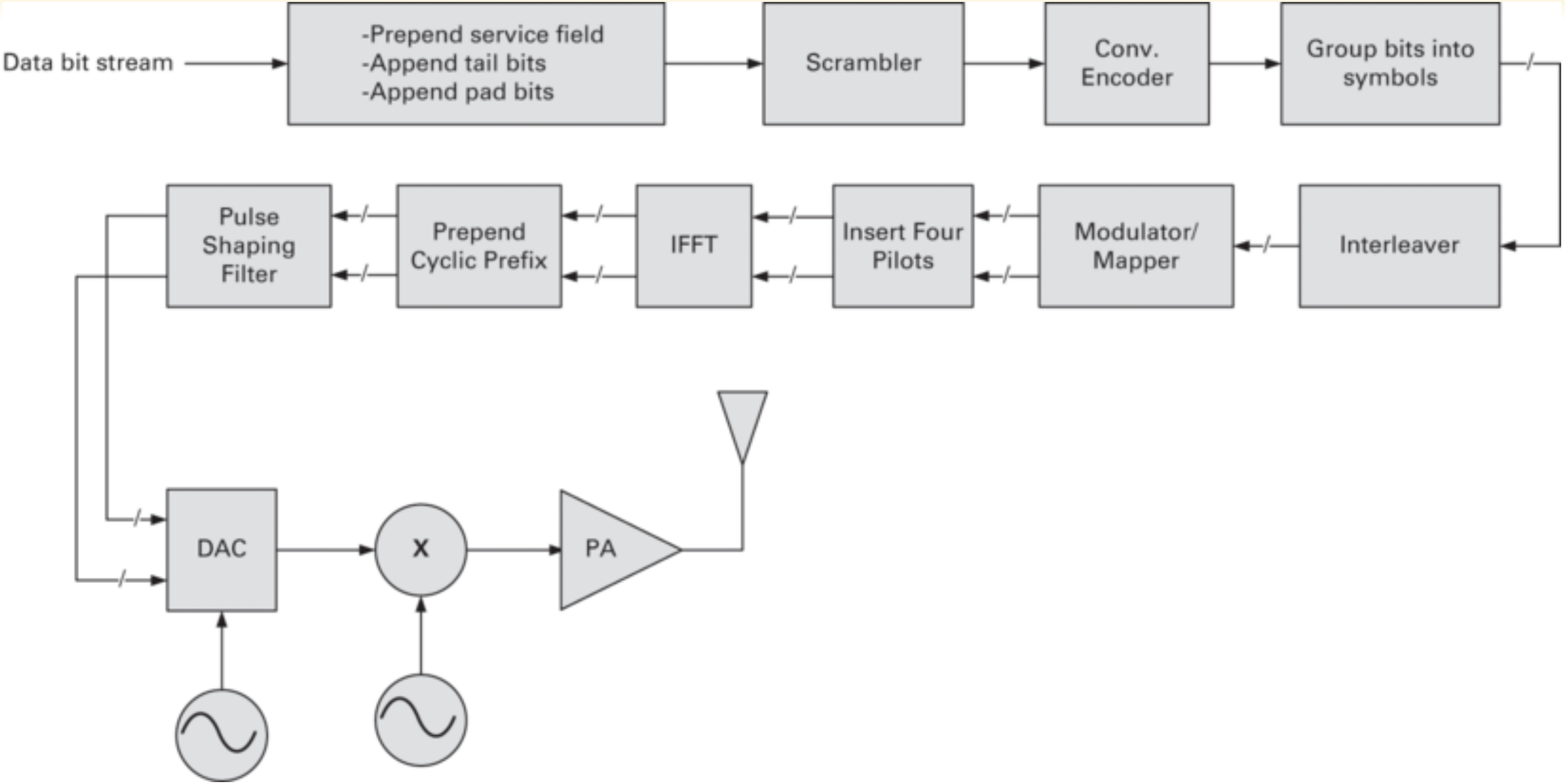

PHY Header
RATE 4 bits
Reserved 1 bit
LENGTH 12 bits
Parity 1 bit
Tail 6 bits
SERVICE 16 bits
PSDU
Tail 6 bits
Pad Bits
Coded/OFDM (BPSK, r = 1/2)
Coded/OFDM (RATE is indicated in SIGNAL)
PHY Preamble 12 Symbols
SIGNAL One OFDM Symbol
DATA Variable Number of OFDM Symbols

OFDM Parameters

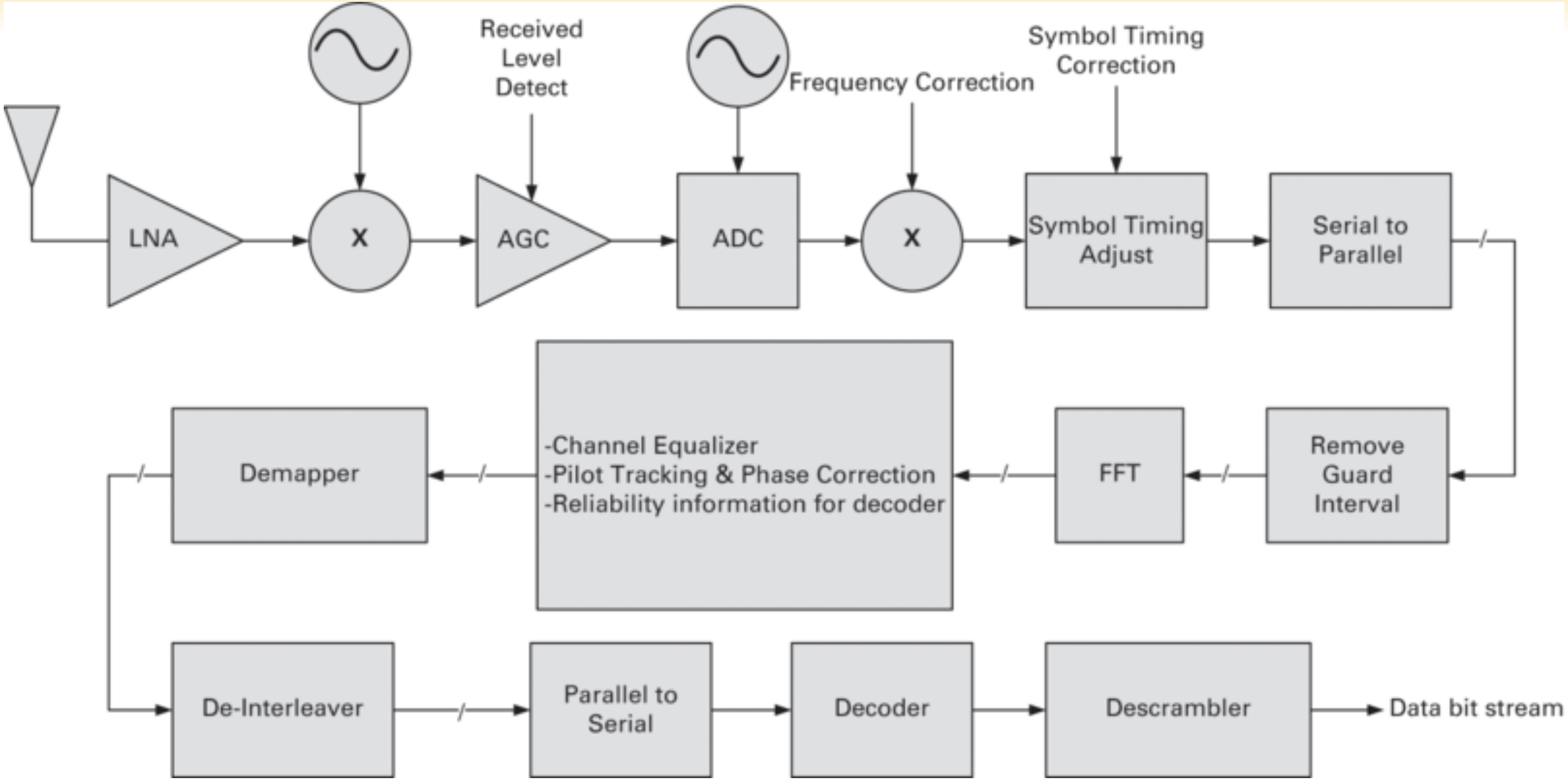
- 64-pt FFT (64 subcarriers)
- FFT convention
- 48 data subcarriers



Transmitter Block for Data



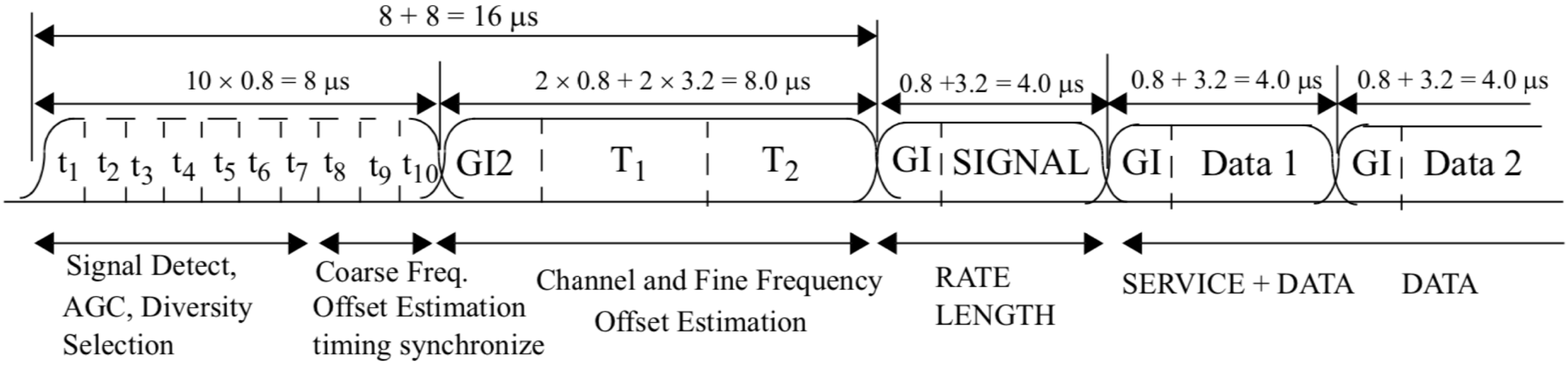
Receiver Block for Data



Steps for encoding PPDU

- **17.3.2.2 Overview of the PPDU encoding process**
  - Step 1 - Produce the PHY Preamble field, composed of 10 repetitions of a “short training sequence” (used for AGC convergence, diversity selection, timing acquisition, and coarse frequency acquisition in the receiver) and two repetitions of a “long training sequence” (used for channel estimation and fine frequency acquisition in the receiver), preceded by a guard interval (GI)

Preamble


8 + 8 = 16 μs
10 × 0.8 = 8 μs
2 × 0.8 + 2 × 3.2 = 8.0 μs
0.8 +3.2 = 4.0 μs
0.8 + 3.2 = 4.0 μs
0.8 + 3.2 = 4.0 μs
t1 t2 t3 t4 t5 t6 t7 t8 t9 t10
GI2
T1
T2
GI
SIGNAL
GI
Data 1
GI
Data 2
Signal Detect, AGC, Diversity Selection
Coarse Freq. Offset Estimation timing synchronize
Channel and Fine Frequency Offset Estimation
RATE LENGTH
SERVICE + DATA
DATA

Short Preamble

$$S_{-26,26} = \sqrt{(13/6)} \times \{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0,0\} \quad (17\text{-}6)$$

The multiplication by a factor of $\sqrt{(13/6)}$ is in order to normalize the average power of the resulting OFDM symbol, which utilizes 12 out of 52 subcarriers.

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Long Preamble

$L_{-26, 26} = \{1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0,$

$1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1\}$

A long OFDM training symbol shall be generated according to the following equation:

$$r_{LONG}(t) = w_{TLONG}(t) \sum_{k=-N_{ST}/2}^{N_{ST}/2} L_k \exp(j2\pi k\Delta_F(t - T_{G12})) \qquad (17\text{-}9)$$

where

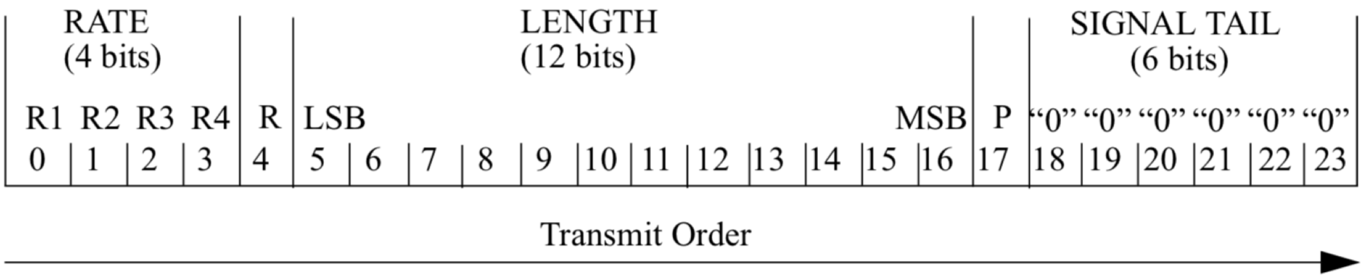
$T_{G12} = 1.6\ \mu s$

Two periods of the long sequence are transmitted for improved channel estimation accuracy, yielding $T_{LONG} = 1.6 + 2 \times 3.2 = 8\ \mu s$.

Steps for encoding PPDU

- **17.3.2.2 Overview of the PPDU encoding process**
  - Step 2 - Produce the PHY header field from the RATE, LENGTH, and SERVICE fields of the TXVECTOR by filling the appropriate bit fields. The RATE and LENGTH fields of the PHY header are encoded by a convolutional code at a rate of R = 1/2, and are subsequently mapped onto a single BPSK encoded OFDM symbol, denoted as the SIGNAL symbol. In order to facilitate a reliable and timely detection of the RATE and LENGTH fields, 6 zero tail bits are inserted into the PHY header. The encoding of the SIGNAL field into an OFDM symbol follows the same steps for convolutional encoding, interleaving, BPSK modulation, pilot insertion, Fourier transform, and prepending a GI as described subsequently for data transmission with BPSK-OFDM modulated at coding rate 1/2. *The contents of the SIGNAL field are not scrambled*.

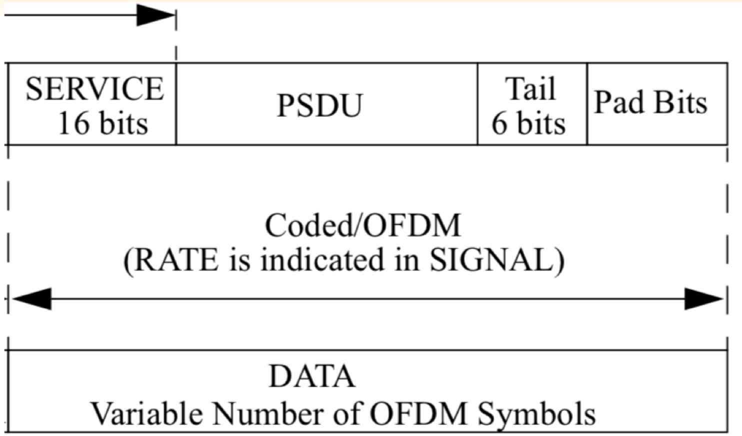
SIGNAL Field

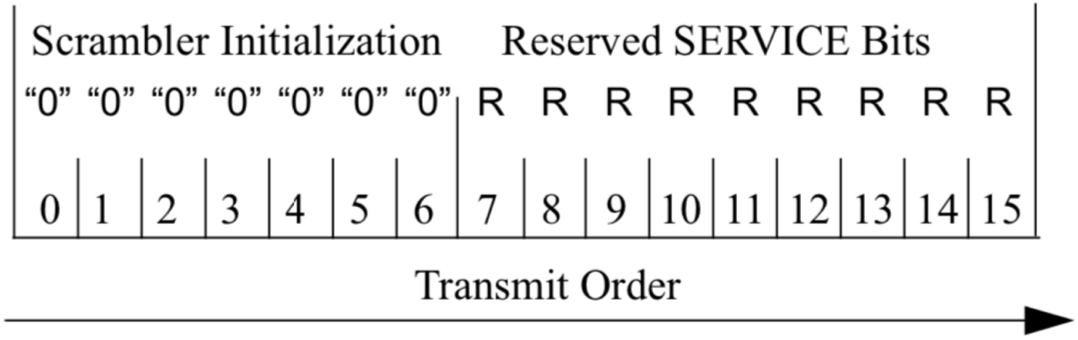


Bit 4 is reserved. It shall be set to 0 on transmit and ignored on receive. Bit 17 shall be a positive parity (even parity) bit for bits 0–16. The bits 18–23 constitute the SIGNAL TAIL field, and all 6 bits shall be set to 0.

R1–R4	**Rate (Mb/s) (20 MHz channel spacing)**	**Rate (Mb/s) (10 MHz channel spacing)**	**Rate (Mb/s) (5 MHz channel spacing)**
1101	6	3	1.5
1111	9	4.5	2.25
0101	12	6	3
0111	18	9	4.5
1001	24	12	6
1011	36	18	9
0001	48	24	12
0011	54	27	13.5

SERVICE Field





R: Reserved

PPDU Tail Bits

- The PPDU TAIL field shall be six bits of 0, which are required to return the convolutional encoder to the zero state.
- This procedure *improves the error probability of the convolutional decoder*, which relies on future bits when decoding and which may be not be available past the end of the message.
- The PPDU TAIL field shall be produced by replacing six scrambled zero bits following the message end with six nonscrambled zero bits.

Pad Bits

- The number of bits in the DATA field shall be a multiple of N_{CBPS}, the number of coded bits in an OFDM symbol (48, 96, 192, or 288 bits).
- To achieve that, the length of the message is extended so that it becomes a multiple of N_{DBPS}, the number of data bits per OFDM symbol.
- 6 bits are appended to the message, in order to accommodate the TAIL bits

$$N_{SYM} = \left\lceil \frac{16 + 8 \times \text{LENGTH} + 6}{N_{DBPS}} \right\rceil$$

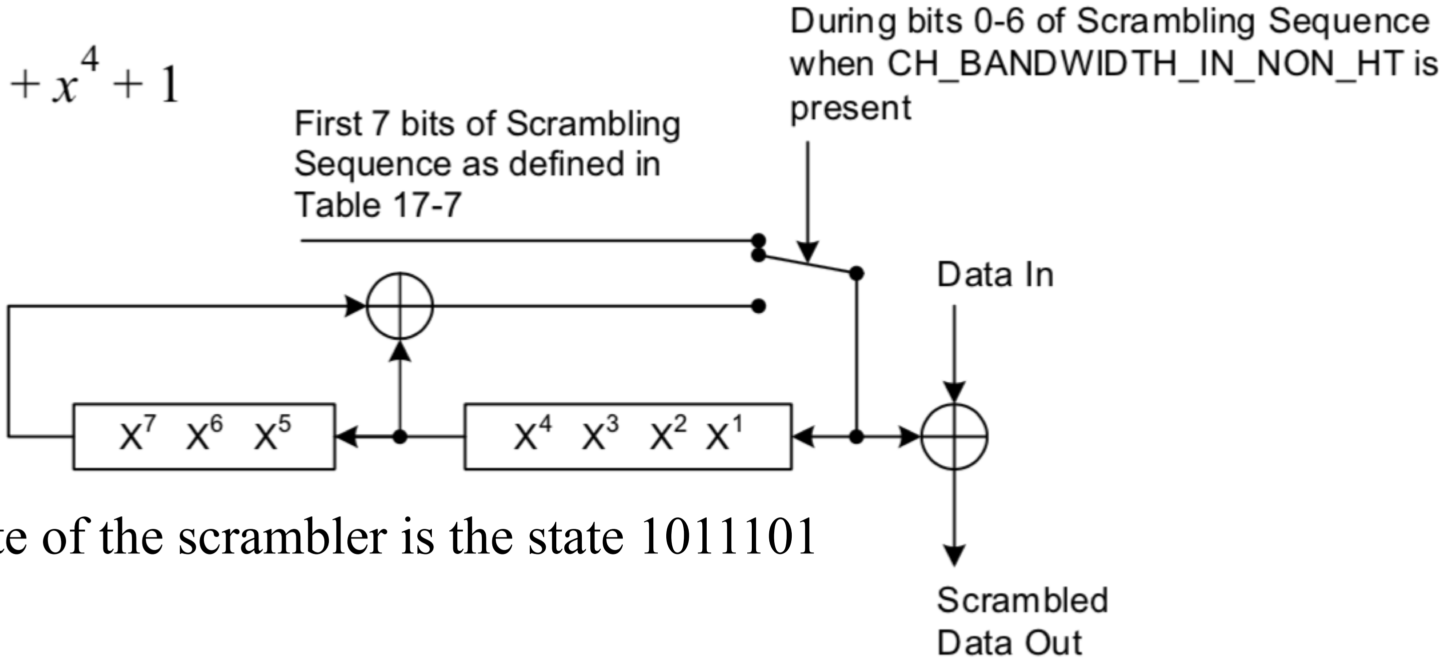
$$N_{DATA} = N_{SYM} \times N_{DBPS}$$

$$N_{PAD} = N_{DATA} - (16 + 8 \times \text{LENGTH} + 6)$$

Scrambler & Descrambler

- The scrambling step at the transmitter side is to avoid long consecutive sequences of 0s or 1s

$$S(x) = x^7 + x^4 + 1$$



The initial state of the scrambler is the state 1011101

Scrambler

- The same scrambler is used to scramble transmit data and to descramble receive data.
- Scrambler depends on TXVECTOR
- If the TXVECTOR parameter CH_BANDWIDTH_IN_NON_HT is not present, when transmitting, the initial state of the scrambler shall be set to a pseudorandom nonzero state.

CH_BANDWIDTH_IN_NON_HT	PHY-TXSTART.request (TXVECTOR)	If present, CBW20, CBW40, CBW80, CBW160, or CBW80+80
DYN_BANDWIDTH_IN_NON_HT	PHY-TXSTART.request (TXVECTOR)	If present, Static or Dynamic

Scrambler Initialization

- The seven LSBs of the SERVICE field shall be set to all 0s prior to scrambling to enable estimation of the initial state of the scrambler in the receiver.

Parameter	Condition	First 7 bits of scrambling sequence: B0 – B3	B4	B5 – B6
		Transmit order →		
TXVECTOR	CH_BANDWIDTH_IN_NON_HT is present and DYN_BANDWIDTH_IN_NOT_HT is not present in TXVECTOR	5-bit pseudorandom nonzero integer if CH_BANDWIDTH_IN_NON_HT equals CBW20 and a 5-bit pseudorandom integer otherwise		CH_BANDWIDTH_IN_NON_HT
TXVECTOR	CH_BANDWIDTH_IN_NON_HT is present and DYN_BANDWIDTH_IN_NOT_HT is present in TXVECTOR	4-bit pseudorandom nonzero integer if CH_BANDWIDTH_IN_NON_HT equals CBW20 and DYN_BANDWIDTH_IN_NON_HT equals Static, and a 4-bit pseudorandom integer otherwise	DYN_BANDWIDTH_IN_NON_HT	
RXVECTOR	CH_BANDWIDTH_IN_NON_HT and DYN_BANDWIDTH_IN_NOT_HT are present in RXVECTOR	—	DYN_BANDWIDTH_IN_NON_HT	CbwInNonHtTemp is set to this subfield of first 7 bits of scrambling sequence; then CbwInNonHtTemp is mapped according to Table 17-9 to CH_BANDWIDTH_IN_NON_HT

Convolutional Encoder

- The DATA field, composed of SERVICE, PSDU, tail, and pad parts, shall be coded with a convolutional encoder of coding rate R = 1/2, 2/3, or 3/4, corresponding to the TXVECTOR parameter RATE.

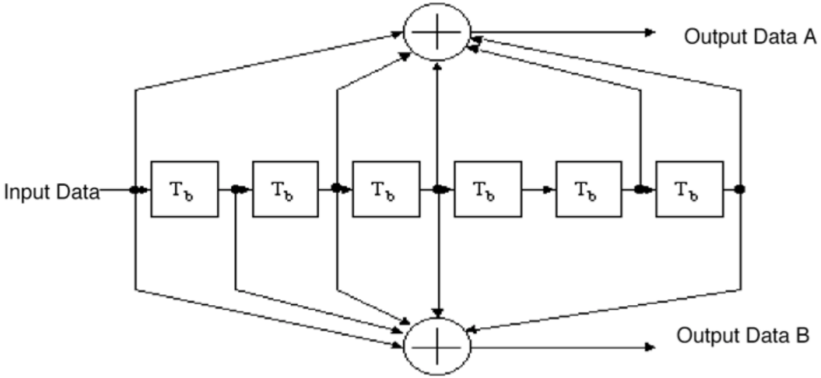
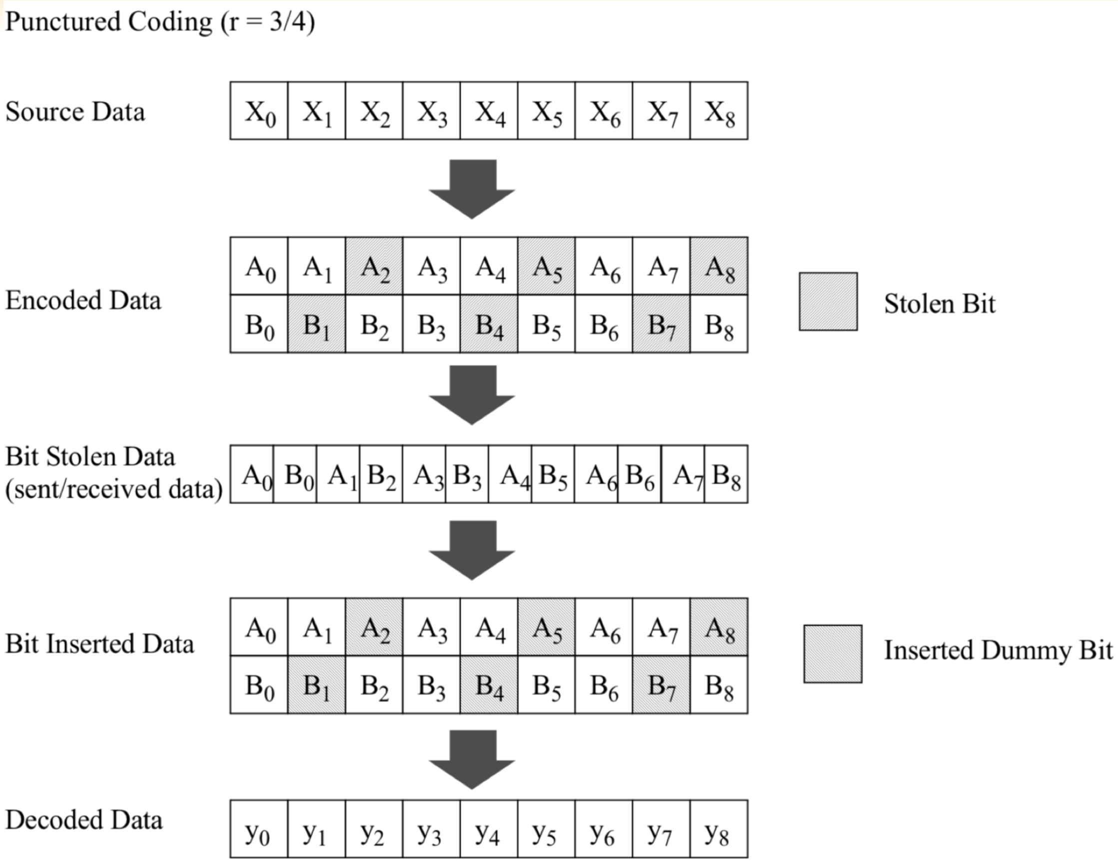


Figure 17-8—Convolutional encoder (k = 7)

The convolutional encoder shall use the industry-standard generator polynomials, $g_0 = 133_8$ and $g_1 = 171_8$, of rate R = 1/2

MATLAB: poly2trellis(7, [133 171]);
https://www.mathworks.com/help/comm/ref/poly2trellis.html

Puncturing (to yield higher data rate)



Data Interleaving

- To avoid burst error
- block interleaver with a block size corresponding to the number of bits in a single OFDM symbol, N_{CBPS}

The first permutation is defined by the rule

$$i = (N_{CBPS}/16) \times (k \bmod 16) + \lfloor k/16 \rfloor \quad k = 0,1,\ldots,N_{CBPS}-1$$

adjacent coded bits to be mapped onto nonadjacent subcarriers

The second permutation is defined by the rule

$$j = s \times \left\lfloor \frac{i}{s} \right\rfloor + \left(i + N_{CBPS} - \left\lfloor \frac{16 \times i}{N_{CBPS}} \right\rfloor \right) \bmod s \quad i = 0,1,\ldots N_{CBPS}-1$$

adjacent coded bits to be mapped alternately onto less and more significant bits of the constellation and, thereby, long runs of low reliability (LSB) bits are avoided

The value of s is determined by the number of coded bits per subcarrier,

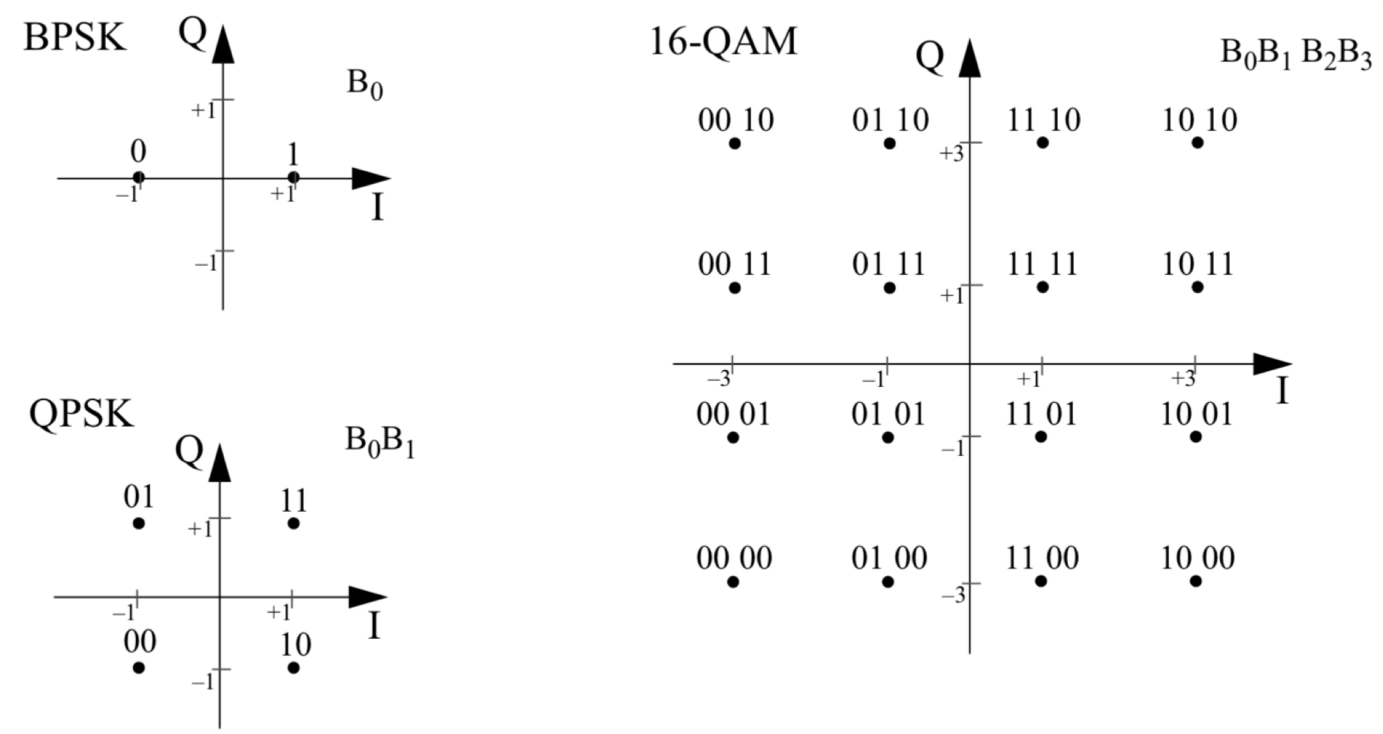
$$s = \max(N_{BPSC}/2,1)$$

Subcarrier Modulation Mapping

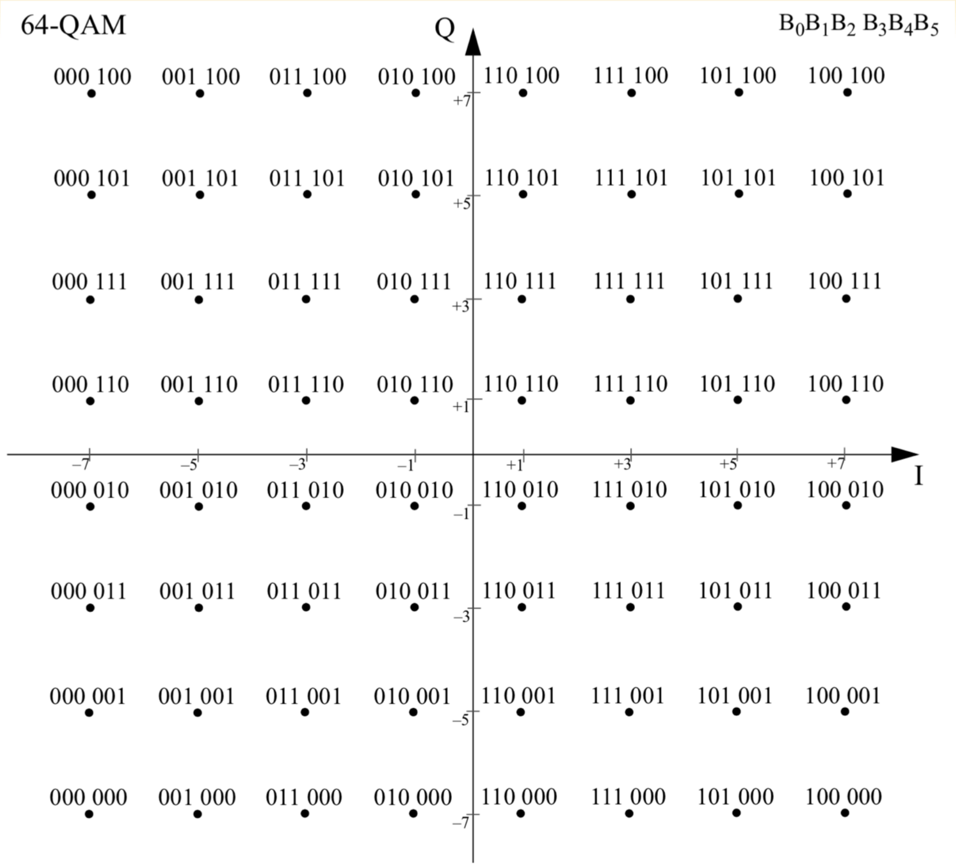
$$d = (I + jQ) \times K_{MOD}$$

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

Gray Coded Mapping



Gray Coded Mapping

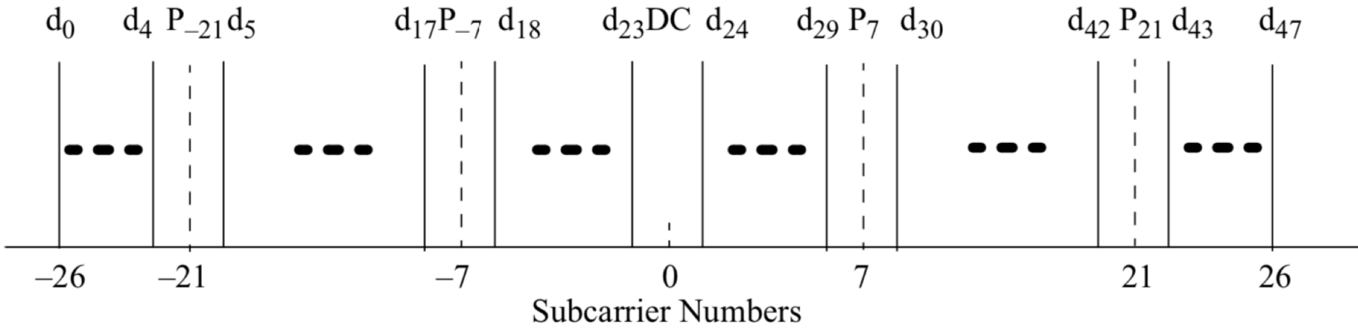


Pilot Subcarriers

- Pilot signals are in –21, –7, 7, 21
- The pilots shall be BPSK modulated by a pseudo-binary sequence to prevent the generation of spectral lines.

$$P_{-26,26} = \{0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1, 0, 0, 0, 0, 0\}$$

To avoid difficulties in D/A and A/D converter offsets and carrier feedthrough in the RF system, the subcarrier falling at DC (0th subcarrier) is not used.



Polarity of Pilot Subcarrier

- Controlled by the sequence, p_n
- The sequence p_n is generated by the scrambler

$$S(x) = x^7 + x^4 + 1$$

- Scrambler initial state all 1s

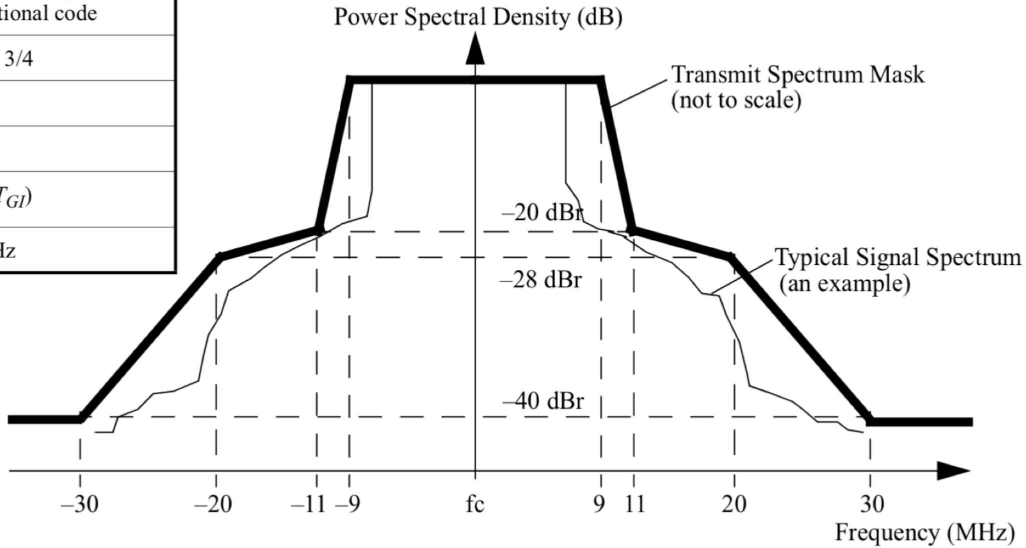
$$p_{0..126v} = \{1,1,1,1,\ -1,-1,-1,1,\ -1,-1,-1,-1,\ 1,1,-1,1,\ -1,-1,1,1,\ -1,1,1,-1,\ 1,1,1,1,\ 1,1,-1,1,\ 1,1,-1,1,\ 1,-1,-1,1,\ 1,1,-1,1,\ -1,-1,-1,1,\ -1,1,-1,-1,\ 1,-1,-1,1,\ 1,1,1,1,\ -1,-1,1,1,\ -1,-1,1,-1,\ 1,-1,1,1,\ -1,-1,-1,1,\ 1,-1,-1,-1,\ -1,1,-1,-1,\ 1,-1,1,1,\ 1,1,-1,1,\ -1,1,-1,1,\ -1,-1,-1,-1,\ -1,1,-1,1,\ 1,-1,1,-1,\ 1,1,1,-1,\ -1,1,-1,-1,\ -1,1,1,1,\ -1,-1,-1,-1,\ -1,-1,-1\}$$

Pilot Generation

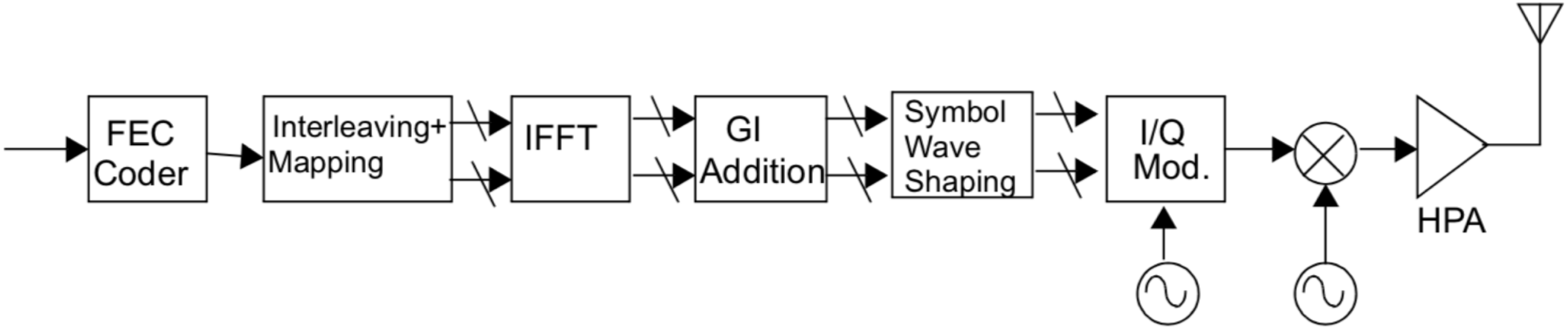
i	OFDM symbol	Element of p_i	Pilot at #–21	Pilot at #–7	Pilot at #7	Pilot at #21
0	SIGNAL	1	1.0 +0 j	1.0 +0 j	1.0 +0 j	–1.0 +0 j
1	DATA 1	1	1.0 +0 j	1.0 +0 j	1.0 +0 j	–1.0 +0 j
2	DATA 2	1	1.0 +0 j	1.0 +0 j	1.0 +0 j	–1.0 +0 j
3	DATA 3	1	1.0 +0 j	1.0 +0 j	1.0 +0 j	–1.0 +0 j
4	DATA 4	–1	–1.0 +0 j	–1.0 +0 j	–1.0 +0 j	1.0 +0 j
5	DATA 5	–1	–1.0 +0 j	–1.0 +0 j	–1.0 +0 j	1.0 +0 j
6	DATA 6	–1	–1.0 +0 j	–1.0 +0 j	–1.0 +0 j	1.0 +0 j

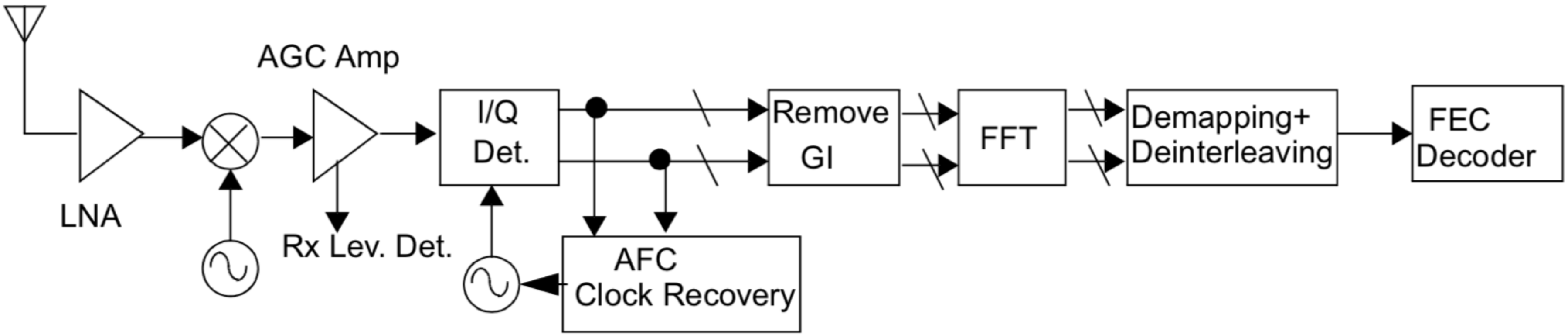
Transmit Spectral Mask

Information data rate	6, 9, 12, 18, 24, 36, 48, and 54 Mb/s (6, 12, and 24 Mb/s are mandatory) (20 MHz channel spacing)	3, 4.5, 6, 9, 12, 18, 24, and 27 Mb/s (3, 6, and 12 Mb/s are mandatory) (10 MHz channel spacing)	1.5, 2.25, 3, 4.5, 6, 9, 12, and 13.5 Mb/s (1.5, 3, and 6 Mb/s are mandatory) (5 MHz channel spacing)
Modulation	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM	BPSK OFDM QPSK OFDM 16-QAM OFDM 64-QAM OFDM
Error correcting code	K = 7 (64 states) convolutional code	K = 7 (64 states) convolutional code	K = 7 (64 states) convolutional code
Coding rate	1/2, 2/3, 3/4	1/2, 2/3, 3/4	1/2, 2/3, 3/4
Number of subcarriers	52	52	52
OFDM symbol duration	4.0 µs	8.0 µs	16.0 µs
GI	0.8 µs[a] (T_{GI})	1.6 µs (T_{GI})	3.2 µs (T_{GI})
Occupied bandwidth	16.6 MHz	8.3 MHz	4.15 MHz

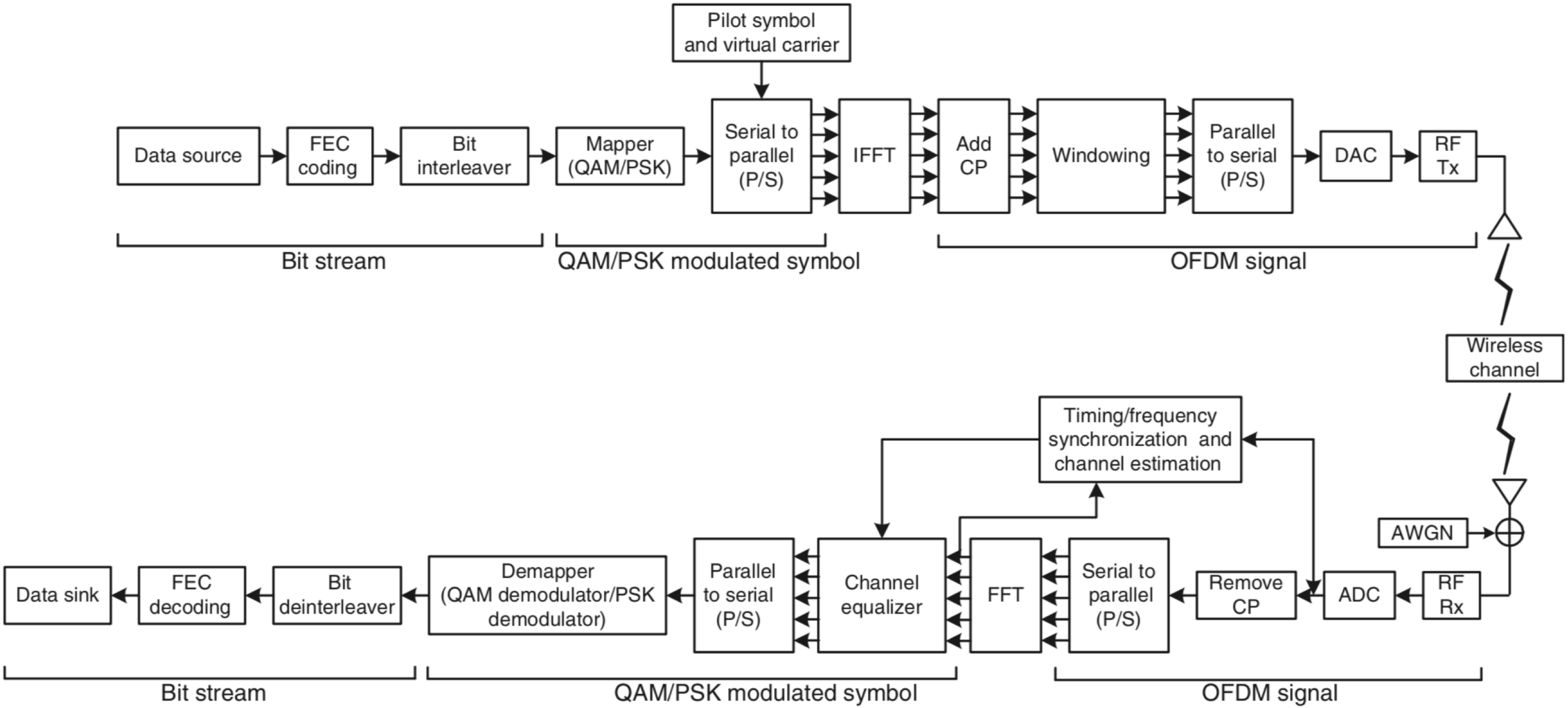


Tx and Rx Blocks (Standard)



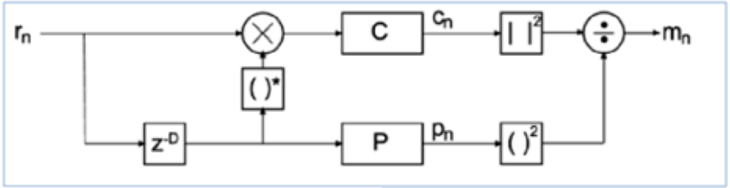


Tx/Rx Blocks



Yong Soo Cho, Jaekwon Kim, Won Young Yang, Chung G. Kang, MIMO-OFDM Wireless Communications with MATLAB

Start of Symbol Detection



$$c_n = \sum_{l=1}^{N_R} \sum_{K=0}^{D-1} r_{n+k,l} r^*_{n+k+D,l} \qquad p_n = \sum_{l=1}^{N_R} \sum_{k=0}^{D-1} |r_{n+k+D,l}|^2$$

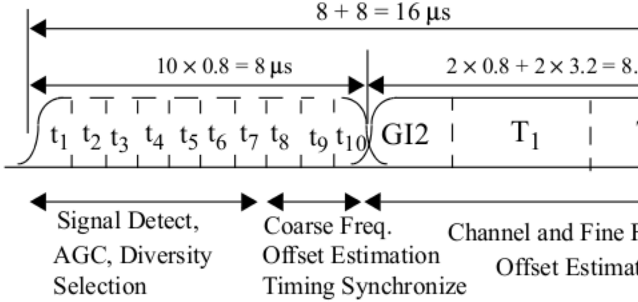
- Correlation with Long Preamble
  - Cross-correlation (Received, Stored)
  - Auto-correlation (Received, Delayed Received)
- Window *C* autocorrelates between the received signal and the delayed version, c_n
- Window *P* calculates the energy received in the autocorrelation window, p_n.

$$m_n = \frac{|c_n|^2}{(p_n)^2}$$

- The decision statistics, m_n, normalize the autocorrelation by p_n so that the decision statistic is not dependent on the absolute received power level.
- The recommended default value of 0.5 for threshold favors false detections over missed detections considering a range of SNRs and various antenna configurations.

Coarse Frequency Offset Correction from SP

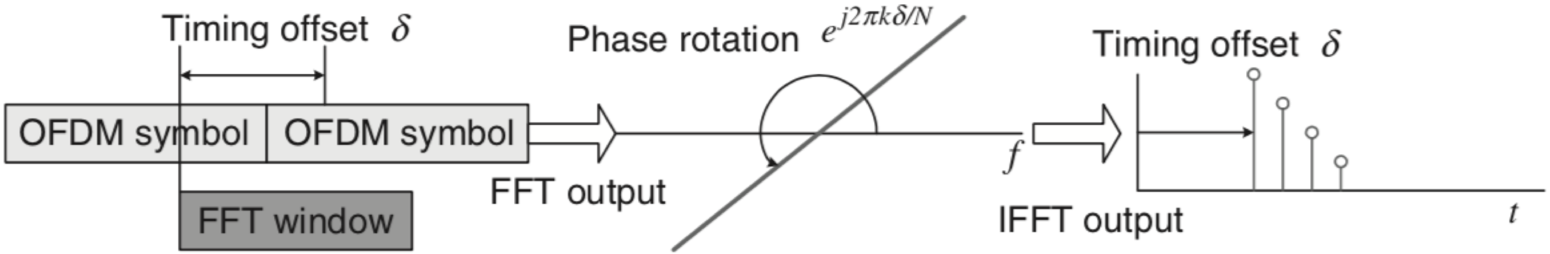
- Carrier Frequency Offset:
  - Device impairments introduce difference between the carrier frequency of the receiver and that of the transmitter.
  - When this happens, the received baseband signal, instead of being centered at DC (0MHz), will be centered at a frequency $f_\Delta = f_{Tx} - f_{Rx}$
  - Received signal in baseband (ignoring noi
    $x(t)e^{j2\pi f_\Delta t}$



- Short Preamble:
  - Periodic with $\delta t = 0.8\mu s = 16$ samples

Coarse Frequency Offset Correction from SP

- $y(t-\delta t)y^*(t) = x(t)e^{j2\pi f_\Delta (t-\delta t)} x^*(t)e^{-j2\pi f_\Delta t} = |x(t)|^2 e^{j2\pi f_\Delta (-\delta t)}$
- Considering only the angle, we get $-2\pi f_\Delta \delta t$
- Hence, $CFO(f_\Delta) = -\frac{\angle y(t-\delta t)y^*(t)}{2\pi \delta t}$
- We can use the same technique for Fine Frequency Offset Correction using Long Preamble



Cho, Yong Soo and Kim, Jaekwon and Yang, Won Young and Kang, Chung G., "MIMO-OFDM Wireless Communications with MATLAB," in *Wiley Publishing*.

https://openofdm.readthedocs.io/en/latest/overview.html

Pilot based Equalization (Frequency Domain)

- Channel gain (H) is the mean of two LTSs.

$$H[i] = \frac{1}{2}(LTS_1[i] + LTS_2[i]) \times L[i], i \in [-26, 26]$$

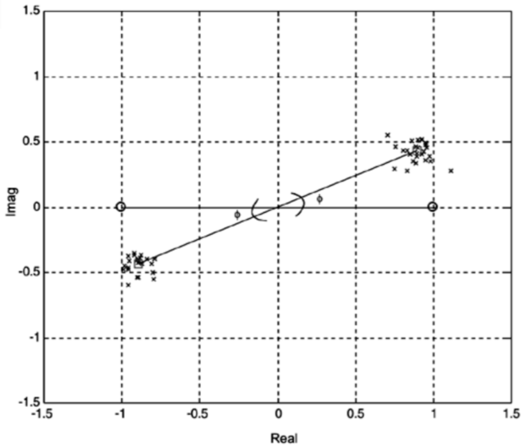
$L[i]$ is the sign of the LTS sequence

- FFT Output *X[i]* is normalized as $Y[i] = \frac{X[i]}{H[i]}, i \in [-26, 26]$
- Residual Phase Offset in symbol *n*

$$\theta_n = \angle\left(\sum_{i \in \{-21,-7,7,21\}} \overline{X^{(n)}[i]} \times P^{(n)}[i] \times H[i]\right)$$

- Combine residual phase offset & channel gain

$$Y^{(n)}[i] = \frac{X^{(n)}[i]}{H[i]} e^{j\theta_n}$$



A. van Zelst and T. C. W. Schenk, "Implementation of a MIMO OFDM-based wireless LAN system," in *IEEE Transactions on Signal Processing*, vol. 52, no. 2, pp. 483-494, Feb. 2004.

Channel Estimation (Training based)

- Since all subcarriers are orthogonal (i.e., ICI-free), the training symbols for N subcarriers can be represented by **X**

$$\mathbf{X} = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix}$$

- Given that the channel gain is *H[k]* for each subcarrier *k*, the received training signal *Y[k]* can be represented as

$$\mathbf{Y} \triangleq \begin{bmatrix} Y[0] \\ Y[1] \\ \vdots \\ Y[N-1] \end{bmatrix} = \begin{bmatrix} X[0] & 0 & \cdots & 0 \\ 0 & X[1] & & \vdots \\ \vdots & & \ddots & 0 \\ 0 & \cdots & 0 & X[N-1] \end{bmatrix} \begin{bmatrix} H[0] \\ H[1] \\ \vdots \\ H[N-1] \end{bmatrix} + \begin{bmatrix} Z[0] \\ Z[1] \\ \vdots \\ Z[N-1] \end{bmatrix}$$

$$= \mathbf{XH} + \mathbf{Z}$$

- **H** is the channel vector
- **Z** is the noise vector

Least-Square (LS) channel estimation

- Goal is to minimize the cost function

$$
\begin{aligned}
J(\hat{\mathbf{H}}) &= \left\|\mathbf{Y}-\mathbf{X}\hat{\mathbf{H}}\right\|^2 \\
&= (\mathbf{Y}-\mathbf{X}\hat{\mathbf{H}})^H(\mathbf{Y}-\mathbf{X}\hat{\mathbf{H}}) \\
&= \mathbf{Y}^H\mathbf{Y}-\mathbf{Y}^H\mathbf{X}\hat{\mathbf{H}}-\hat{\mathbf{H}}^H\mathbf{X}^H\mathbf{Y}+\hat{\mathbf{H}}^H\mathbf{X}^H\mathbf{X}\hat{\mathbf{H}}
\end{aligned}
$$

- By setting the derivative of the function with respect to $\widehat{H}$ to zero,

$$
\frac{\partial J(\hat{\mathbf{H}})}{\partial \hat{\mathbf{H}}} = -2\left(\mathbf{X}^H\mathbf{Y}\right)^* + 2\left(\mathbf{X}^H\mathbf{X}\hat{\mathbf{H}}\right)^* = 0
$$

$$
\mathbf{X}^H\mathbf{X}\hat{\mathbf{H}} = \mathbf{X}^H\mathbf{Y}
$$

$$
\hat{\mathbf{H}}_{LS} = (\mathbf{X}^H\mathbf{X})^{-1}\mathbf{X}^H\mathbf{Y} = \mathbf{X}^{-1}\mathbf{Y}
$$

$$
\hat{H}_{LS}[k] = \frac{Y[k]}{X[k]}, \quad k = 0, 1, 2, \cdots, N-1
$$

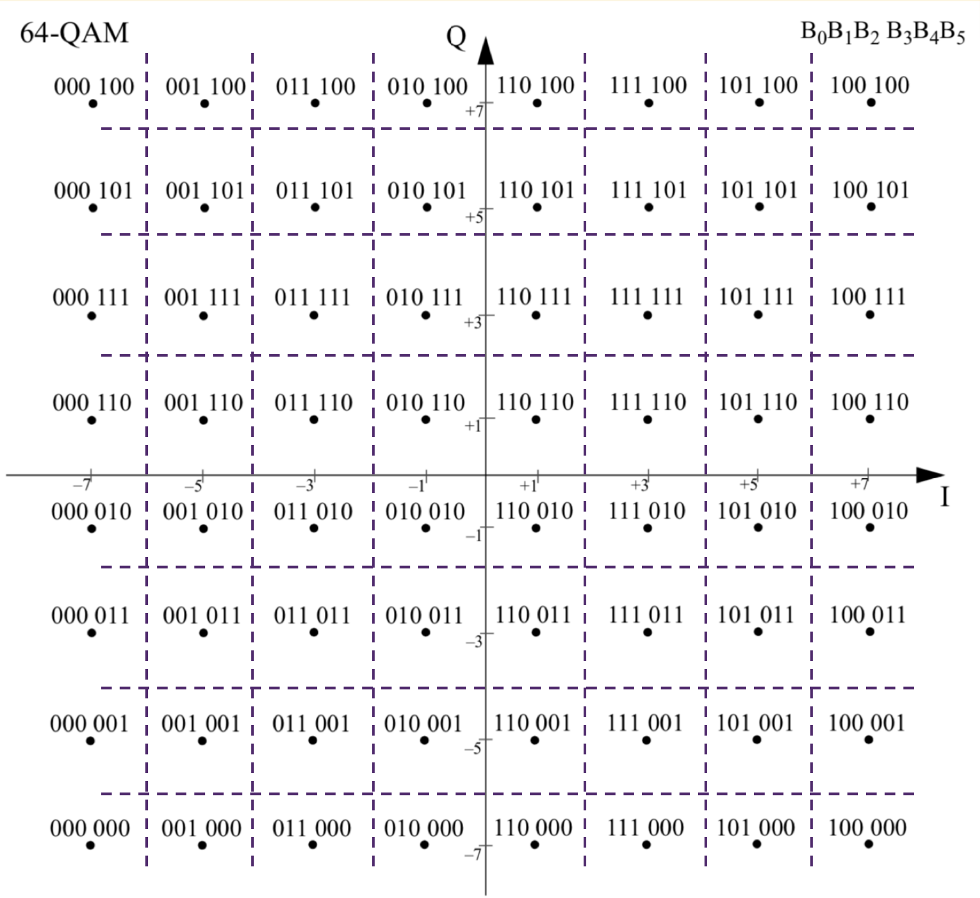
Channel Estimation for WLAN

$$\hat{H}_{LS}[k] = \frac{Y[k]}{X[k]}, \quad k = 0, 1, 2, \cdots, N-1$$

- Long Preamble: contains N=52 subcarriers
- Pilot: contains only 4 (-21, -7, 7, 21)
- Use above equation for 4 pilots
- Then intrapolate/extrapolate rest of the subcarriers
- We can assume channel is fairly constant over duration of one packet in low mobility WLAN
- Often channel estimation is done over LP, pilots are used for phase tracking

Demodulation

- Find the nearest Euclidian distance to a transmitted constellation
- Use Thresholds



Deinterleave

- Inverse of Interleave
- First Permutation

$$i = s \times \lfloor j/s \rfloor + \left(j + \left\lfloor \frac{16 \times j}{N_{CBPS}} \right\rfloor \right) \bmod s \quad j = 0,1,\ldots N_{CBPS} - 1$$

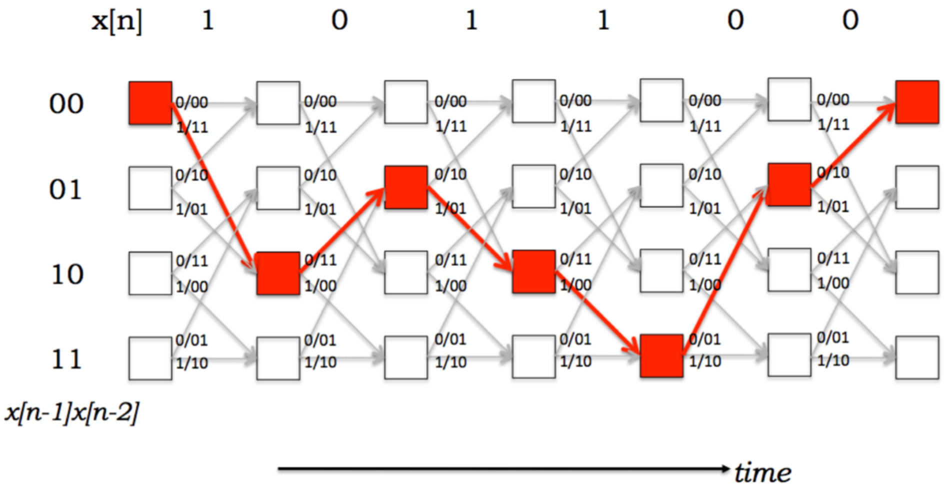
- Second Permutation

$$k = 16 \times i - (N_{CBPS} - 1) \times \left\lfloor \frac{16 \times i}{N_{CBPS}} \right\rfloor, \; i = 0,1,\ldots N_{CBPS} - 1$$

$$s = \max(N_{BPSC}/2, 1)$$

Viterbi Decoding

- The Viterbi algorithm can be used for decoding the space-time trellis-coded systems.
- Soft Decision Decoder – samples before digitizing
- Hard Decision Decoder – bits received

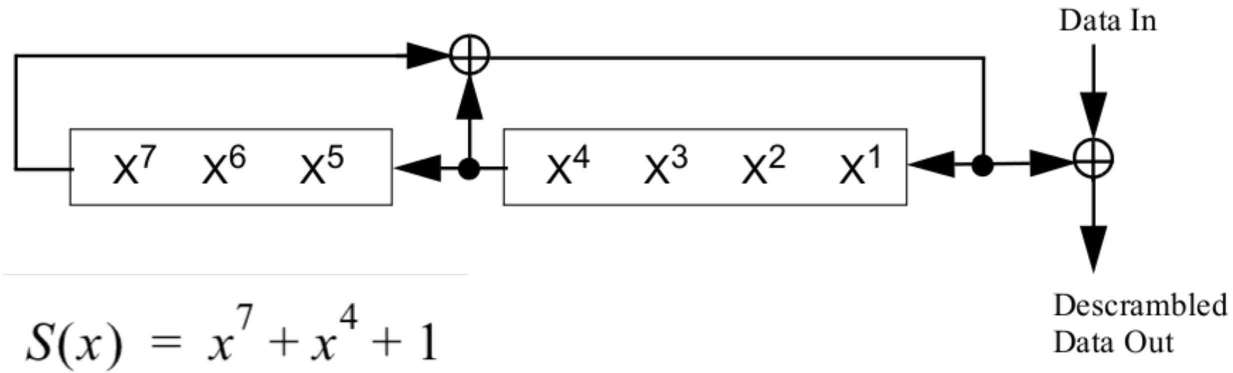


MATLAB Function: vitdec()
https://www.mathworks.com/help/comm/ref/vitdec.html

http://web.mit.edu/6.02/www/f2010/handouts/lectures/L9.pdf

Descrambling

- Inverse of scrambling procedure
- the first 7 un-scrambled bits (B0 to B6) are all zeros

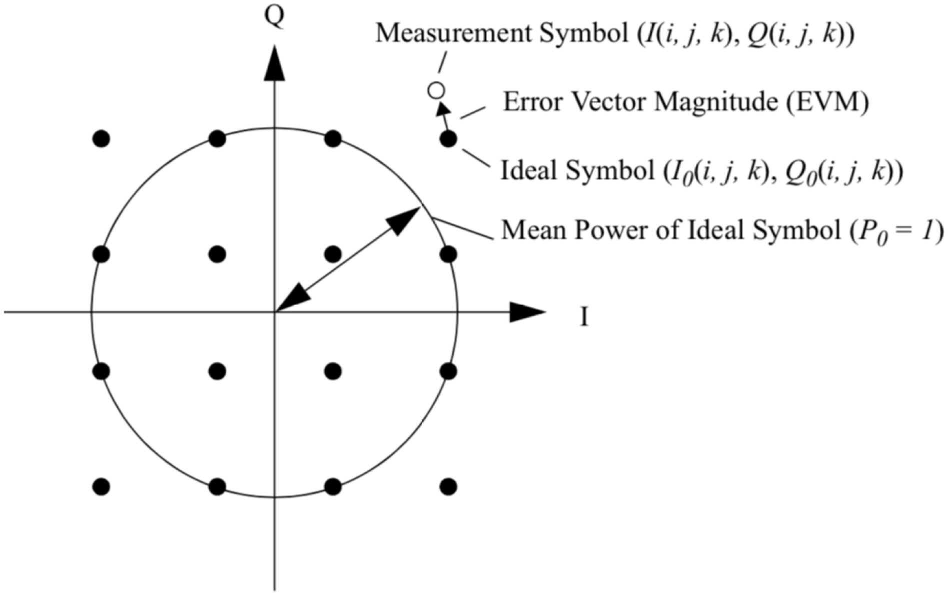


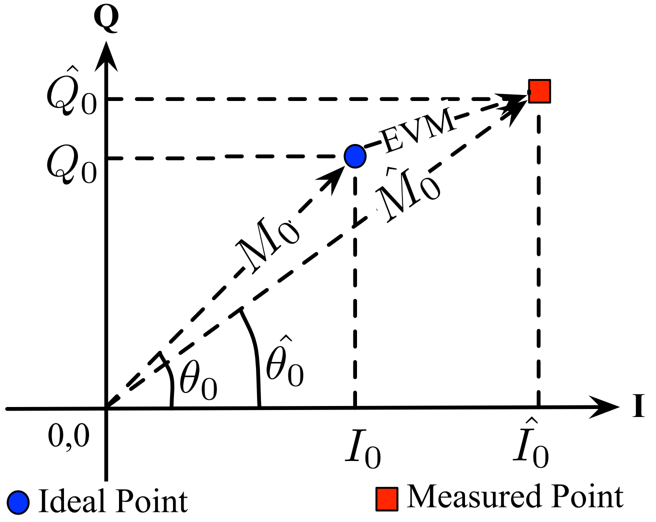
$$S(x) = x^7 + x^4 + 1$$

The initial state of the scrambler is the state 1011101

Constellation Error

- Error Vector Magnitude (EVM)





$\{I_0, Q_0, M_0, \theta_0\}$ = Ideal I, Q, Magnitude, Phase

$\{\hat{I}_0, \hat{Q}_0, \hat{M}_0, \hat{\theta}_0\}$ = Measured I, Q, Magnitude, Phase

$$EVM = \sqrt{\left(I_0 - \hat{I}_0\right)^2 + \left(Q_0 - \hat{Q}_0\right)^2}$$

I_{Disp} = Dispersion in I $= I_0 - \hat{I}_0$

Q_{Disp} = Dispersion in Q $= Q_0 - \hat{Q}_0$

M_{Disp} = Dispersion in Magnitude $= M_0 - \hat{M}_0$

RMS Average of all Errors in a Packet

$$Error_{RMS} = \frac{\displaystyle\sum_{i=1}^{N_f} \sqrt{\frac{\displaystyle\sum_{j=1}^{L_P}\left[\sum_{k=1}^{52}\{(I(i,j,k)-I_0(i,j,k))^2+(Q(i,j,k)-Q_0(i,j,k))^2\}\right]}{52L_P \times P_0}}}{N_f} \qquad (17\text{-}28)$$

where

L_P is the length of the packet;

N_f is the number of frames for the measurement;

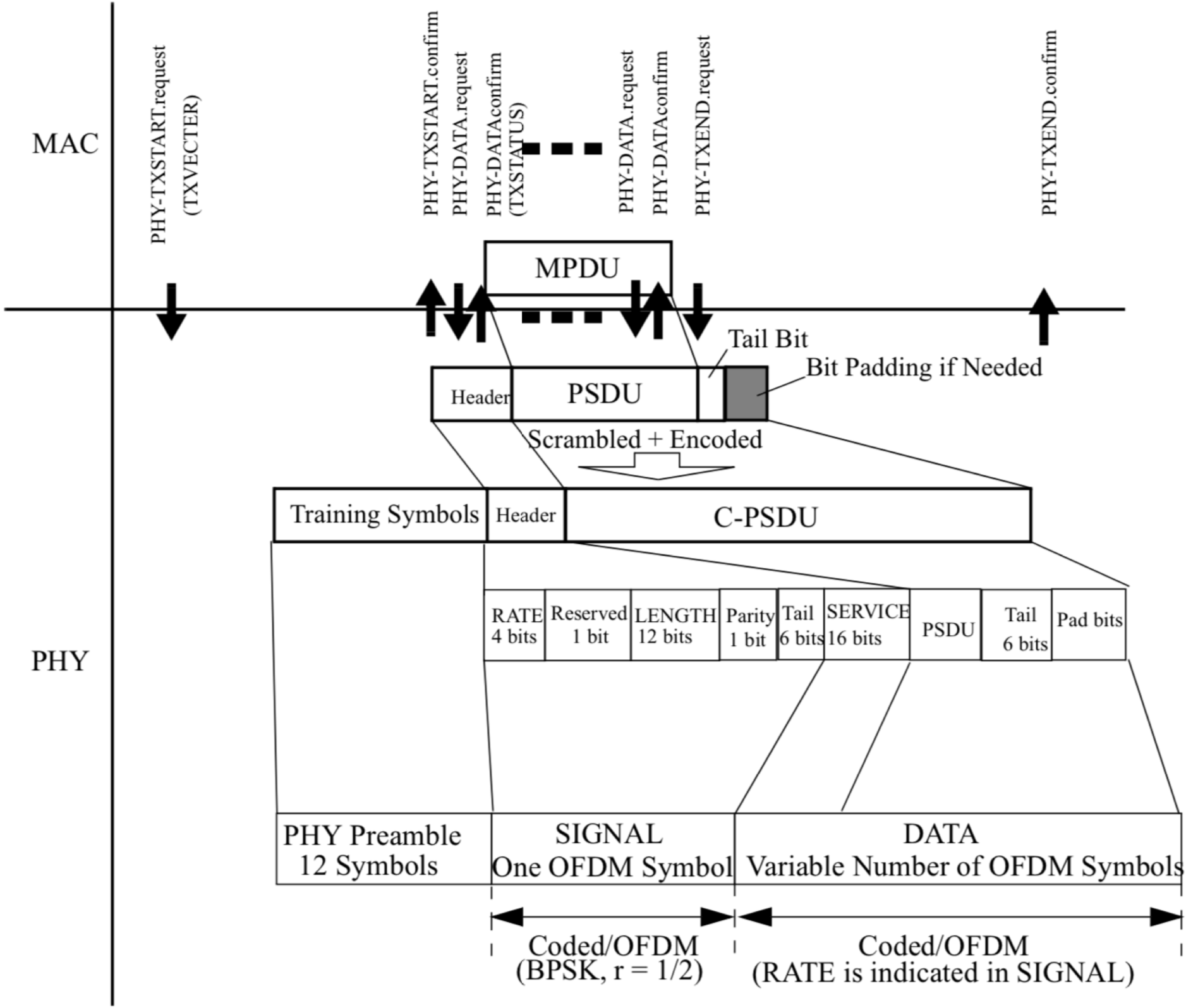
$(I_0(i,j,k), Q_0(i,j,k))$ denotes the ideal symbol point of the i^{th} frame, j^{th} OFDM symbol of the frame, k^{th} subcarrier of the OFDM symbol in the complex plane;

$(I(i,j,k), Q(i,j,k))$ denotes the observed point of the i^{th} frame, j^{th} OFDM symbol of the frame, k^{th} subcarrier of the OFDM symbol in the complex plane (see Figure 17-16);

P_0 is the average power of the constellation.

MAC/PHY

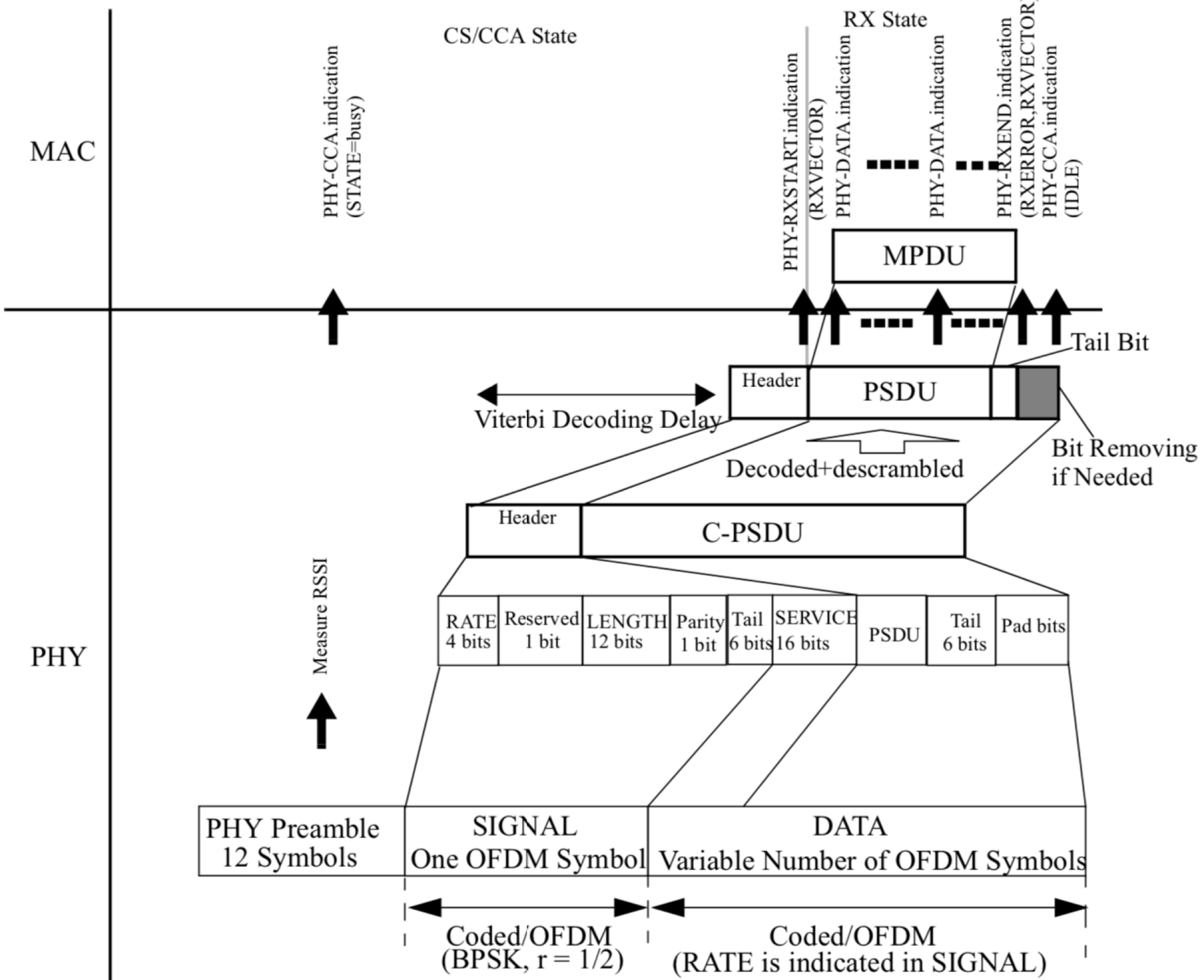
- Tx



MAC
PHY-TXSTART.request
(TXVECTER)
PHY-TXSTART.confirm
PHY-DATA.request
PHY-DATAconfirm
(TXSTATUS)
PHY-DATA.request
PHY-DATAconfirm
PHY-TXEND.request
PHY-TXEND.confirm
MPDU
Tail Bit
Bit Padding if Needed
Header
PSDU
Scrambled + Encoded
Training Symbols
Header
C-PSDU
PHY
RATE 4 bits
Reserved 1 bit
LENGTH 12 bits
Parity 1 bit
Tail 6 bits
SERVICE 16 bits
PSDU
Tail 6 bits
Pad bits
PHY Preamble 12 Symbols
SIGNAL One OFDM Symbol
DATA Variable Number of OFDM Symbols
Coded/OFDM (BPSK, r = 1/2)
Coded/OFDM (RATE is indicated in SIGNAL)

MAC/PHY

- Rx



MAC
PHY
CS/CCA State
RX State
PHY-CCA.indication (STATE=busy)
PHY-RXSTART.indication (RXVECTOR)
PHY-DATA.indication
PHY-DATA.indication
PHY-RXEND.indication (RXERROR,RXVECTOR)
PHY-CCA.indication (IDLE)
MPDU
Tail Bit
Header
PSDU
Viterbi Decoding Delay
Decoded+descrambled
Bit Removing if Needed
Header
C-PSDU
Measure RSSI
RATE 4 bits
Reserved 1 bit
LENGTH 12 bits
Parity 1 bit
Tail 6 bits
SERVICE 16 bits
PSDU
Tail 6 bits
Pad bits
PHY Preamble 12 Symbols
SIGNAL One OFDM Symbol
DATA Variable Number of OFDM Symbols
Coded/OFDM (BPSK, r = 1/2)
Coded/OFDM (RATE is indicated in SIGNAL)

802.11 MAC

- MAC layer covers three functional areas:
  - Reliable data delivery
  - Access control
  - Security

MAC: Reliable Data Delivery

- More efficient to deal with errors at the MAC level than higher layer (such as TCP)
- Frame exchange protocol
  - Source station transmits data
  - Destination responds with acknowledgment (ACK)
  - If source doesn't receive ACK, it retransmits frame
- Four frame exchange
  - Source issues request to send (RTS)
  - Destination responds with clear to send (CTS)
  - Source transmits data
  - Destination responds with ACK

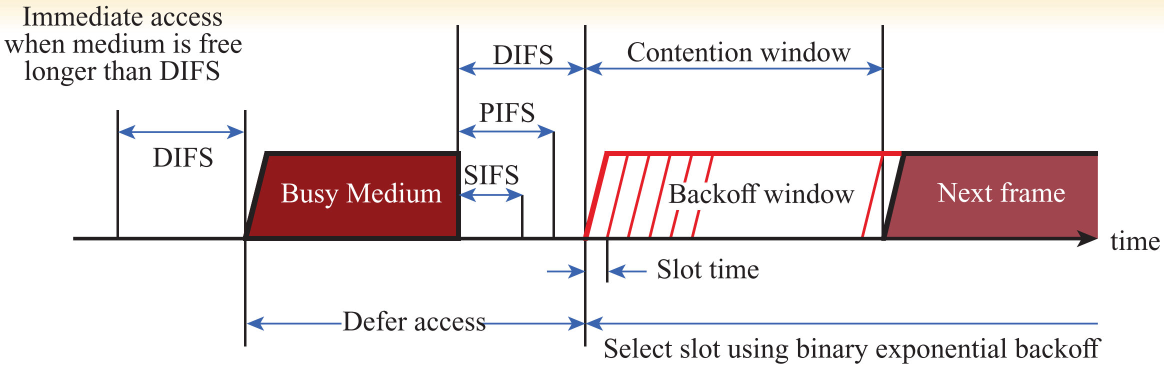
Distributed Coordination Function

- Decentralized
- Carrier sense multiple access (CSMA)
  - Listen to the medium
  - If idle, then transmit
  - If not, wait a random time
    - If busy again, expand the mean waiting time, randomly wait, and try again.
  - *Binary exponential backoff* describes this procedure
    - The backoff is the waiting process
    - Mean random waiting times get exponentially larger
      - ✓ By a factor of 2 each time, hence the term *binary*.
  - This process responds to heavy loads
    - Since nodes do not know the loads of other nodes trying to send.

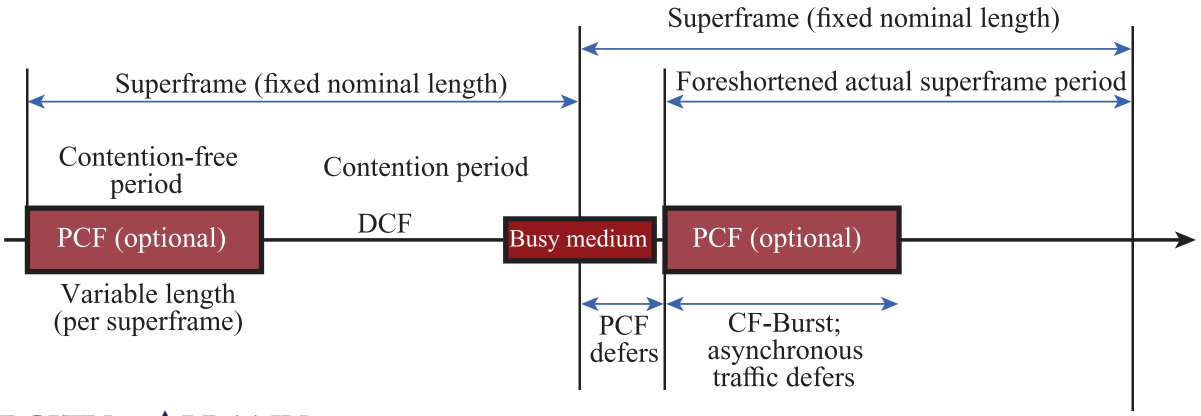
Interframe Spaces (IFS)

- Short IFS (SIFS)
  - Shortest IFS
  - Used for immediate response actions (ACK, CTS)
- Point coordination function IFS (PIFS)
  - Midlength IFS
  - Used by centralized controller in PCF scheme when using polls
  - Takes precedence over normal contention traffic
- Distributed coordination function IFS (DIFS)
  - Longest IFS
  - Used as minimum delay of asynchronous frames contending for access
  - Used for all ordinary asynchronous traffic

MAC Frame Timing



(a) Basic access method

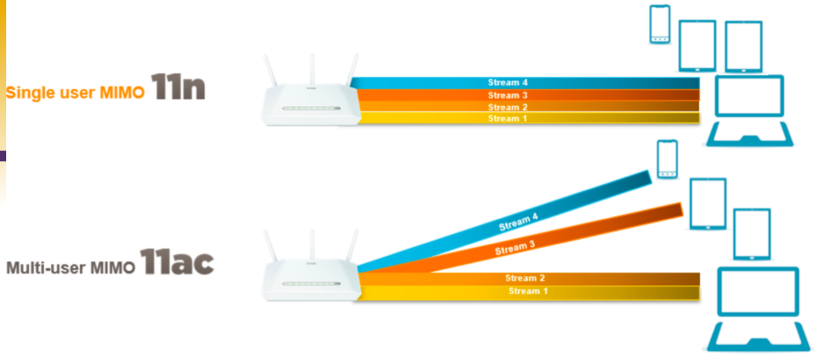


(b) PCF superframe construction

High & Very High Throughput PHY

UNIVERSITY AT ALBANY
State University of New York

802.11n and 802.11ac



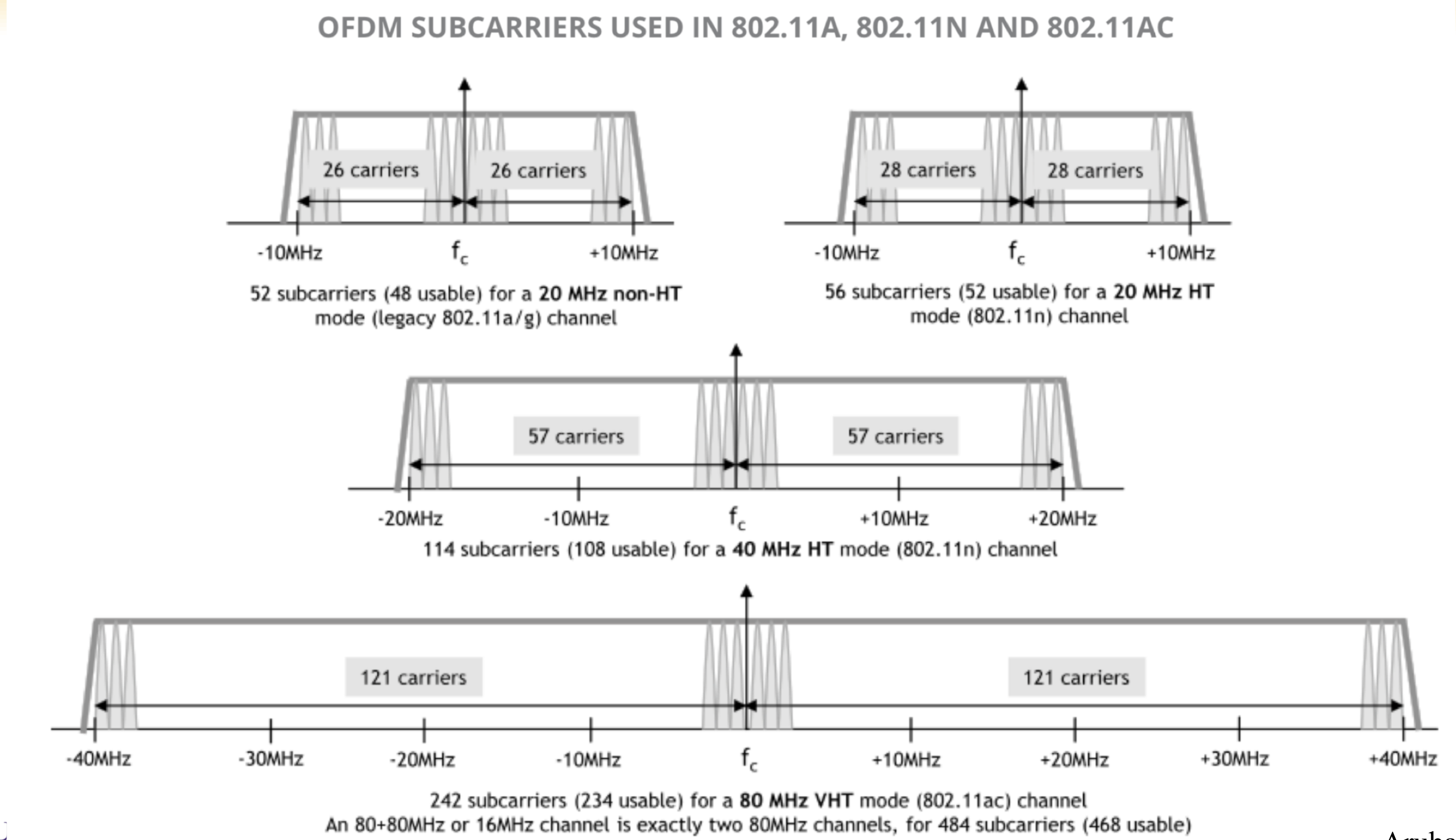
802.11n	802.11ac
Supports 20 and 40 MHz channels	Adds 80 and 160 MHz channels
Supports 2.4 GHz and 5 GHz frequency bands	Supports 5 GHz only
Supports BPSK, QPSK, 16-QAM, and 64-QAM	Adds 256-QAM
Supports many types of explicit beamforming	Supports only null data packet (NDP) explicit beamforming
Supports up to four spatial streams	Supports up to eight spatial streams (AP); client devices up to four spatial streams
Supports single-user transmission only	Adds multi-user transmission
Includes significant MAC enhancements (A-MSDU, A-MPDU)	Supports similar MAC enhancements, with extensions to accommodate high data rates

PHY Parameters

PHY standard	Subcarrier range	Pilot subcarriers	Subcarriers (total/ data)	Capacity relative to 802.11a/g	Capacity relative to 20 MHz 802.11ac
802.11a/g	−26 to −1, +1 to +26	±7, ±21	52 total, 48 usable (8% pilots)	x1.0	n/a
802.11n/ 802.11ac, 20 MHz	−28 to −1, +1 to +28	±7, ±21	56 total, 52 usable (7% pilots)	x1.1	x1.0
802.11n/ 802.11ac, 40 MHz	−58 to −2, +2 to +58	±11, ±25, ±53	114 total, 108 usable (5% pilots)	x2.3	x2.1
802.11ac, 80 MHz	−122 to −2, +2 to +122	±11, ±39, ±75, ±103	242 total, 234 usable (3% pilots)	x4.9	x4.5
802.11ac, 160 MHz[a]	−250 to −130, −126 to −6, +6 to +126, +130 to +250	±25, ±53, ±89, ±117, ±139, ±167, ±203, ±231	484 total, 468 usable (3% pilots)	x9.75	x9.0

[a] For 80+80 MHz channels, the numbers are identical to the 160 MHz channel numbers.

OFDM Subcarriers



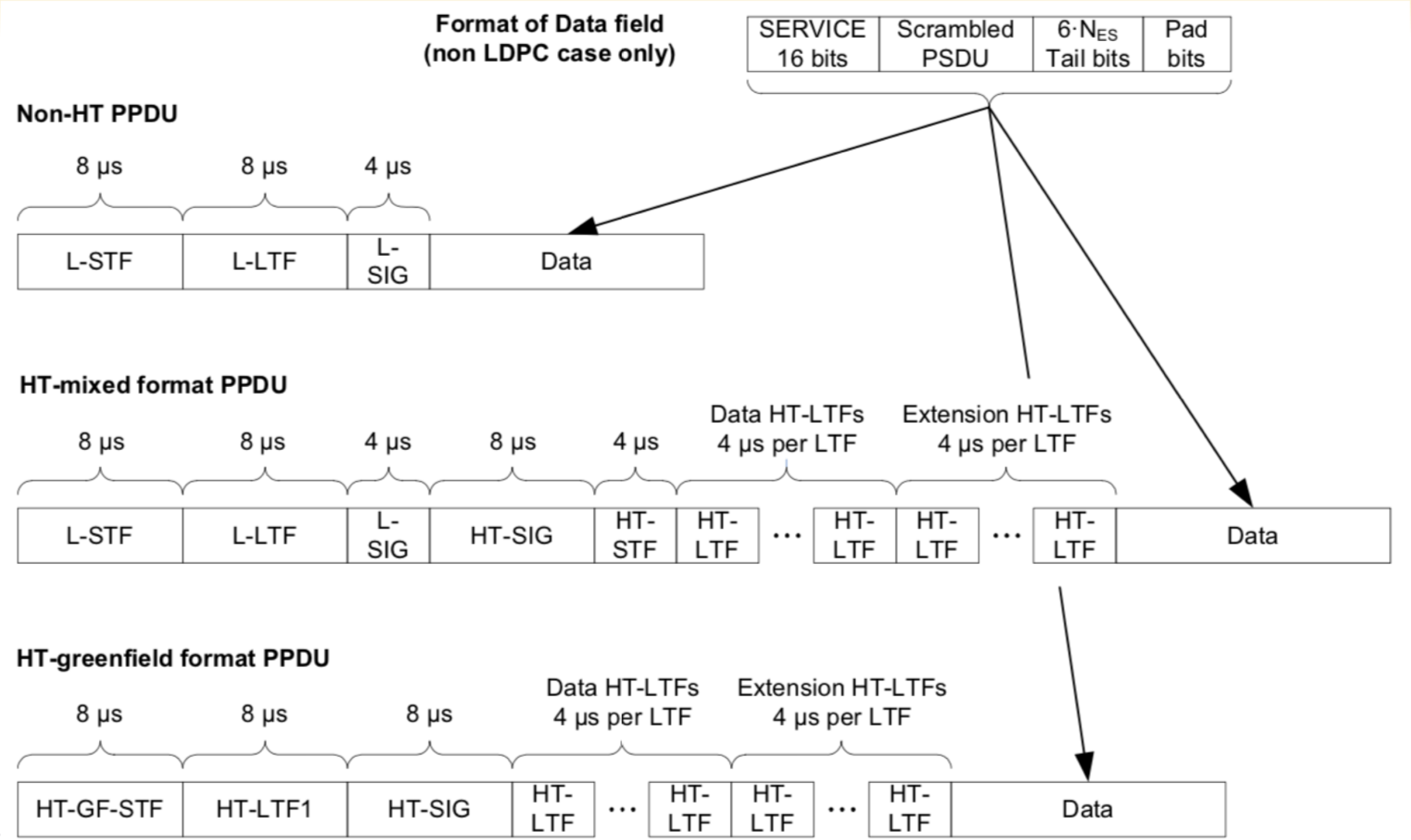
HT PHY Highlights

- OFDM PHY with up to 4 spatial streams in 20MHz
- One to four spatial streams in 40MHz
- Data rates up to 600Mb/s (4 spatial streams, 40MHz)
- Modulation: BPSK, QPSK, 16-QAM, 64-QAM
- Convolution Coding Rates: 1/2, 2/3, 3/4, or 5/6
- Optional Features:
  - LDPC, STBC codes
  - 400ns (short) guard interval (GI)
  - transmit beamforming
  - HT-greenfield format

PPDU Format

- Non-HT Format:
  - OFDM 20MHz packet
  - Support for non-HT format is mandatory
- HT-mixed Format
  - Packets of this format contain a preamble compatible with non-HT STAs
  - STF, LTF & SIGNAL can be decoded by non-HT STAs
  - Rest of the packet cannot be decoded by non-HT STAs
  - Mandatory
- HT-greenfield format
  - do not contain a non-HT compatible part
  - optional

PPDU Format



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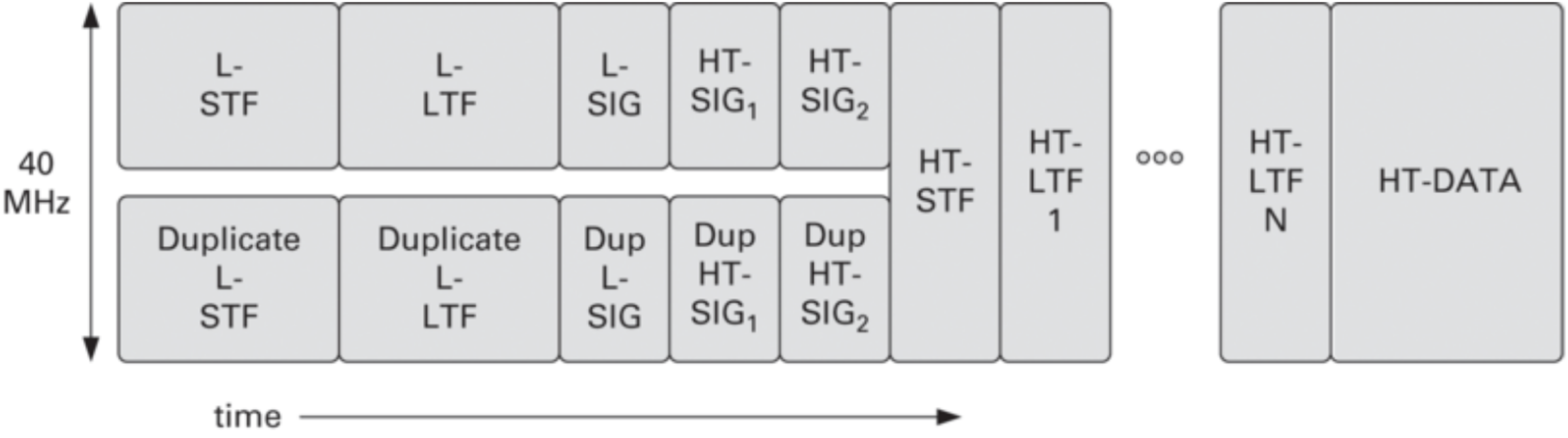
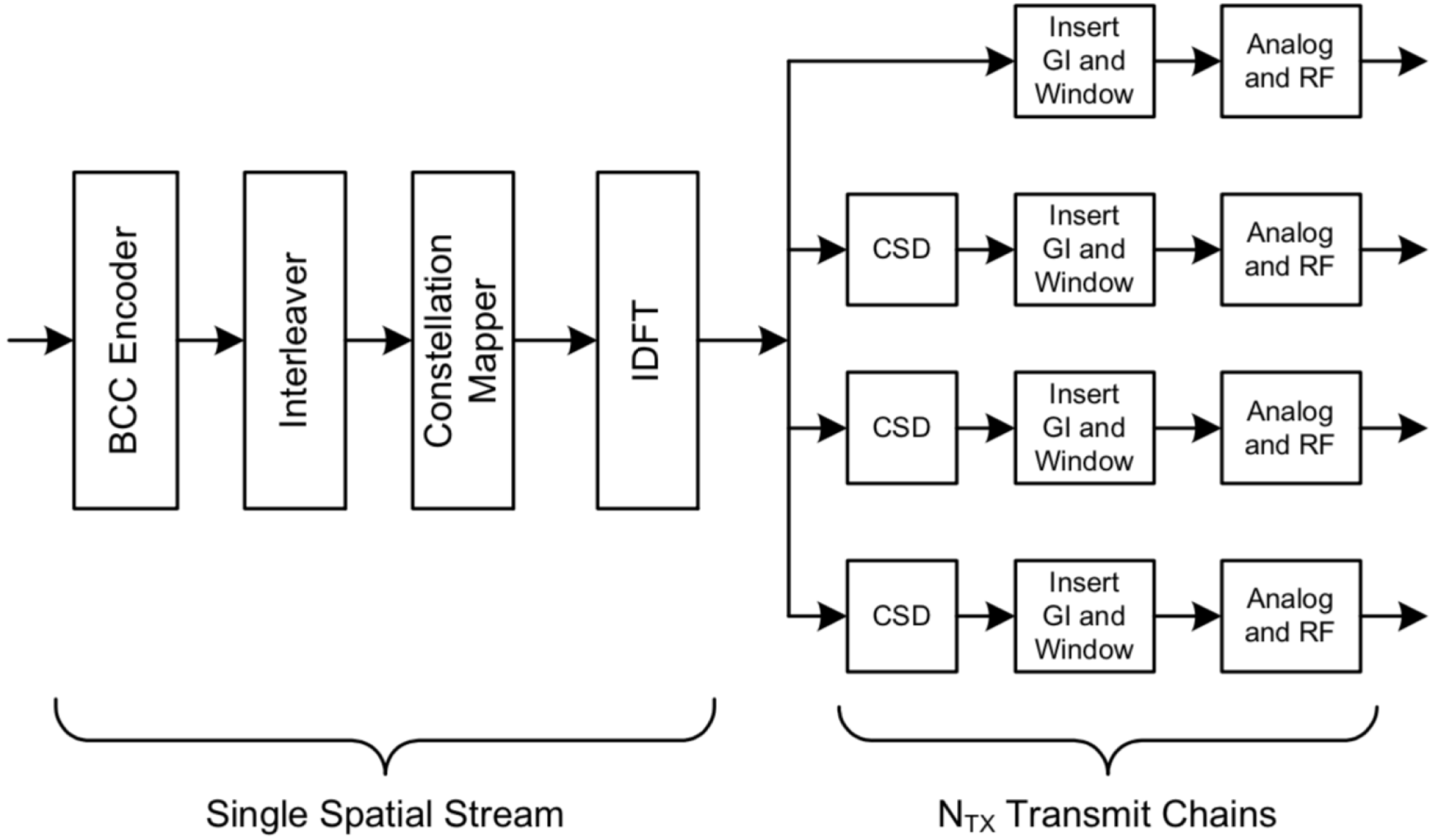
State University of New York

40MHz Transmission



Mixed Format Tx Blocks



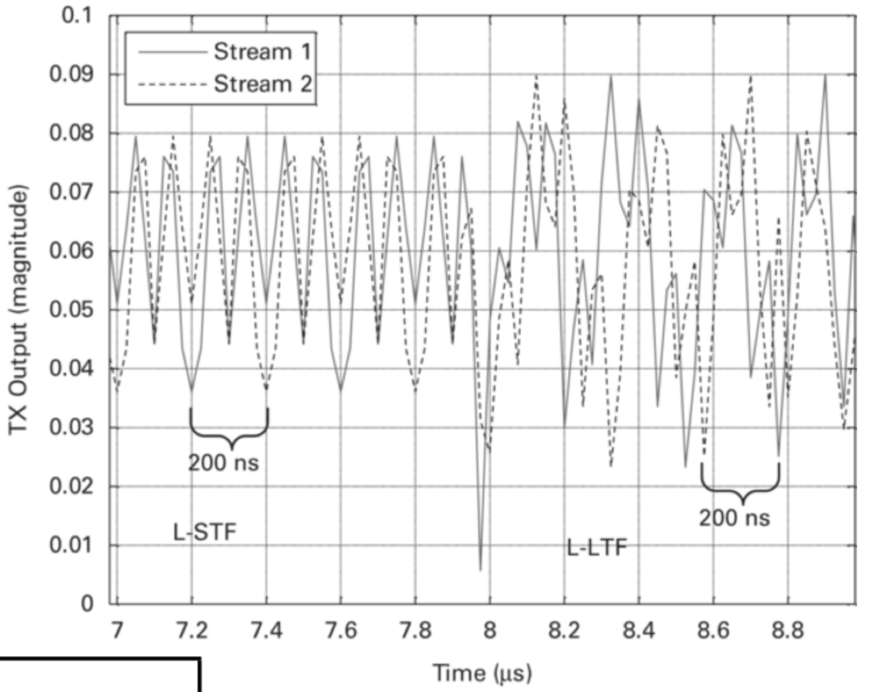
Cyclic Shift Diversity (CSD)

- How to transmit the legacy training from all antennas?
- Cyclic shifts are used to prevent unintentional beamforming
  - When the same signal or scalar multiples of one signal are transmitted through different spatial streams or transmit chains
- A cyclic shift of duration T_{CS} on a signal $s(t)$ on interval $0 \leq t \leq T$, where $T = T_{DFT}$

$$s_{CS}(t;T_{CS})\big|_{T_{CS}<0} = \begin{cases} s(t - T_{CS}) & 0 \leq t < T + T_{CS} \\ s(t - T_{CS} - T) & T + T_{CS} \leq t \leq T \end{cases}$$

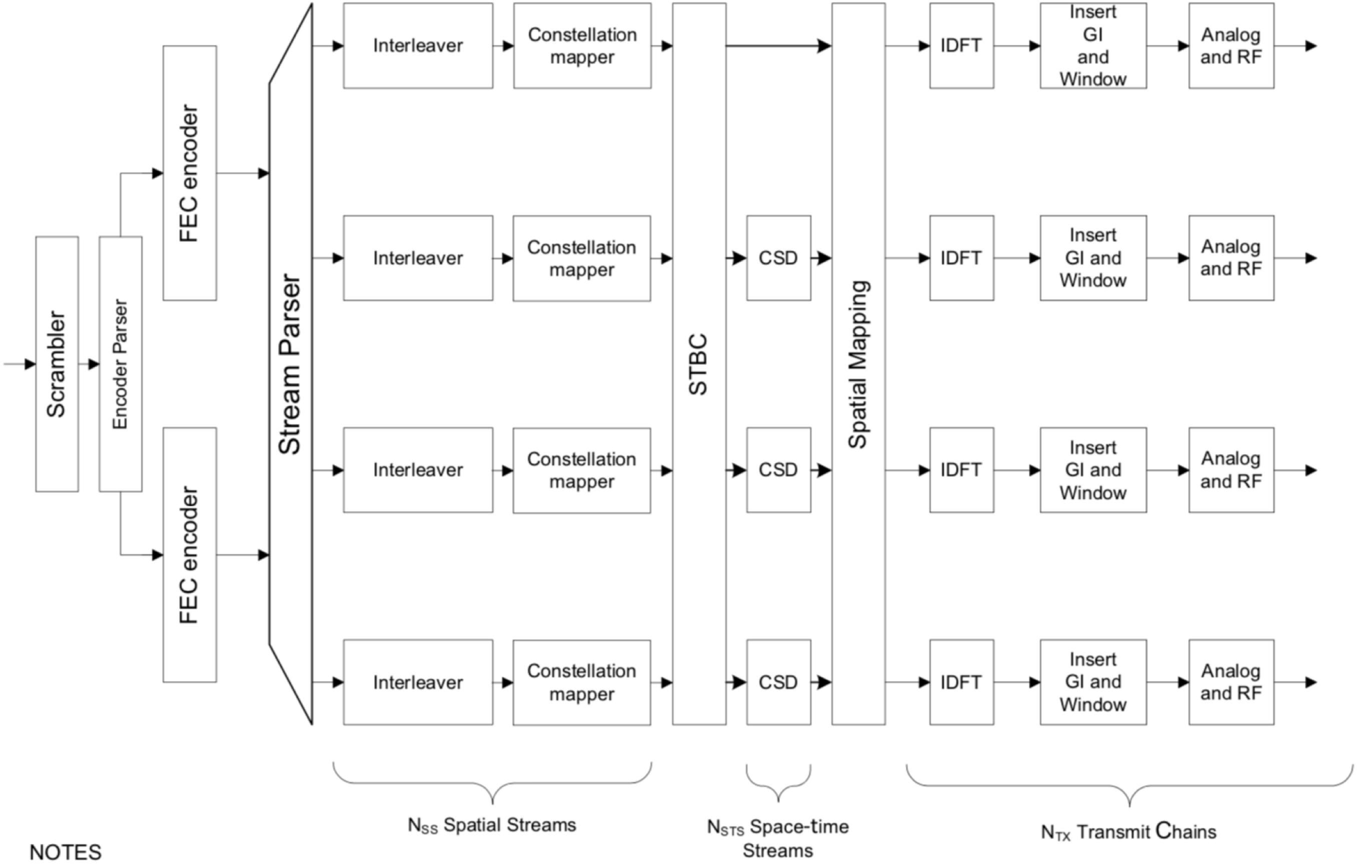
CSD

- The cyclic delay is chosen to be within the limits of the guard interval (GI) so that it does not cause excessive inter-symbol interference (ISI)



$T_{CS}^{i_{TX}}$ values for non-HT portion of packet				
Number of transmit chains	**Cyclic shift for transmit chain 1 (ns)**	**Cyclic shift for transmit chain 2 (ns)**	**Cyclic shift for transmit chain 3 (ns)**	**Cyclic shift for transmit chain 4 (ns)**
1	0	—	—	—
2	0	–200	—	—
3	0	–100	–200	—
4	0	–50	–100	–150

High Throughput Transmitter Blocks



L-STF

$$S_{-26,26} = \sqrt{1/2}$$
$$\{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0,$$
$$0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0\}$$

$$S_{-58,58} = \sqrt{1/2}$$
$$\{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0,$$
$$0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0,$$
$$0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j,$$
$$0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0\}$$

$$r_{L-STF}^{(i_{TX})}(t) = \frac{1}{\sqrt{N_{TX} \cdot N_{L-STF}^{Tone}}} w_{T_{L-STF}}(t) \sum_{k=-N_{SR}}^{N_{SR}} \Upsilon_k S_k \exp(j2\pi k \Delta_F (t - T_{CS}^{i_{TX}}))$$

$$\Upsilon_k = \begin{cases} 1, & k \le 0, \text{ in a 40 MHz channel} \\ j, & k > 0, \text{ in a 40 MHz channel} \end{cases}$$

$$\Upsilon_k = 1, \text{ in a 20 MHz channel}$$

L-LTF

$$L_{-26,26} = \{1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0, 1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1\}$$

$$L_{-58,58} = \{1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0, 1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, -1, 1, 1, -1, 1, -1, 1, 1, 1, 1, 0, 1, -1, -1, 1, 1, -1, 1, -1, 1, -1, -1, -1, -1, -1, 1, 1, -1, -1, 1, -1, 1, -1, 1, 1, 1, 1\}$$

$$r_{L-LTF}^{(i_{TX})}(t) = \frac{1}{\sqrt{N_{TX} \cdot N_{L-LTF}^{Tone}}} w_{T_{L-LTF}}(t) \sum_{k=-N_{SR}}^{N_{SR}} \Upsilon_k L_k \exp(j2\pi k \Delta_F (t - T_{GI2} - T_{CS}^{i_{TX}}))$$

T_{GI2} is 1.6 μs

L-SIG

Rate (4 bits)				R	Length (12 bits)												P	Tail (6 bits)					
R1	R2	R3	R4															"0"	"0"	"0"	"0"	"0"	"0"
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

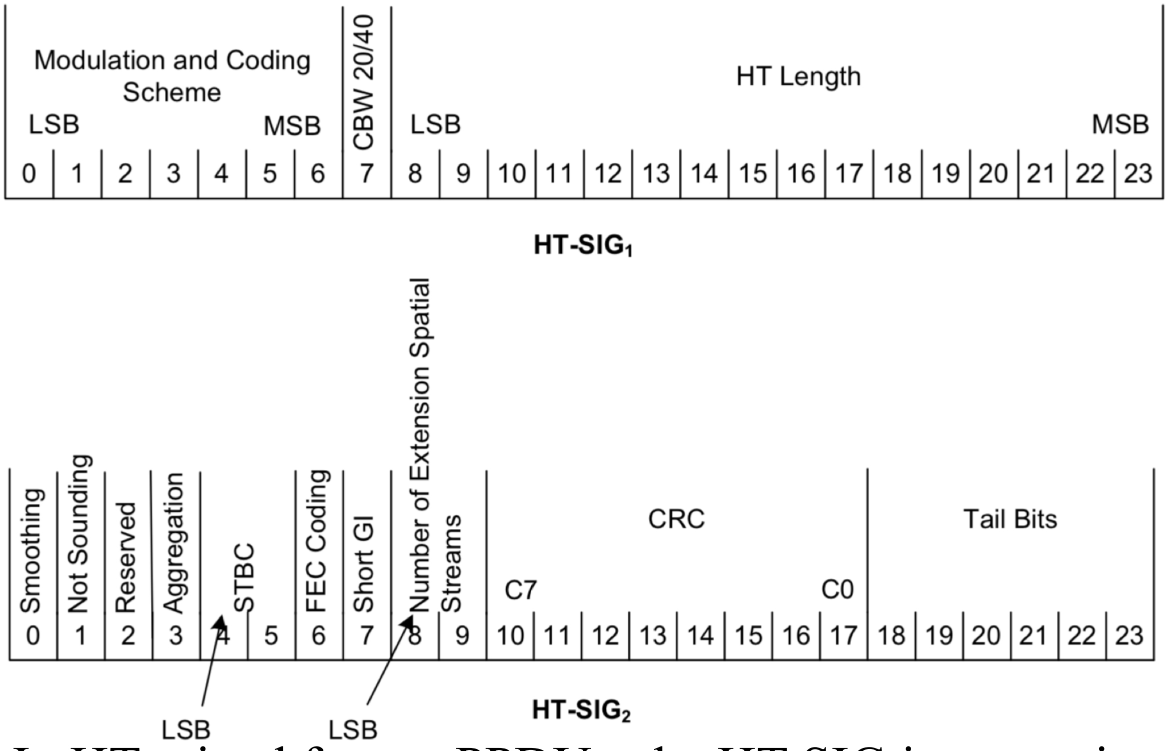
Time Domain Representation

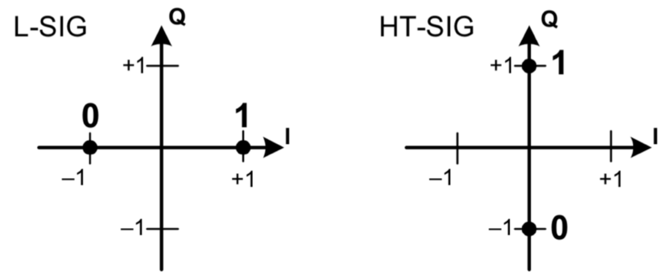
$$r^{(i_{TX})}_{L-SIG}(t) = \frac{1}{\sqrt{N_{TX} \cdot N^{Tone}_{L-SIG}}} w_{T_{SYM}}(t) \sum_{k=-26}^{26} (D_k + p_0 P_k)\exp(j2\pi k\Delta_F(t - T_{GI} - T^{i_{TX}}_{CS}))$$

Cyclic Shift for HT portion

$T_{CS}^{i_{STS}}$ values for HT portion of packet				
Number of space-time streams	**Cyclic shift for space-time stream 1 (ns)**	**Cyclic shift for space-time stream 2 (ns)**	**Cyclic shift for space-time stream 3 (ns)**	**Cyclic shift for space-time stream 4 (ns)**
1	0	—	—	—
2	0	–400	—	—
3	0	–400	–200	—
4	0	–400	–200	–600

HT-SIG1 and HT-SIG2





Quadrature binary phase shift keying (QBPSK) modulation is used in which the constellation of the data tones is rotated by 90° relative to the L-SIG in HT-mixed format PPDUs.

In HT-mixed format PPDUs, the HT-SIG is transmitted with the same number of subcarriers and the same cyclic shifts as the preceding non-HT portion of the preamble.

HT-STF

- The purpose of the HT-STF is to improve automatic gain control estimation in a MIMO system.

Spatial Streams

$N_{STS} \times N_{SS}$	STBC field value
2 × 1	1
3 × 2	1
4 × 2	2
4 × 3	1
No STBC	0

For 20 MHz:

$$HTS_{-28,28} = \sqrt{1/2}\{0, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 0\}$$

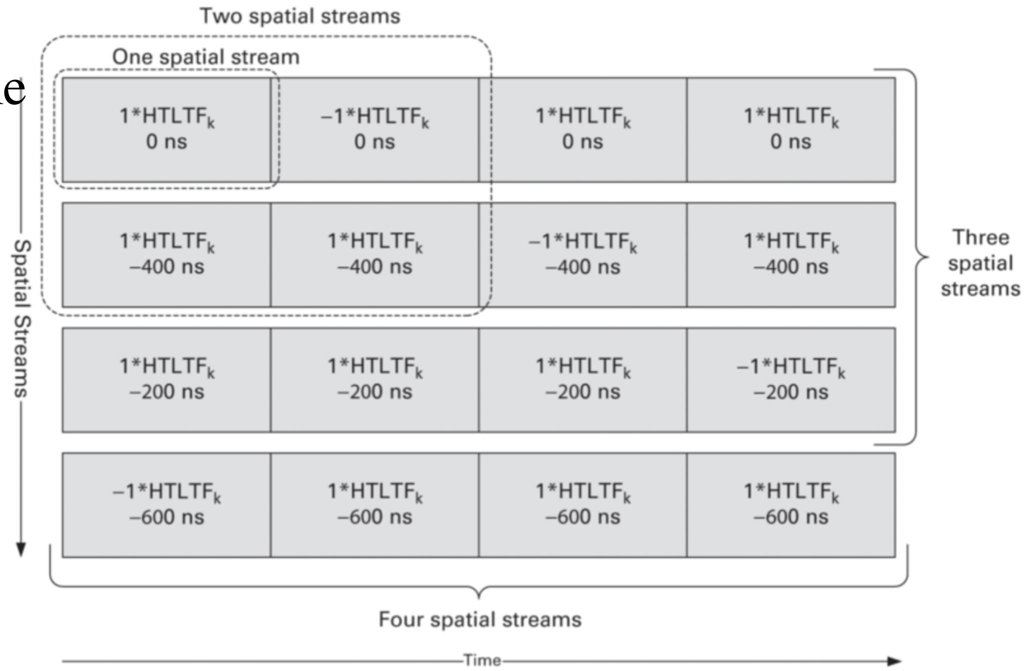
For 40 MHz:

$$HTS_{-58,58} = \sqrt{1/2}\{0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 0, 0, 0, 0, 0, 0, -1-j, 0, 0, 0, -1-j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0, 0, 1+j, 0, 0\}$$

$$r_{HT-STF}^{i_{TX}}(t) = \frac{1}{\sqrt{N_{STS} \cdot N_{HT-STF}^{Tone}}} w_{T_{HT-STF}}(t) \sum_{k=-N_{SR}}^{N_{SR}} \sum_{i_{STS}=1}^{N_{STS}} [Q_k]_{i_{TX}, i_{STS}} \Upsilon_k HTS_k \exp(j2\pi k\Delta_F(t - T_{CS}^{i_{STS}})) \quad (19\text{-}21)$$

HT-LTF

- The HT-LTF provides a means for the receiver to estimate the MIMO channel between the set of QAM mapper outputs (or, if STBC is applied, the STBC encoder outputs) and the receive chains.
- If the transmitter is providing training for exactly the space-time streams (spatial mapper inputs) used for the transmission of the PSDU, the number of training symbols, N_{LTF} , is equal to the number of space-time streams, N_{STS}, except that for three space-time streams, four training symbols are required.

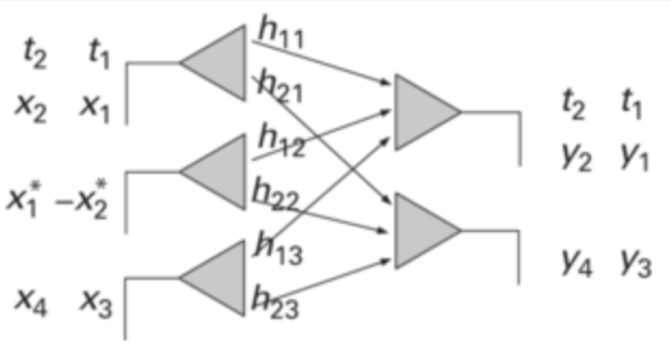


Pilots for multiple streams

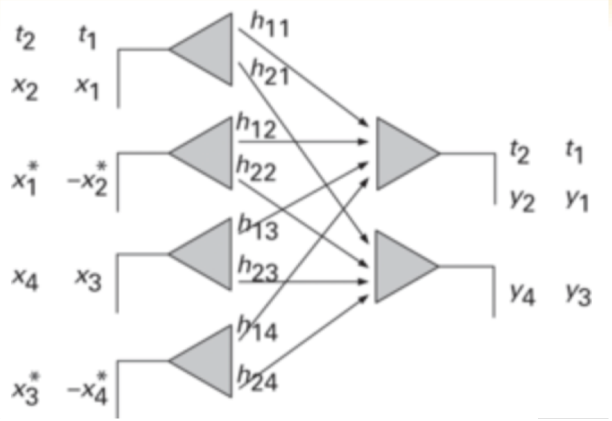
Table 19-19—Pilot values for 20 MHz transmission

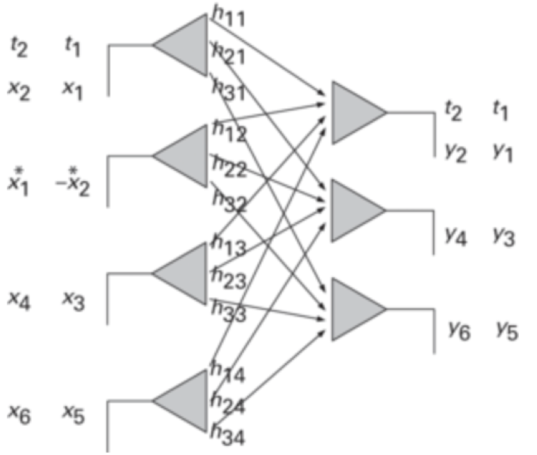
N_{STS}	i_{STS}	$\Psi_{i_{STS},0}^{(N_{STS})}$	$\Psi_{i_{STS},1}^{(N_{STS})}$	$\Psi_{i_{STS},2}^{(N_{STS})}$	$\Psi_{i_{STS},3}^{(N_{STS})}$
1	1	1	1	1	–1
2	1	1	1	–1	–1
2	2	1	–1	–1	1
3	1	1	1	–1	–1
3	2	1	–1	1	–1
3	3	–1	1	1	–1
4	1	1	1	1	–1
4	2	1	1	–1	1
4	3	1	–1	1	1
4	4	–1	1	1	1

STBC Possibilities beyond 2 antennas



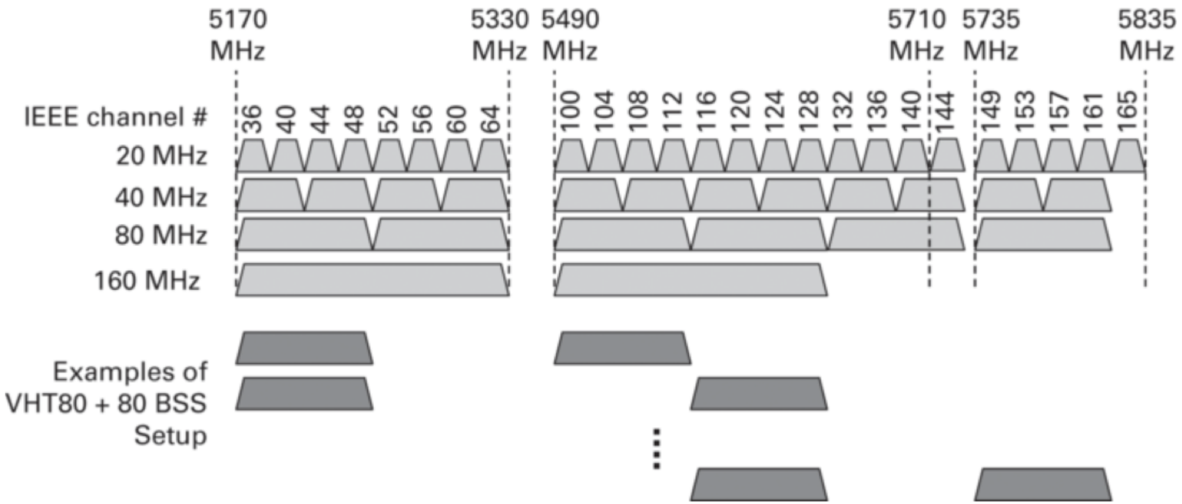
$$y_1 = \sqrt{\rho/3} \cdot h_{11} \cdot x_1 + \sqrt{\rho/3} \cdot h_{12} \cdot -x_2^* + \sqrt{\rho/3} \cdot h_{13} \cdot x_3 + z_1$$
$$y_2 = \sqrt{\rho/3} \cdot h_{11} \cdot x_2 + \sqrt{\rho/3} \cdot h_{12} \cdot x_1^* + \sqrt{\rho/3} \cdot h_{13} \cdot x_4 + z_2$$
$$y_3 = \sqrt{\rho/3} \cdot h_{21} \cdot x_1 + \sqrt{\rho/3} \cdot h_{22} \cdot -x_2^* + \sqrt{\rho/3} \cdot h_{23} \cdot x_3 + z_3$$
$$y_4 = \sqrt{\rho/3} \cdot h_{21} \cdot x_2 + \sqrt{\rho/3} \cdot h_{22} \cdot x_1^* + \sqrt{\rho/3} \cdot h_{23} \cdot x_4 + z_4$$



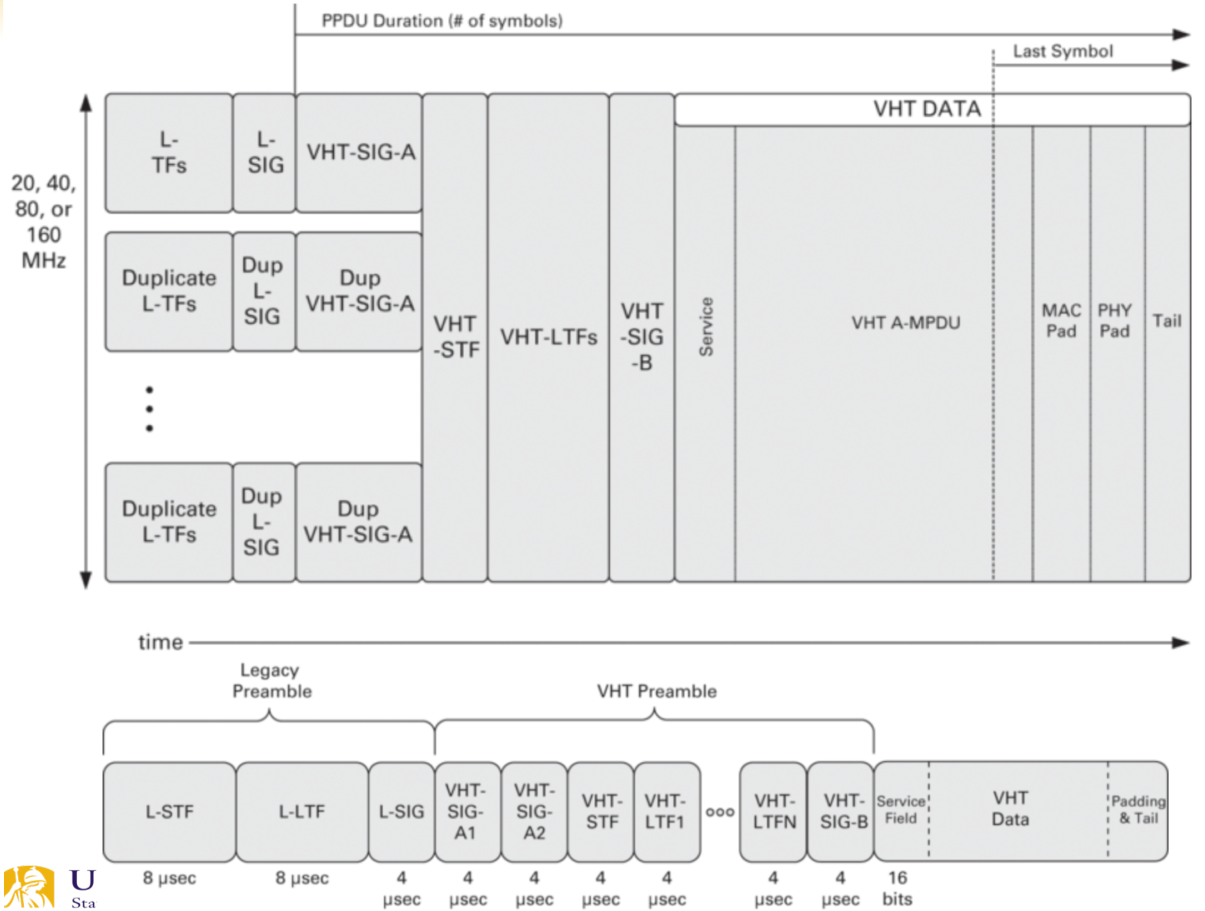


Very High Throughput PHY

- Six non-overlapping 80 MHz channels and two non-overlapping 160 MHz channels
- Non-contiguous 160 MHz mode (or 80+80 MHz) is created by selecting any two nonadjacent 80 MHz channels
- 80MHz uses 256pt FFT
- 160MHz uses 512pt FFT



VHT Preamble



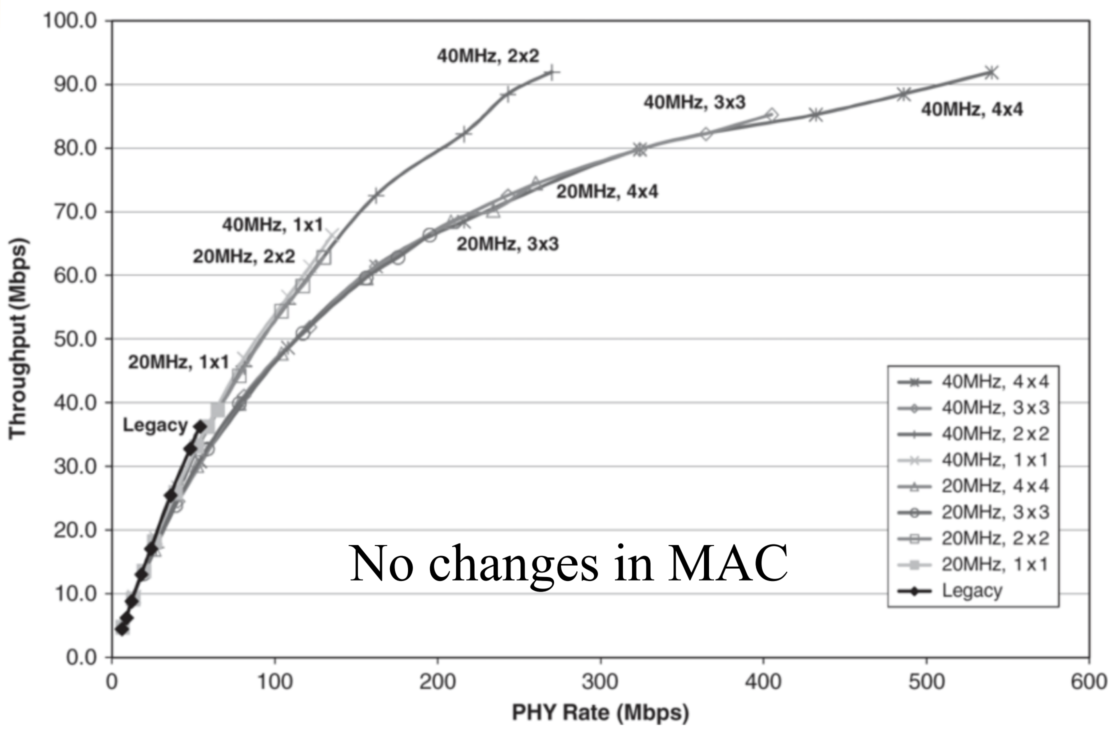
Cyclic Shift for VHT

Total number of transmit antennas (N_{TX})	Cyclic shift for transmit antenna i_{TX} (in units of ns)								
	1	2	3	4	5	6	7	8	>8
1	0	–	–	–	–	–	–	–	–
2	0	−200	–	–	–	–	–	–	–
3	0	−100	−200	–	–	–	–	–	–
4	0	−50	−100	−150	–	–	–	–	–
5	0	−175	−25	−50	−75	–	–	–	–
6	0	−200	−25	−150	−175	−125	–	–	–
7	0	−200	−150	−25	−175	−75	−50	–	–
8	0	−175	−150	−125	−25	−100	−50	−200	–
>8	0	−175	−150	−125	−25	−100	−50	−200	Between −200 and 0 inclusive

MCS for VHT

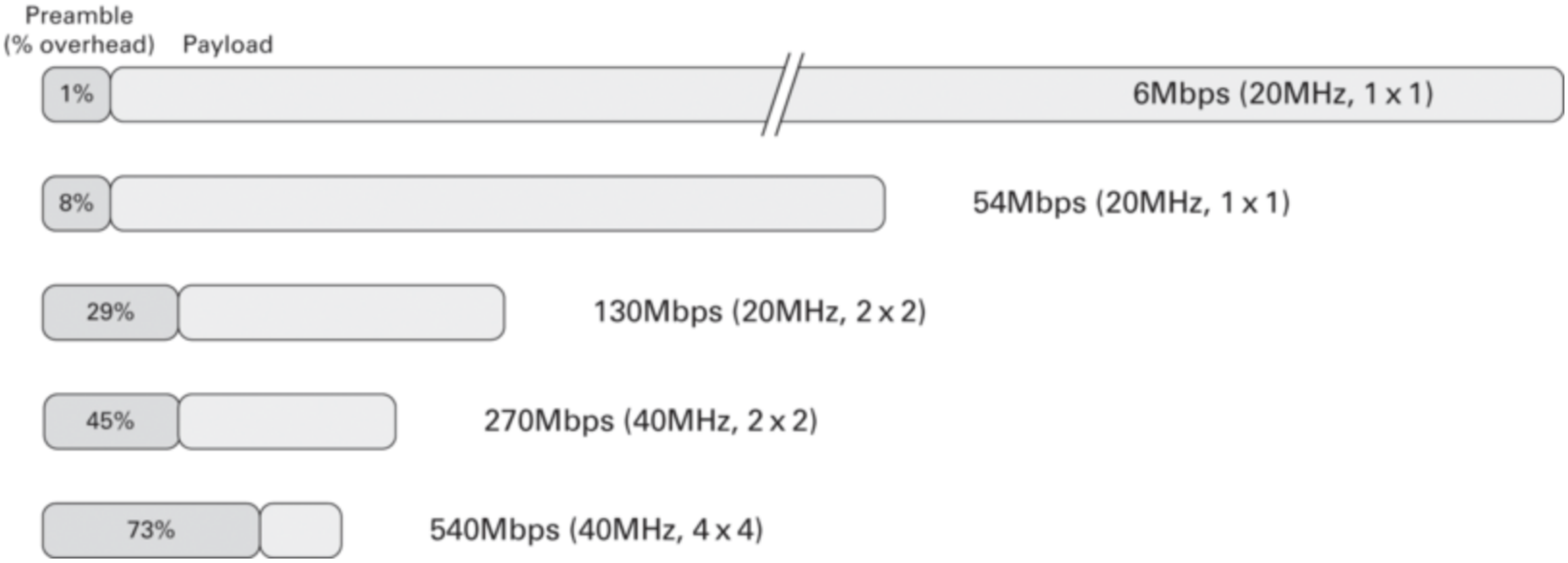
MCS index	Modulation	Rate (R)	N_{BPSCS}
0	BPSK	1/2	1
1	QPSK	1/2	2
2	QPSK	3/4	2
3	16-QAM	1/2	4
4	16-QAM	3/4	4
5	64-QAM	2/3	6
6	64-QAM	3/4	6
7	64-QAM	5/6	6
8	256-QAM	3/4	8
9	256-QAM	5/6	8

MAC Changes

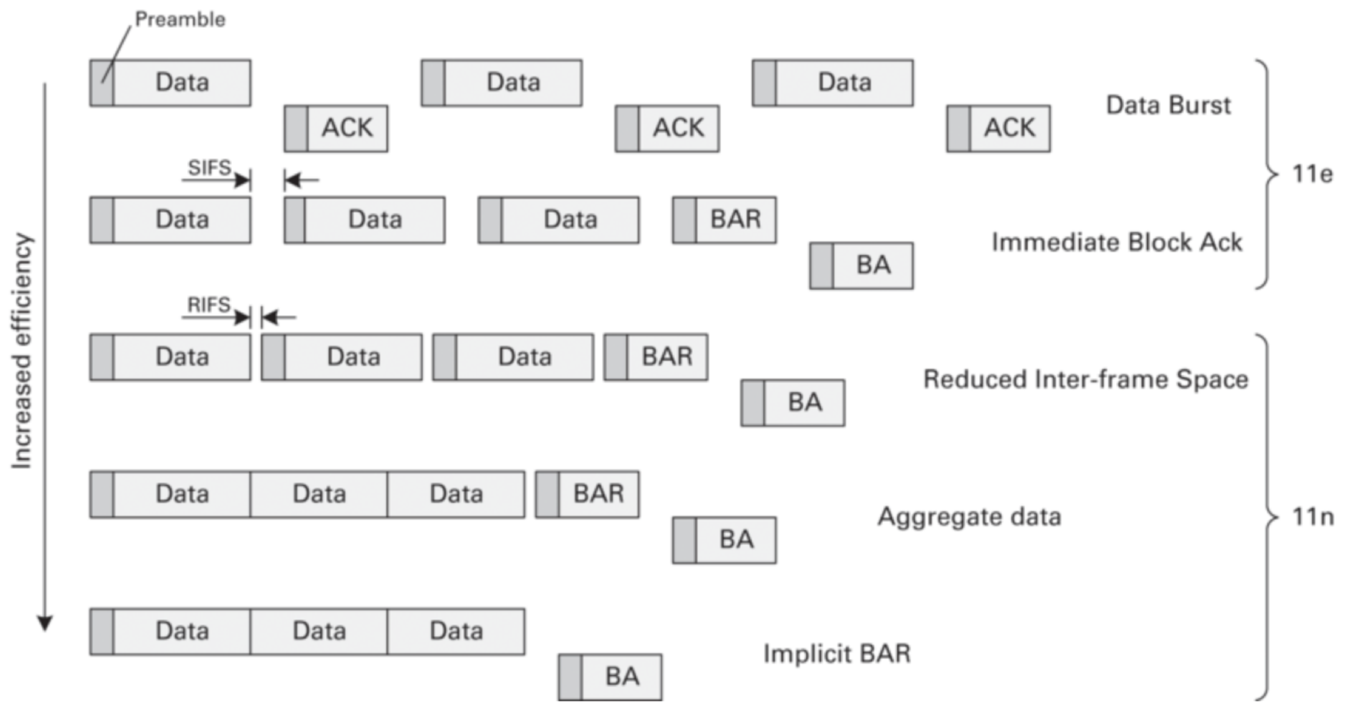


- Xput does not increase with more spatial streams

Preamble Overhead



MAC Throughput Enhancements

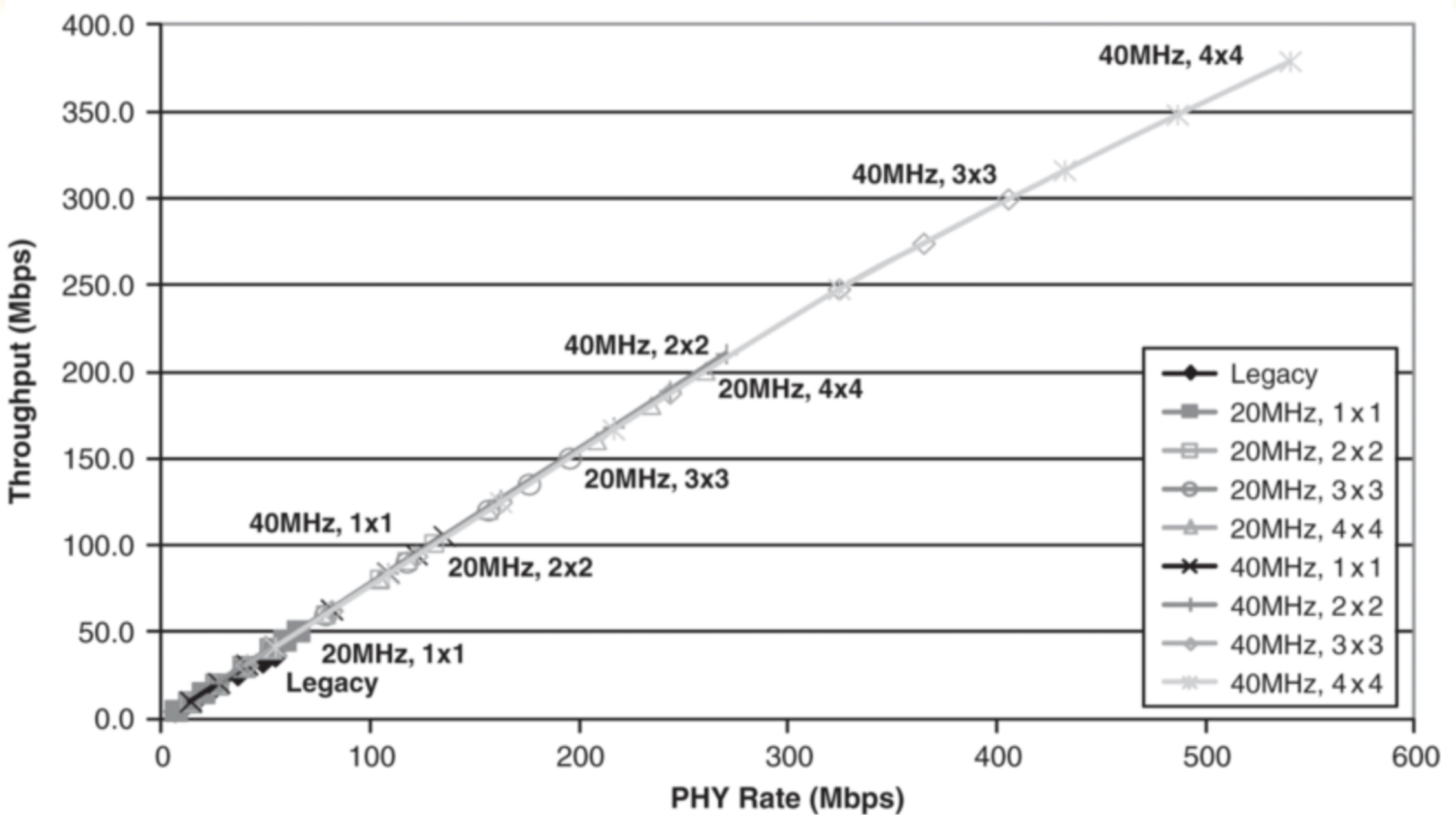


BAR: Block Ack Request

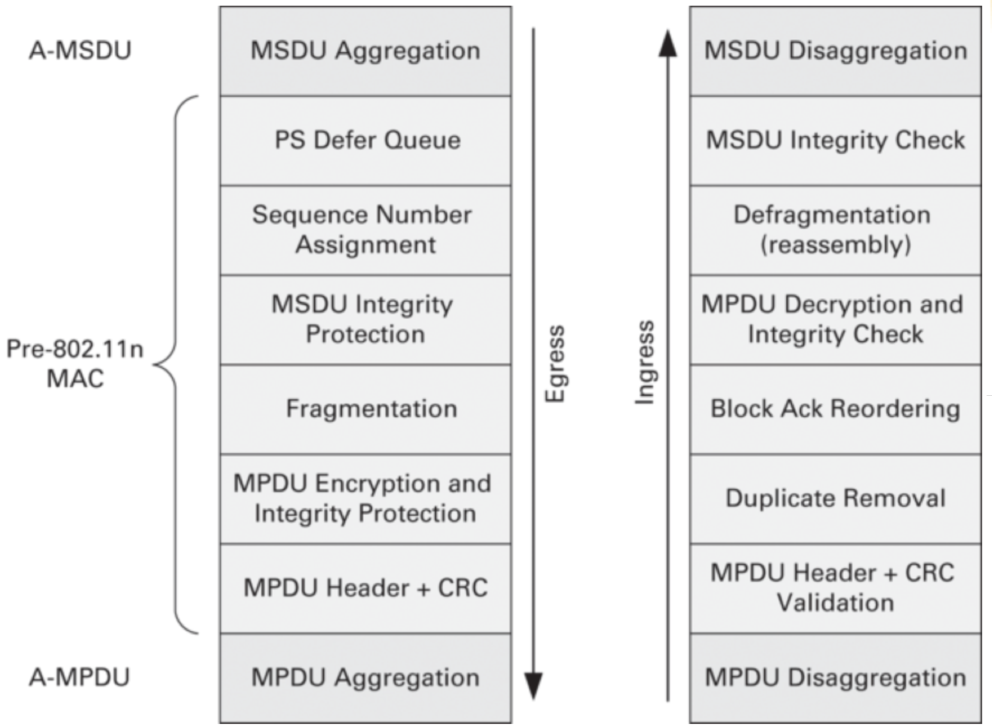
BA: Block Ack

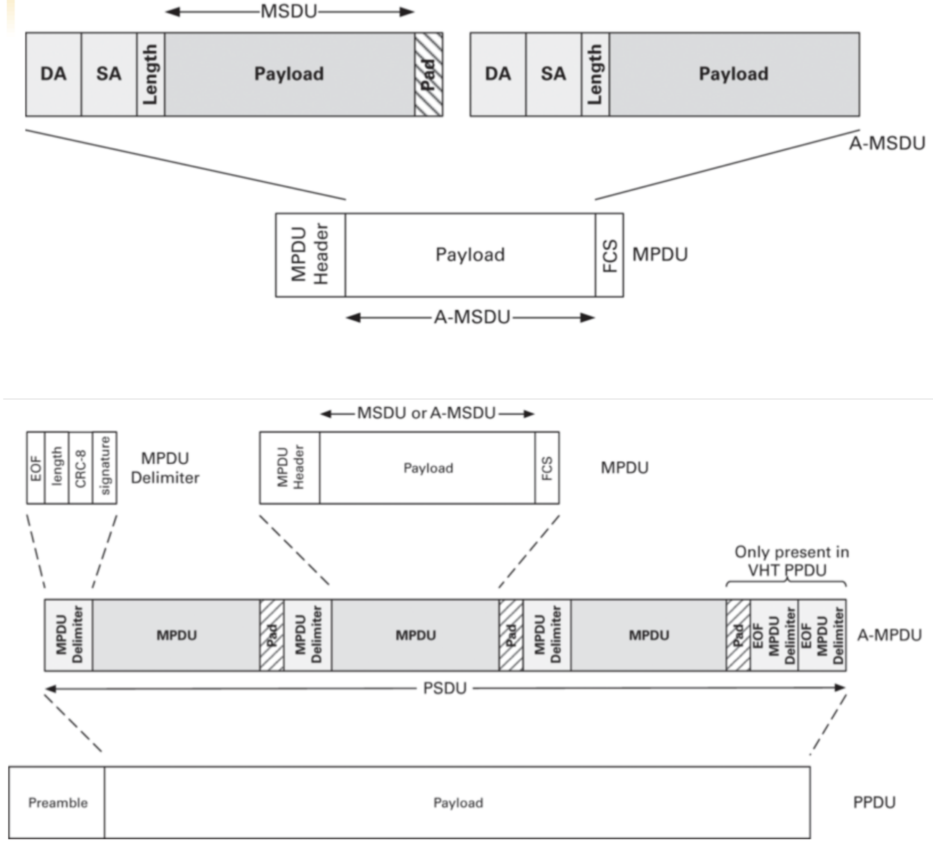
TXOP: Transmission Opportunity period

Throughput with MAC Enhancements



Aggregation (MSDU and MPDU)





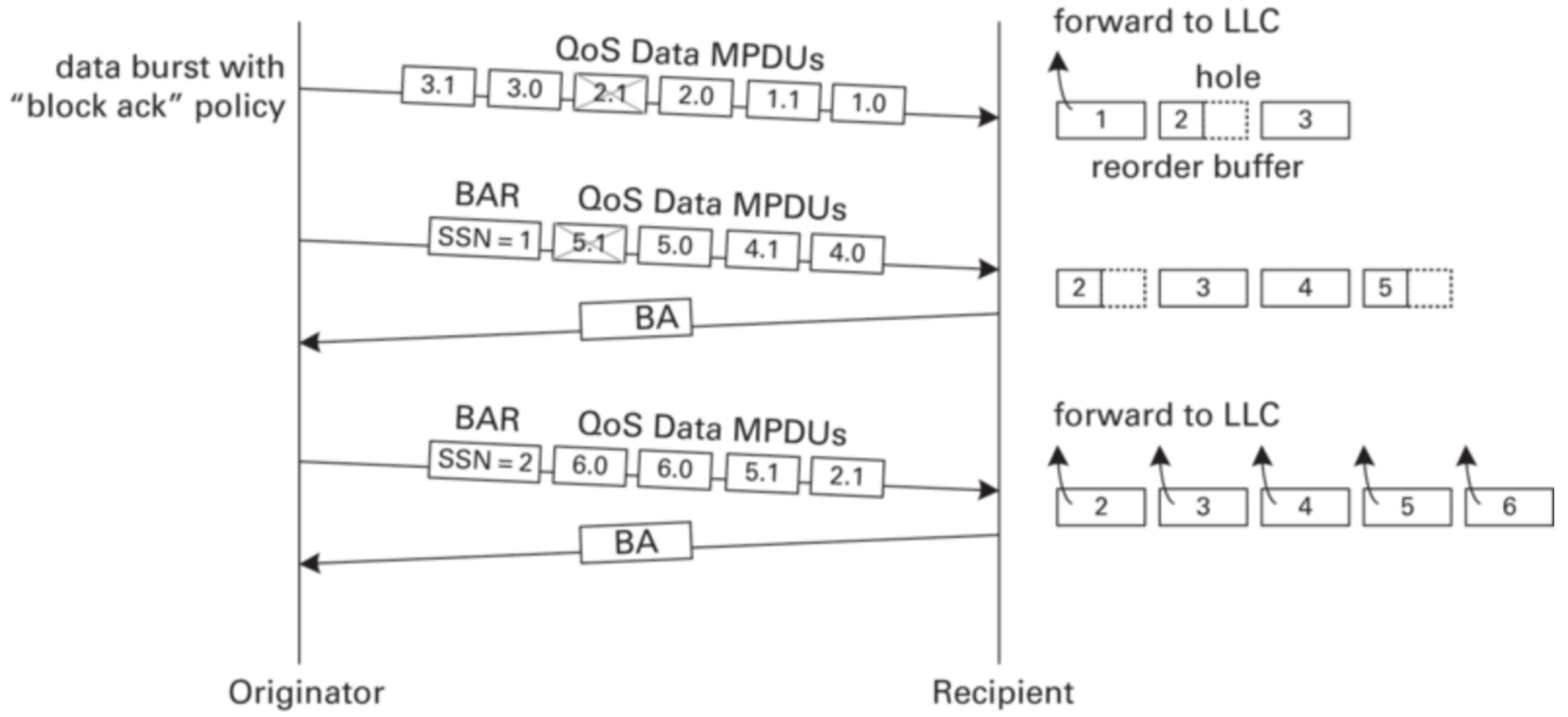
A-MSDU

- In the A-MSDU format, multiple frames from higher layers are combined and processed by the MAC layer as a single entity.
- Each original frame becomes a subframe within the aggregated MAC frame.
- Thus this method must be used for frames with the same source and destination, and only MSDUs of the same priority (access class, as in 802.11e) can be aggregated.

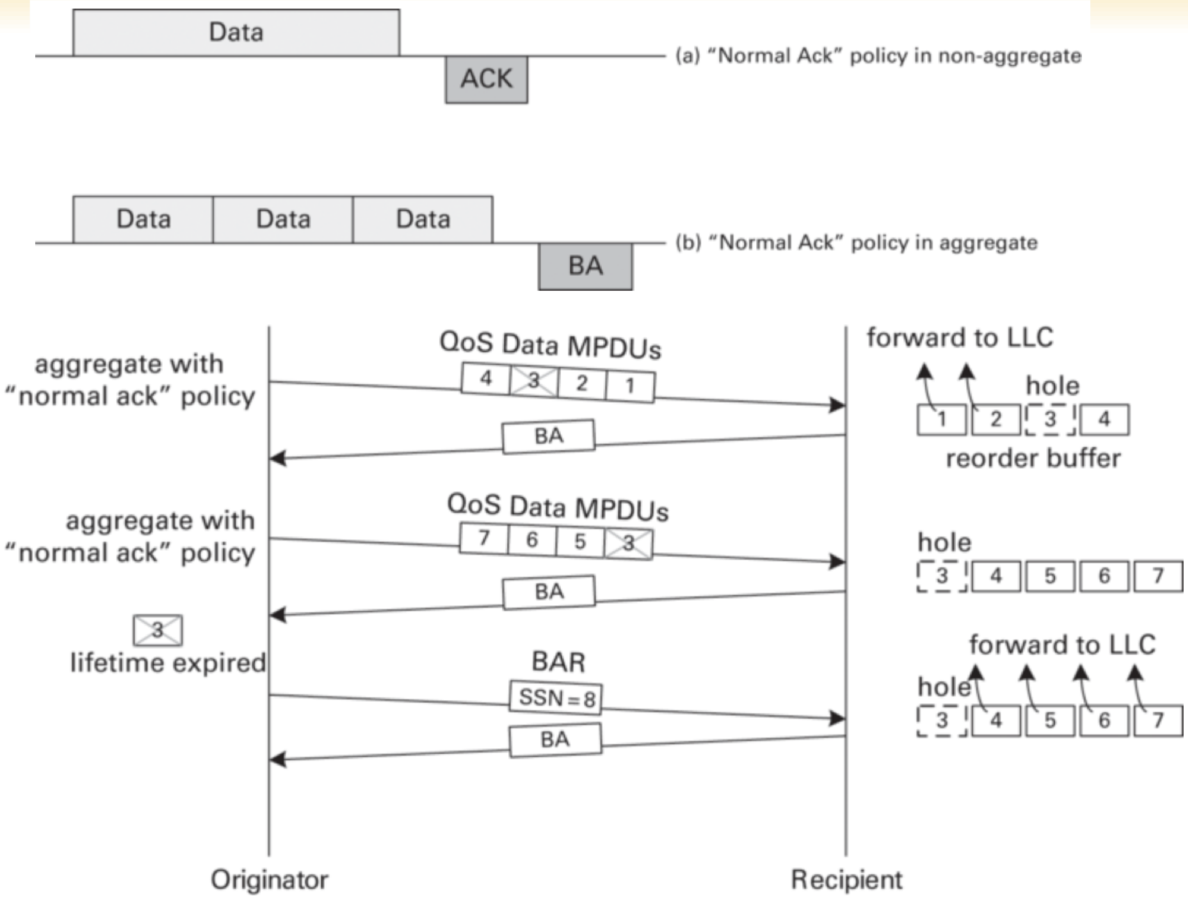
A-MPDU

- A-MPDU format, allows concatenation of MPDUs into an aggregate MAC frame.
- Each individual MPDU is encrypted and decrypted separately.
- Since MPDUs are packed together, this method cannot use the earlier 802.11 per-MPDU acknowledgement mechanism for unicast frames.
- A-MPDU must be used with the new Block Acknowledgement function of 802.11n.

Reorder Buffer



Block ACK (Normal vs BAR)

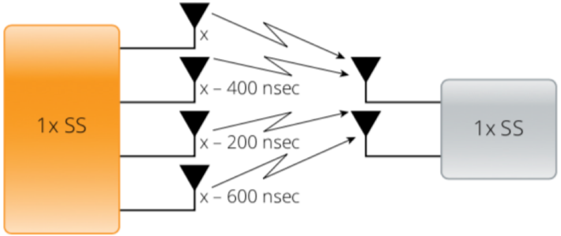


SSN is set to the sequence number of the next MSDU to be transmitted

BAR: it solicits a BA response and it flushes the MSDUs in the reorder buffer that are held up due to an earlier incomplete MSDU

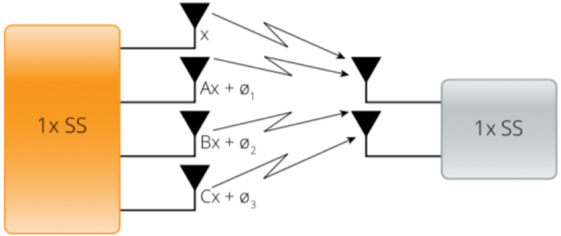
NOTE: MSDU 3 never reaches to recipient.

Tx/Rx Techniques



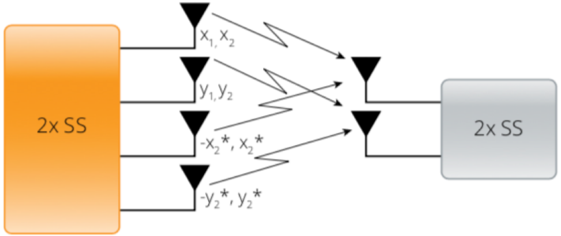
Cyclic Shift Diversity (CSD, CDD)

Transmit diversity by blindly transmitting from each antenna with a fixed phase shift. Receiver picks best signal. Can be combined with MRC, (also termed Cyclic Delay Diversity)



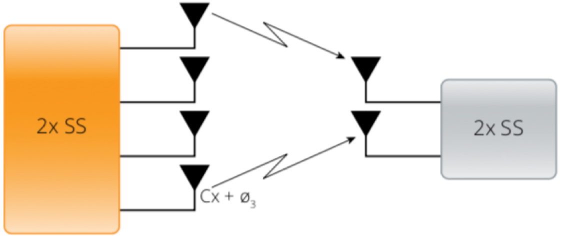
Transmit Beamforming (TxBF)

Transmitter receives channel state information from receiver (compressed V feedback matrix) and computes parameters to drive local signal maximum at receiver. The transmitter can form on several antennas if silicon allows.



Space Time Block Coding (STBC)

Transmitter codes a pair of symbols in successive timeslots form different antennas. Only works with even numbers of anntennas, two per SS. All-or-nothing, all SS must use STBC if any use it. Here combined with SDM. STBC halves the effective data rate.

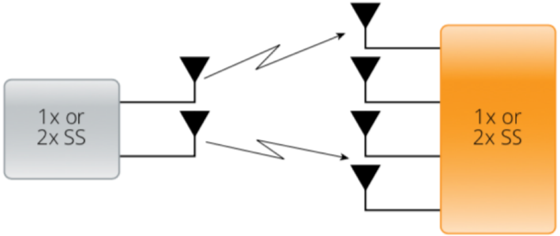


Spatial Division Multiplexing (SDM)

Transmitter sends one spatial stream per antenna, chosen for the best performance. Feedback from the receiver is not required; channel stateis inferred by assuming reciprocity. Can be combined with STBC.

Combining Techniques

Some combinations are disallowed by the 'equal modulation' restriction, others by silicon implementation. Equal modulation requires all driven antennas to use the same MCS.

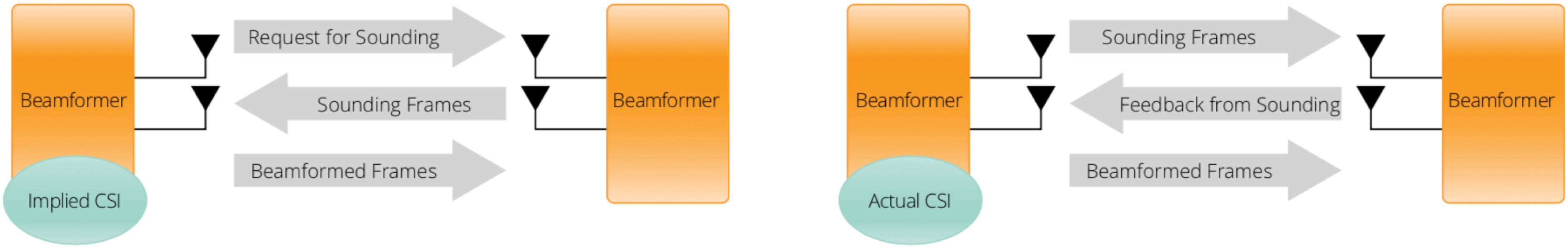


Maximal Ratio Combining (MRC)

Receive-only technique to combine multiple copies of the same signal at RF for the best SNR. Can be combined with CSD, SDM or SDBC.

Beamforming

IMPLICIT AND EXPLICIT FEEDBACK FOR BEAMFORMING



Implicit Feedback for Beamforming (802.11n not 802.11ac)

1. (Beamformer) Send me a sounding frame
2. (Beamformee) Here's the sounding frame
3. OK, I'll pre-code assuming you hear me like I heard you

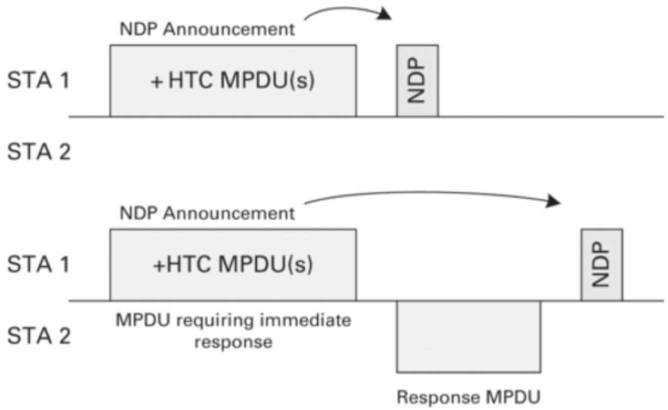
Explicit Feedback for Beamforming (802.11n and 802.11ac)

1. (Beamformer) Here's a sounding frame
2. (Beamformee) Here's how I heard the sounding frame
3. Now I will pre-code to match how you heard me

- Differences: hardware complexity and limitations, overhead, and dependency of the beamformer on the beamformee

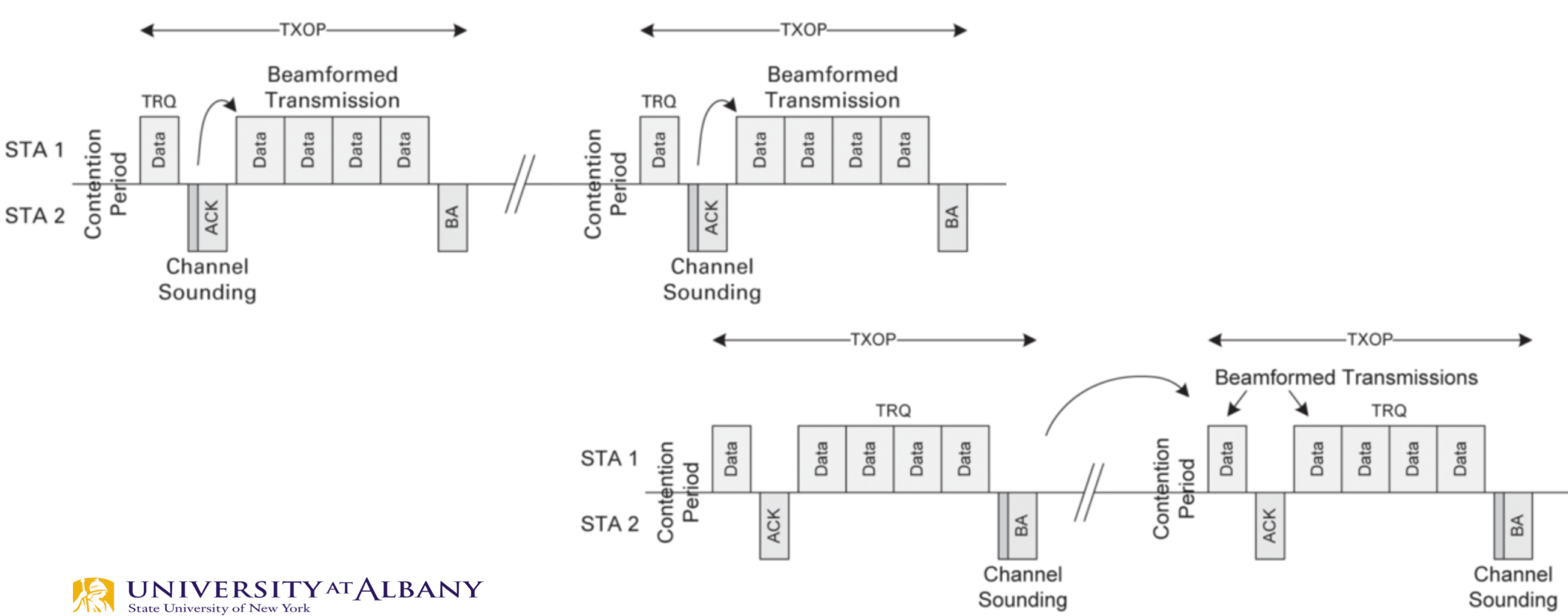
NDP for channel sounding

- The NDP can also be used in calibration for implicit feedback beamforming.
  - With calibration, channel sounding is required in both link directions closely spaced in time. A special sequence to perform calibration is defined and described later.
- The NDP may also be used for antenna selection, a technique for selecting the optimal receive and transmit antennas.
  - When performing antenna selection multiple NDP transmissions may be needed since up to 8 antennas may be present.



Implicit Feedback

- To sound the channel, the beamformer sends a PPDU containing one or more +HTC MPDUs which have the TRQ bit set to 1



Explicit Feedback (Immediate or Delayed)