



STANFORD

*Supplementary Lecture 5A*  
**Wi-Fi Example**  
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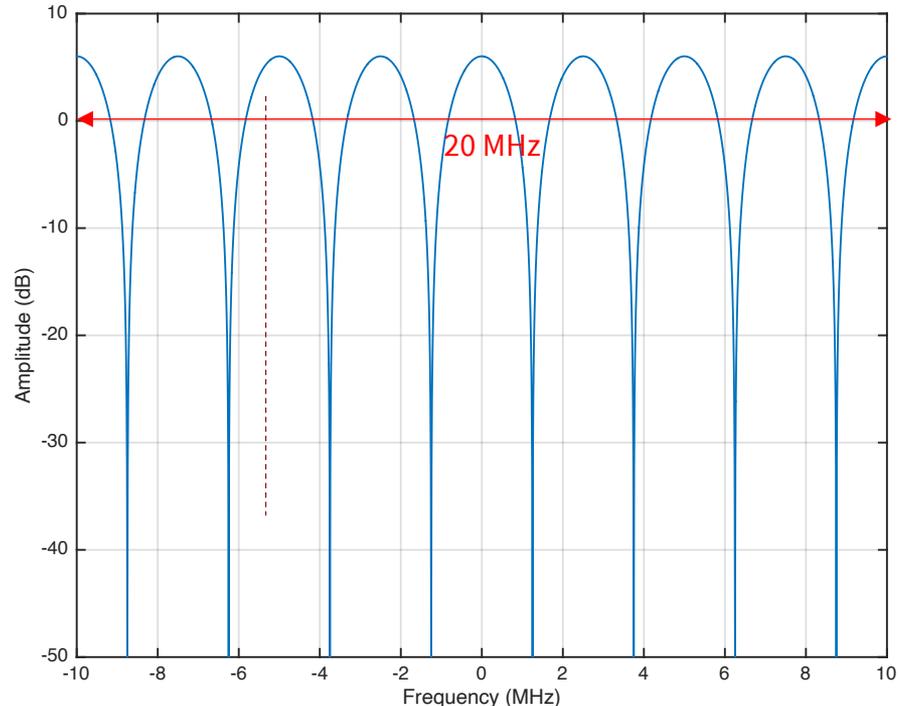
# Wi-Fi Use-Case Example

## *Section 4.7*

# Wi-Fi Channel Variability/Range

- The basic W-Fi transmission bandwidth is 20 MHz wide ( $T' = 50$  ns), or power-of-2 multiples thereof.
- Example channel has 2 paths, 1 with extra path with delay = 200 ns = 60 m @ speed of light.
- Some tones have higher gain, but
- roughly  $\frac{1}{4}$  -  $\frac{1}{3}$  of tones' gains are below the previous single path threshold (red line).
- Code roughly needs at least  $\frac{1}{4}$  parity
  - to recover this lost  $\frac{1}{4}$  of information.
- Thus  $\frac{3}{4}$ ,  $\frac{2}{3}$ , and  $\frac{1}{2}$  code rates are of interest.

**Coded OFDM**



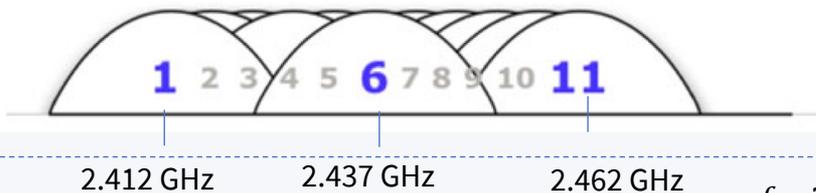
# Wi-Fi's 20-320 MHz Channels

11g, n

“Wi-Fi 4”

n has  $L \leq 4$

## 2.4 GHz channels (U.S.)



Only 1, 6, 11 avoid Overlap, so really 3 channels

$$f_c = 2407 + i \cdot 5 \text{ MHz for } i = 1, \dots, 11$$

(max  $L$ )

Wi-Fi 4 - 11a (1)

Wi-Fi 5 - 11ac (4)

Wi-Fi 6 - 11ax (8)

Wi-Fi 7 - 11be (16)

$$f_c = 5180 + (i - 36) \cdot 5; i \in 36 + [0:3]; 5250 + (i - 36) \cdot 5; i \in 36 + [4:7]; 5470 + (i - 100) \cdot 5; i \in 100 + [0:11]; 5725 + (i - 149) \cdot 5; i \in 149 + [0:4];$$

5170-5340 MHz ;  $i$  and channel band)

0	1	2	3	4	5	6	7
20	20	20	20	20	20	20	20
40		40		40		40	
80				80			
160							

25 channels @ 20 MHz

6GHz WiFi? - Up to 71 channels  
(20 MHz)  
when 6MHz,  
Allows 320 MHz also

- Unlicensed – so multiple systems can collide – detect collect, retransmit after random wait.



# Base Wi-Fi OFDM for 20 MHz

- Complex sampling rate

$$\frac{1}{T'} = 20 \text{ MHz}$$

- Number of carriers

$$N=64$$

- Carrier Spacing

$$\Delta f = \frac{20}{64} = 312.5 \text{ kHz}$$

- Cyclic Extension, Symbol Period  $T = (N + \nu)T'$

$$\nu=16$$

$$T = 4 \mu\text{s} \ \& \ 1/T = 250 \text{ KHz}$$
$$\text{cp length} = 1600 \text{ ns}$$

- Bits/tone

$$b_n \in \{2, 4, 6, 8, 10\}$$

- Used Carriers = 48

- Tone 32 at edge is not used, nor are -27...-31, 27 ... 31
- Pilots are at -21, -7, 7, 21 and 0 is not user data



# 802.11a, g Table

Statistical loaded  
On a single  
 $SNR_{ofdm}$

$R$ (Mbps)	“ $M$ ” constellation	code rate	$b_n$	$\bar{b}_n$	$b$
6	BPSK	1/2	1/2	1/4	24
9	BPSK	3/4	3/4	3/8	36
12	4QAM	1/2	1	1/2	48
18	4QAM	3/4	3/2	3/4	72
24	16QAM	1/2	2	1	96
36	16QAM	3/4	3/2	3/4	144
48	64QAM	1/2	3	3/2	192
54	64QAM	3/4	9/2	9/4	216

$$R = \log_2(M) \cdot (\text{code rate}) \cdot (48 \text{ tones}) \cdot 250 \text{ kHz} = [0.5, 1, 2, \text{ or } 3] \cdot (12 \text{ or } 18) \text{ Mbps.}$$

- All tones have equal energy: Power is 16 dBm, 20 dBm, or 29 dBm.
- Receiver (effectively) chooses 1 of these 8 loadings or “profiles” by reverse-channel indications to transmitter.



# Example Computations & Codes

- 48 tones x 4 bits/tone (16QAM) x  $\frac{3}{4}$  (code rate) x 250 kHz = 36 Mbps.
- 48 tones x 6 bits/tone (64 QAM) x  $\frac{2}{3}$  (code rate) x 250 kHz = 48 Mbps.
- MCS indication is returned by rcvr to xmit via control/reverse channel.
- Codes are convolutional:
  - 64-state rate-1/2 code (organized 6 of 12)
    - Punctured (2/3 - delete 4 bits from 12)
    - Punctured (3/4 - delete 3 bits from 12)

Code rate	Free distance	coding gain $10 \log(r \cdot d_{free})$
$\frac{1}{2}$	10	7 dB
$\frac{2}{3}$	6	6 dB
$\frac{3}{4}$	5	5.7 dB



# 802.11 n, ac , ax (Wi-Fi 4,5, and 6)

- n,ac,ax allow a shorter cyclic extension & up to 256 QAM.
- N, ac, ax allow  $1/T' = 40$  MHz (N=128). The number of data-carrying tones is 108.
  - So 20 are used for pilots, or silenced at edges.

**40 MCS choices**

constellation	code rate	$1/T' = 20$ $\nu = 16$ Mbps	$1/T' = 20$ MHz $\nu = 8$ Mbps	$1/T' = 40$ $\nu = 32$ Mbps	$1/T' = 40$ MHz $\nu = 16$ Mbps
BPSK	1/2	6.5	7.2	13.5	15
4QAM	1/2	13	14.4	27	30
4QAM	3/4	19.5	21.7	40.5	45
16QAM	1/2	26	28.9	54	60
16QAM	3/4	39	43.3	81	90
64QAM	2/3	52	57.8	108	120
64QAM	3/4	58.5	65	121.5	135
64QAM	5/6	65	72.2	135	150
256QAM	3/4	78	86.6	162	180
256QAM	5/6	86.7	96.3	180	200

- For 20 MHz,
  - Carriers -28,-27,27 and 28 are used, so data rates increase by  $52/48 = 13/12 \times (12 \text{ or } 18)$  Mbps – so thus 13 or 19.5 Mbps

$$R = \log_2(M) \cdot r \cdot 52 \cdot 250\text{kHz} = [.5,1.2,3] \cdot (13 \text{ or } 19.5) \text{ Mbps}$$

- For 40 MHz:

$$R = \log_2(M) \cdot (\text{code rate}) \cdot (108 \text{ tones}) \cdot 250 \text{ kHz} = [0.5, 1, 2, \text{ or } 3] \cdot (27 \text{ or } 40.5) \text{ Mbps}$$

Or 10/9 x these numbers for cyclic prefix of length 800 ns



# 802.11n Table with 4 x 4 MIMO

constellation	code rate	$1/T' = 20$	$1/T' = 20$ MHz	$1/T' = 40$	$1/T' = 40$ MHz
		$\nu = 16$ Mbps	$\nu = 8$ Mbps	$\nu = 16$ Mbps	$\nu = 8$ Mbps
BPSK	1/2	6.5	7.2	13.5	15
4QAM	1/2	13	14.4	27	30
4QAM	3/4	19.5	21.7	40.5	45
16QAM	1/2	26	28.9	54	60
16QAM	3/4	39	43.3	81	90
64QAM	2/3	52	57.8	108	120
64QAM	3/4	58.5	65	121.5	135
64QAM	5/6	65	72.2	135	150
256QAM	3/4	78	86.6	162	180
256QAM	5/6	86.7	96.5	180	200

ONLY FOR 802.11ac/ax (Wi-Fi 6)

40 MHz  
2 adjacent  
channels  
as one



Can make  
collisions  
more likely,  
effectively  
reducing # of channels

- 802.11n allows 4 x 4 Vector OFDM, so data rates in any column can be multiplied by 4,
  - which means 600 Mbps on the 64 QAM (would be 800 Mbps if 256 QAM were used).
- While there is SVD on each tone, all 802.11n spatial dimensions use the same coding line chosen above.



# Wi-Fi 6 = 802.11ax – up to 4 channels bonded

Modulation and coding schemes for single spatial stream

MCS index <sup>[a]</sup>	Modulation type	Coding rate	Data rate (in Mb/s) <sup>[b]</sup>							
			20 MHz channels		40 MHz channels		80 MHz channels		160 MHz channels	
			1600 ns GI <sup>[c]</sup>	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI	1600 ns GI	800 ns GI
0	BPSK	1/2	4(?)	4(?)	8(?)	9(?)	17(?)	18(?)	34(?)	36(?)
1	QPSK	1/2	16	17	33	34	68	72	136	144
2	QPSK	3/4	24	26	49	52	102	108	204	216
3	16-QAM	1/2	33	34	65	69	136	144	272	282
4	16-QAM	3/4	49	52	98	103	204	216	408	432
5	64-QAM	2/3	65	69	130	138	272	288	544	576
6	64-QAM	3/4	73	77	146	155	306	324	613	649
7	64-QAM	5/6	81	86	163	172	340	360	681	721
8	256-QAM	3/4	98	103	195	207	408	432	817	865
9	256-QAM	5/6	108	115	217	229	453	480	907	961
10	1024-QAM	3/4	122	129	244	258	510	540	1021	1081
11	1024-QAM	5/6	135	143	271	287	567	600	1134	1201

160 MHz  
8 adjacent  
Channels  
as one



Back to only  
3 non-overlapping  
channels,  
So Wi-Fi 6E  
(expands 5-7 GHz)

- 4 channels use N=256 with 234 carrying user data.
- 8 channels use N=512 with 484 carrying user data,
- With up to 8x8 MIMO on 11ax → 10 Gbits (almost).

96 choices in loading

*M* is also sent to xmit for MIMO  
(one for each tone).

Web tutorial on  
this by former  
student of this class  
[R. Nabar](#)



# Wi-Gig is Wi-Fi, 802.11ad ~ 60 GHz

- Carrier frequencies (Six 2.16 GHz channels)

Channel	Center (GHz)	Min. (GHz)	Max. (GHz)	BW (GHz)
1	58.32	57.24	59.4	2.16
2	60.48	59.4	61.56	
3	62.64	61.56	63.72	
4	64.8	63.72	65.88	
5	66.96	65.88	68.04	
6	69.12	68.04	70.2	

- Parameters:  $\frac{1}{T'} = 2.64 \text{ GHz}$     $\Delta f = \frac{2640}{512} = 5.15625 \text{ MHz}$

$N=512$  with 336 used

$\nu=128$

$$\frac{1}{T} = \left( \frac{N}{N+\nu} \right) \cdot \Delta f = 4.125 \text{ MHz}$$

## OFDM data rates [\[ edit \]](#)

MCS index	Modulation type	Coding rate	Phy rate (Mbit/s)	Sensitivity (dBm)	EVM (dB)
13	SQPSK	1/2	693	-66	-7
14		5/8	866.25	-64	-9
15	QPSK	1/2	1386	-63	-10
16		5/8	1732.5	-62	-11
17		3/4	2079	-60	-13
18	16-QAM	1/2	2772	-58	-15
19		5/8	3465	-56	-17
20		3/4	4158	-54	-19
21		13/16	4504.5	-53	-20
22	64-QAM	5/8	5197.5	-51	-22
23		3/4	6237	-49	-24
24		13/16	6756.75	-47	-26

EVM is same as MSE





# End Supplementary Lecture 5A