The IEEE 802.11 family of standards

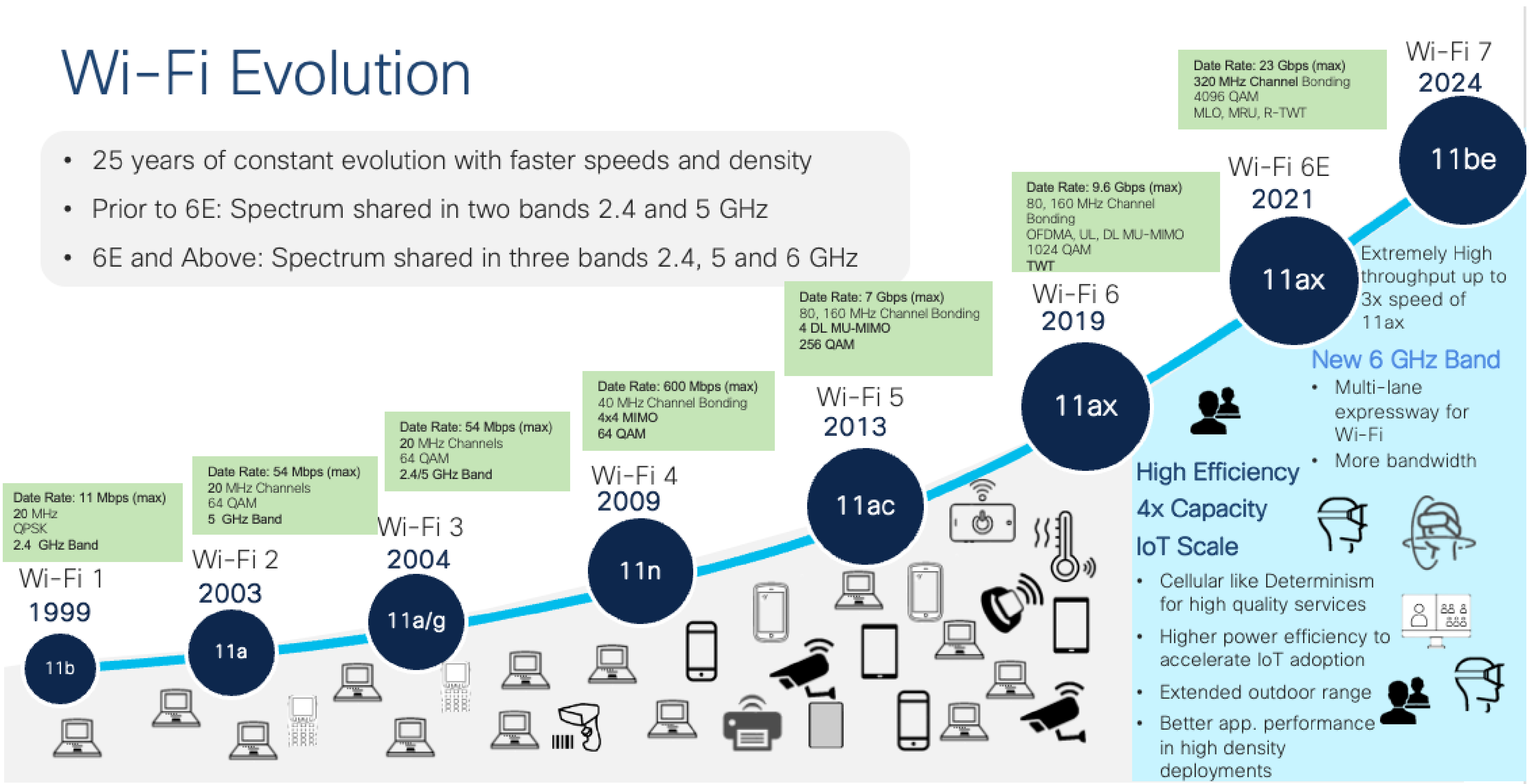
continued

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

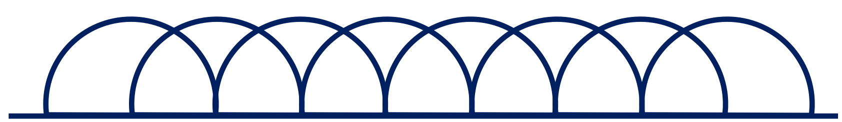
PHY-I:
OFDM and modulation

PHY-II:
MIMO and beamforming

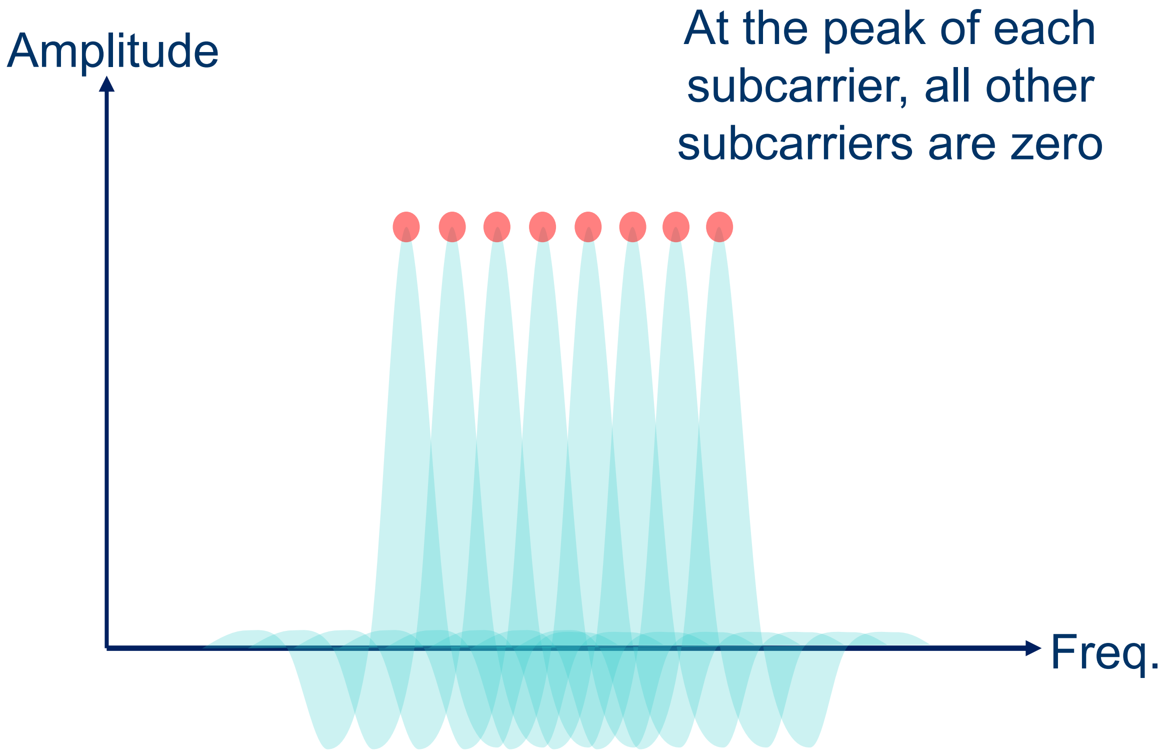
OFDM vs FDM

- 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

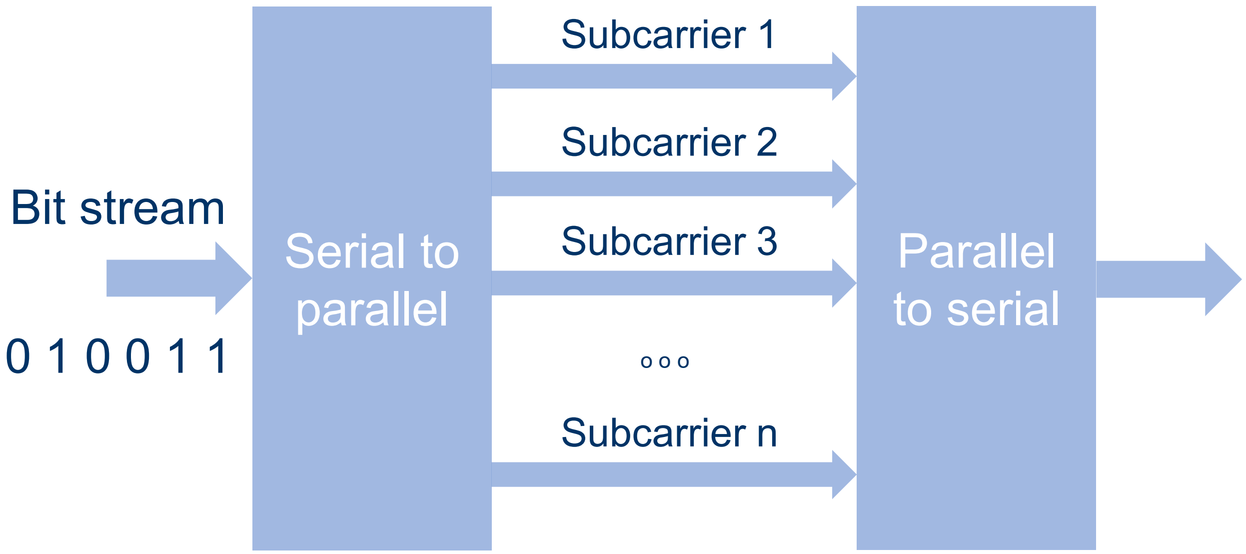


OFDM subcarriers



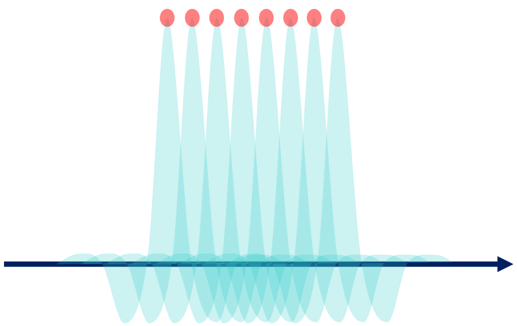
OFDM

- 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

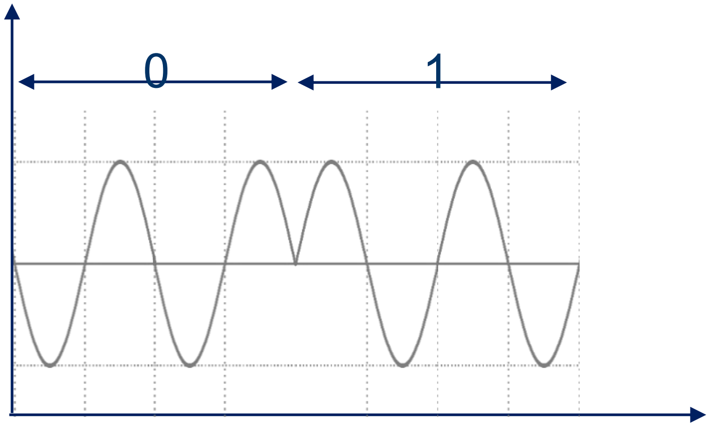
Step 1: Serial to parallel

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

BPSK

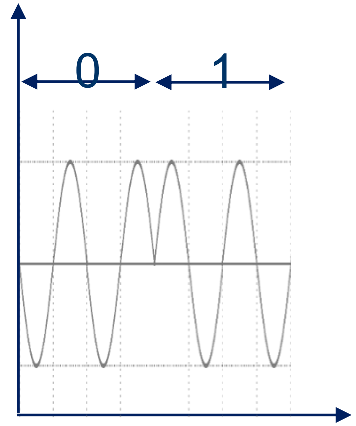


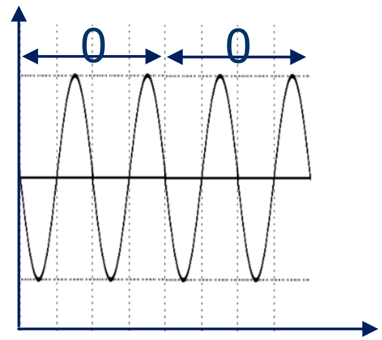
OFDM

- Step 2: Modulate bits on each subcarrier

BPSK

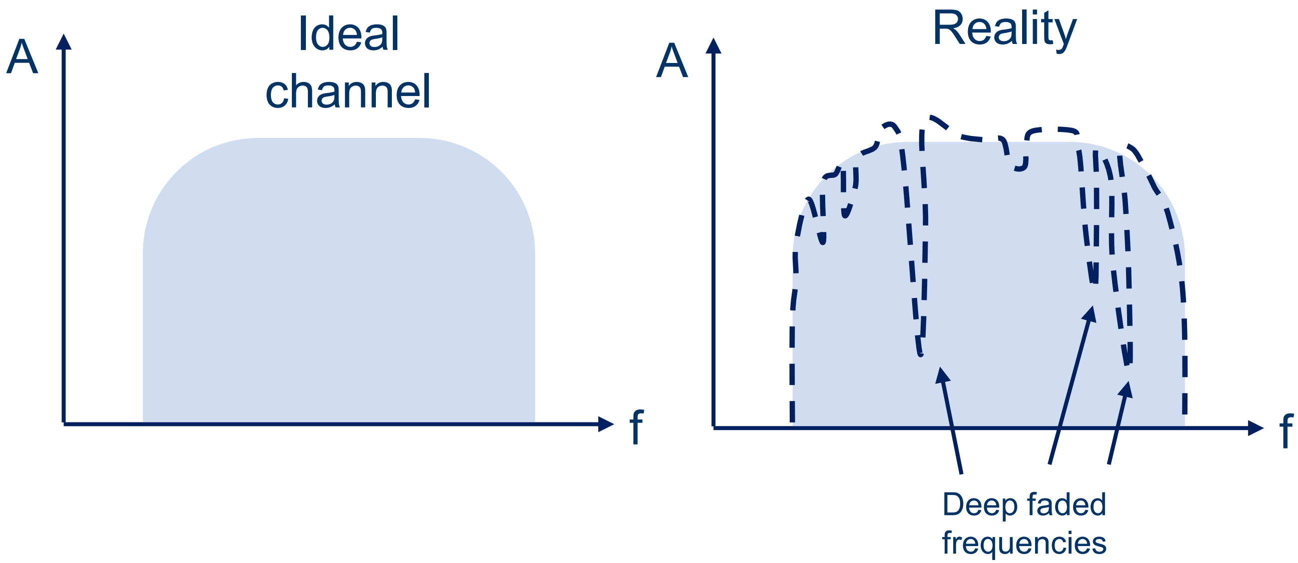
Sub 1	0	1
Sub 2	1	0
Sub 3	0	0
Sub 4	0	1
Sub 5	1	0
Sub 6	1	1
Sub 7	0	0
Sub 8	1	1



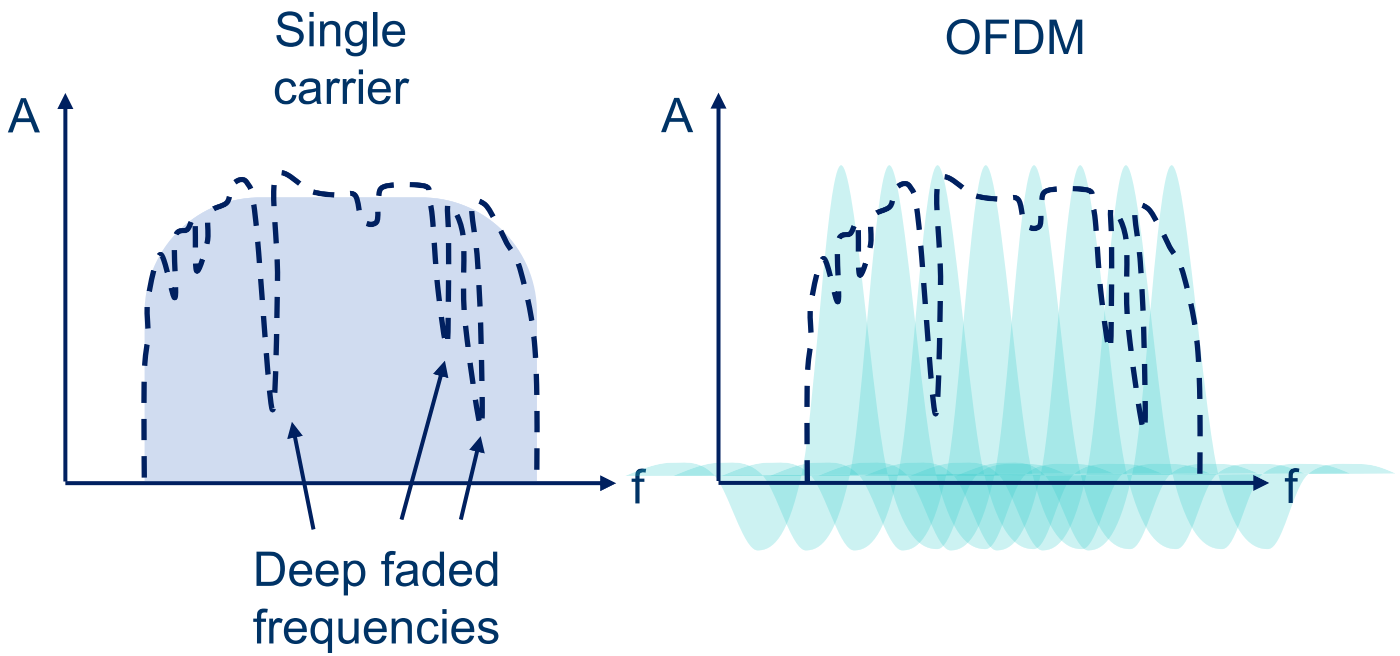


Why OFDM?

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



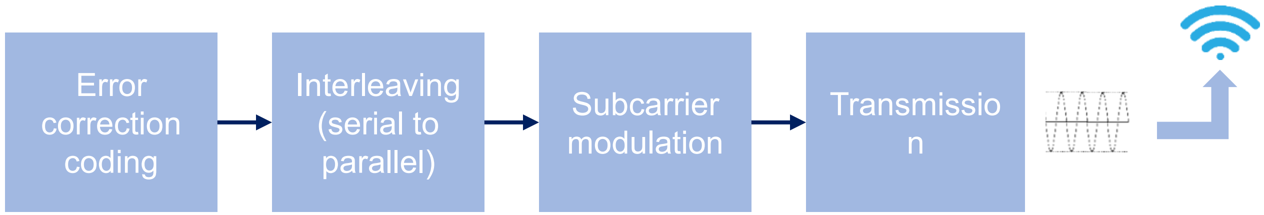
Why OFDM?



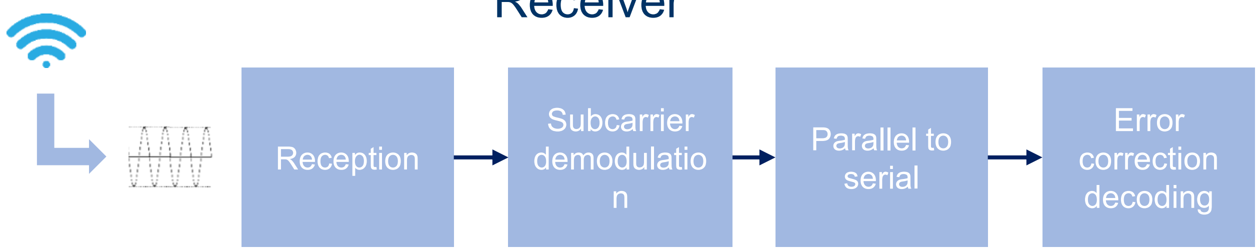
- Frequency selective affects only some subcarriers in OFDM
  - Lower bit error rate

OFDM Block Diagram

Transmitter



Receiver

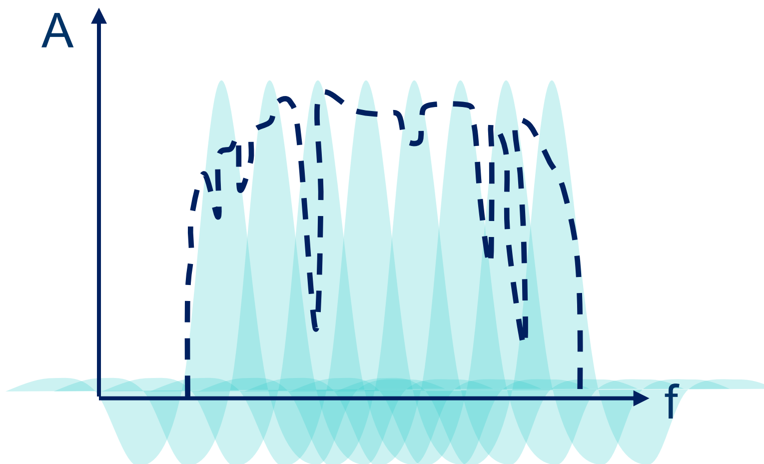


Interleaving

- 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

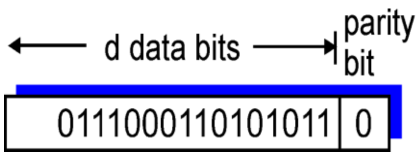
0 1 0 0 1 1 0



Error control - Parity checking

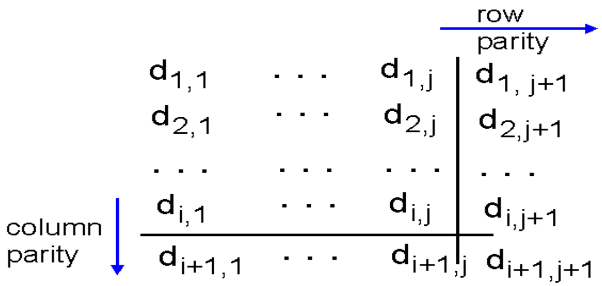
single bit parity:

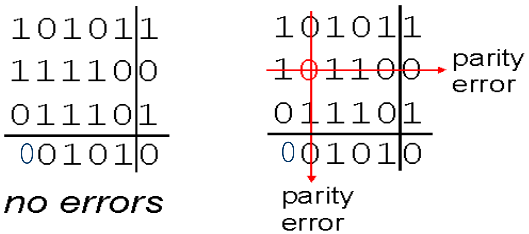
- *d*etect single bit errors



two-dimensional bit parity:

- detect and correct single bit errors





no errors

correctable single bit error

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

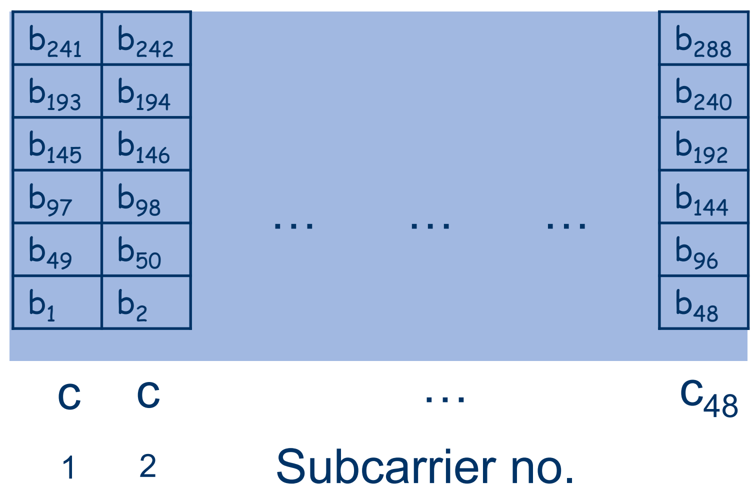
Block Interleaving

- 802.11a example
  - 48 subcarriers
  - Modulation chosen - 64 QAM (6 bits per symbol)
- Interleaver buffer size = 48 x 6 = 288 bits

More complex versions of block interleavers can be used

0, 1, 0, … , 1

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

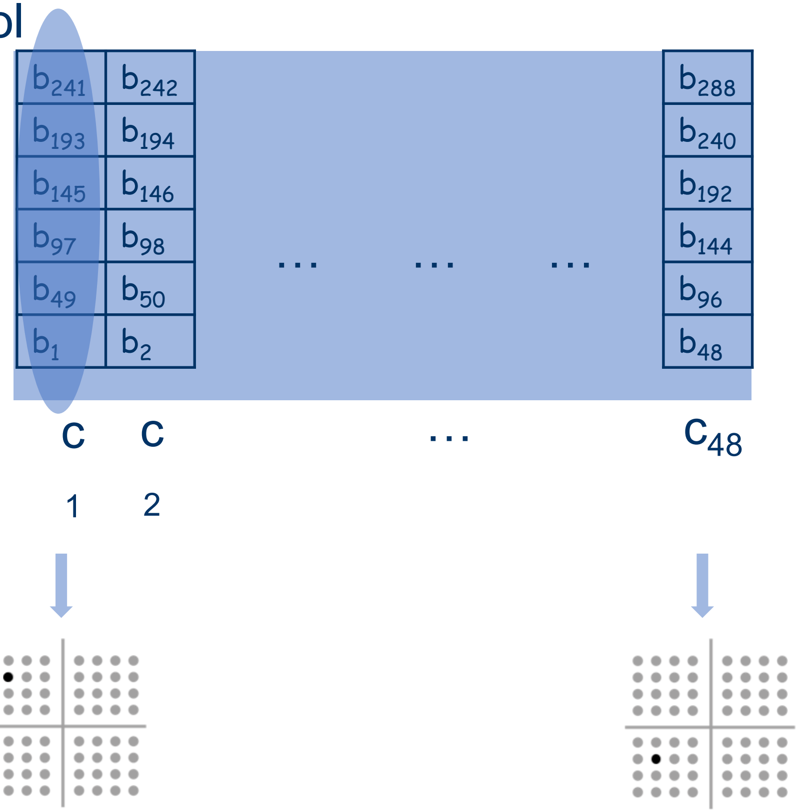


Subcarrier Modulation

- Subcarrier symbol

0, 1, 0, …, 1

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

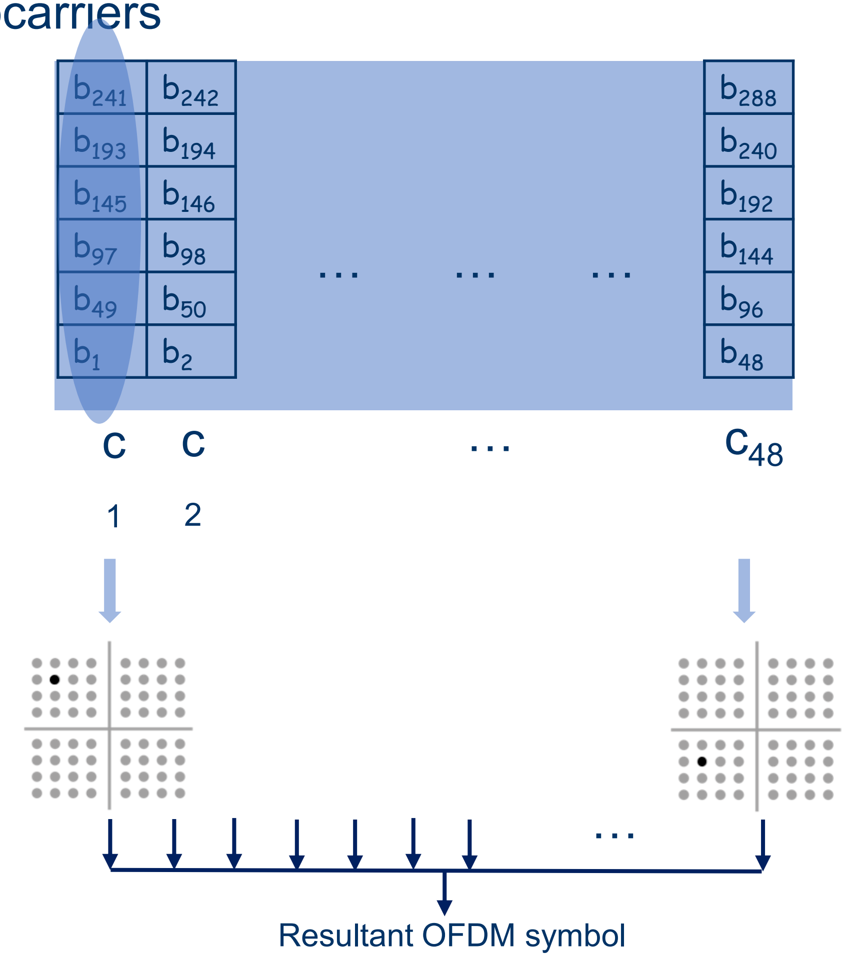


Final transmission

- Combine subcarriers

0, 1, 0, … , 1

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



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

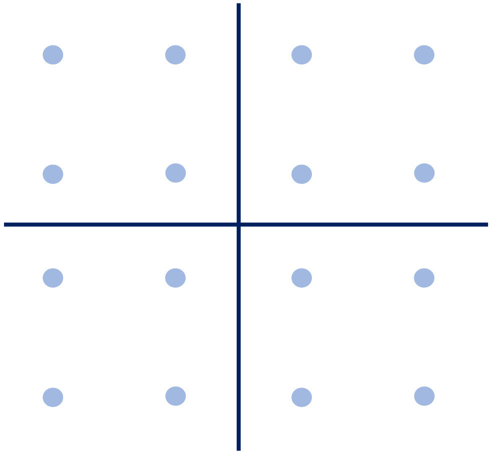
Modulation	Coding rate	Coded bits per subcarrier symbol	Coded bits per OFDM symbol	Data bits per OFDM symbol	Data rate (Mbps)
BPSK	1/2	1	48	24	
BPSK	3/4	1	48	36	
QPSK	1/2	2	96	48	
QPSK	3/4	2	96	72	
16-QAM	1/2	4	192	96	
16-QAM	3/4	4	192	144	
64-QAM	2/3	6	288	192	
64-QAM	3/4	6	288	216	

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

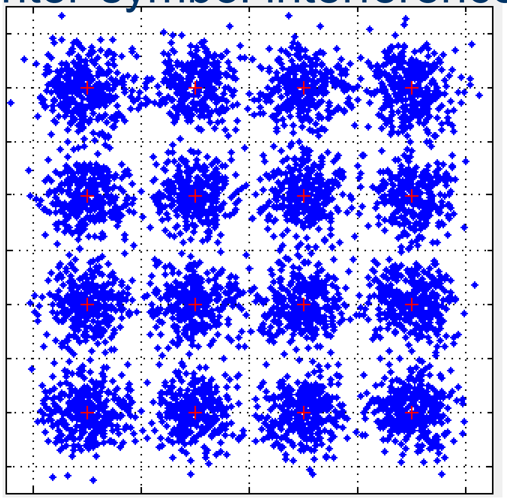
Demodulation

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



Transmitter

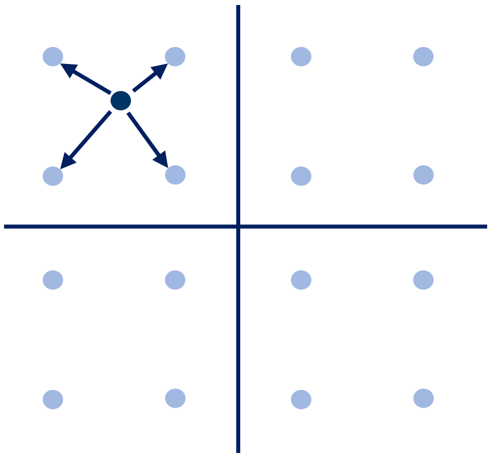
Inter-symbol interference



Receiver

Demodulation

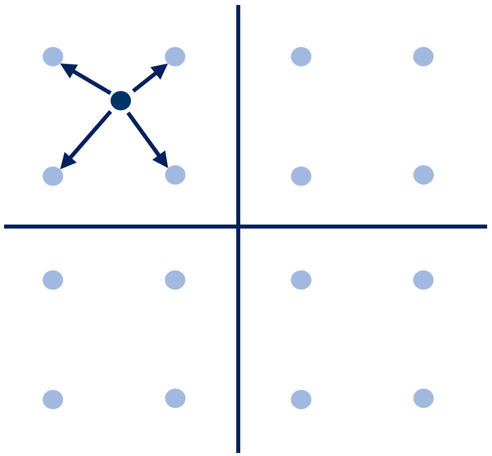
- Hard decision
  - Calculate the distance to the constellation points, pick the one with the lowest distance
  - Can be overly conservative



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

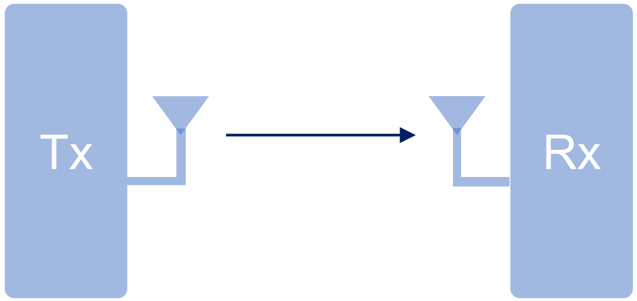
OFDM in 802.11ac

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

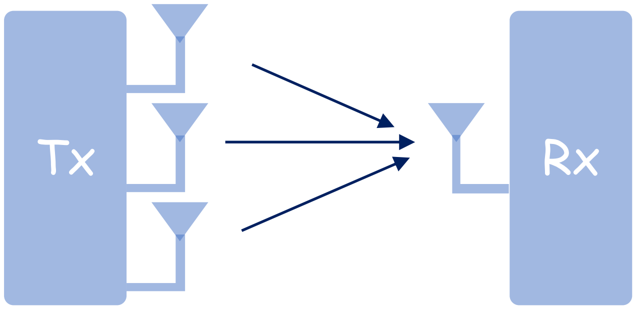
Channel width (MHz)	OFDM subcarriers
20	52
40	108
80	234
160	468

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

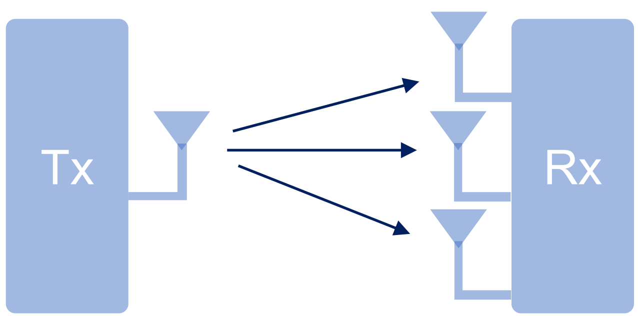
MIMO



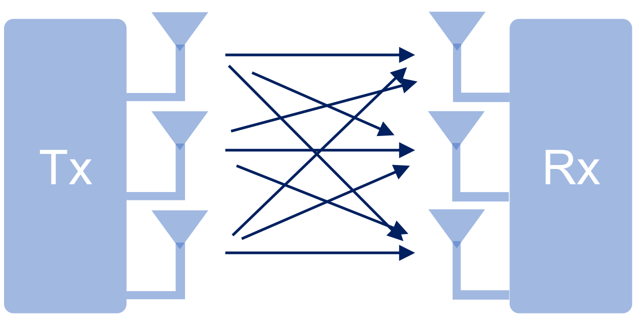
SISO (Single Input Single Output)



MISO (Multiple Input Single Output)

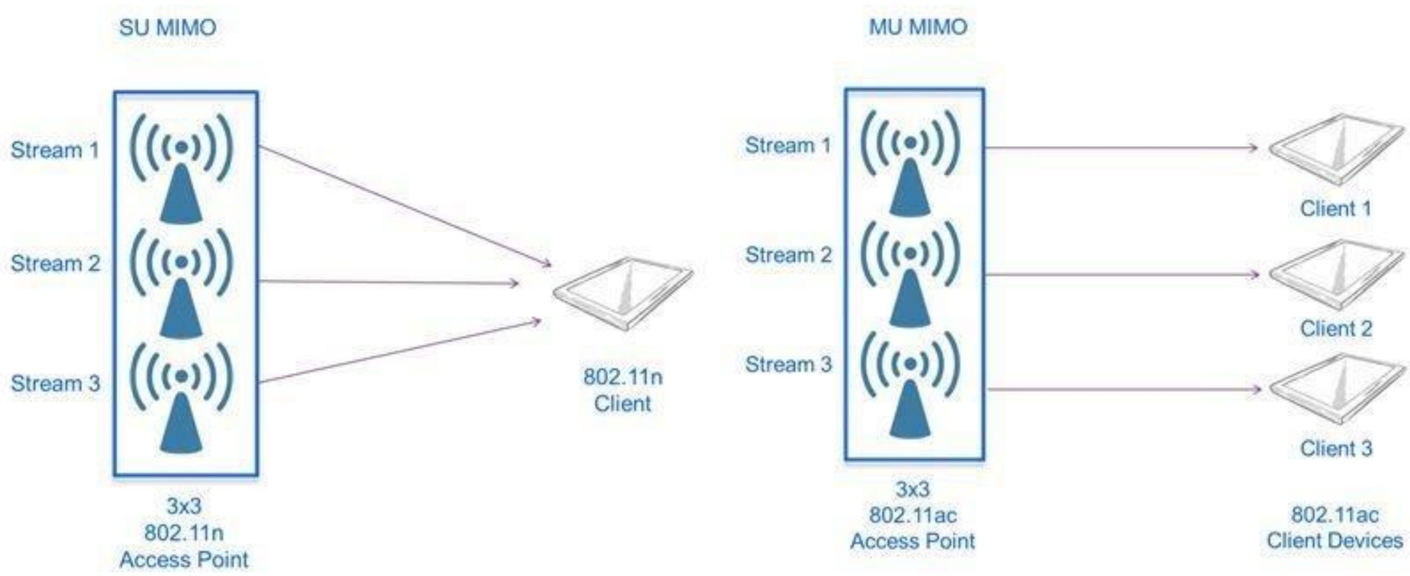


SIMO (Single Input Multiple Output)



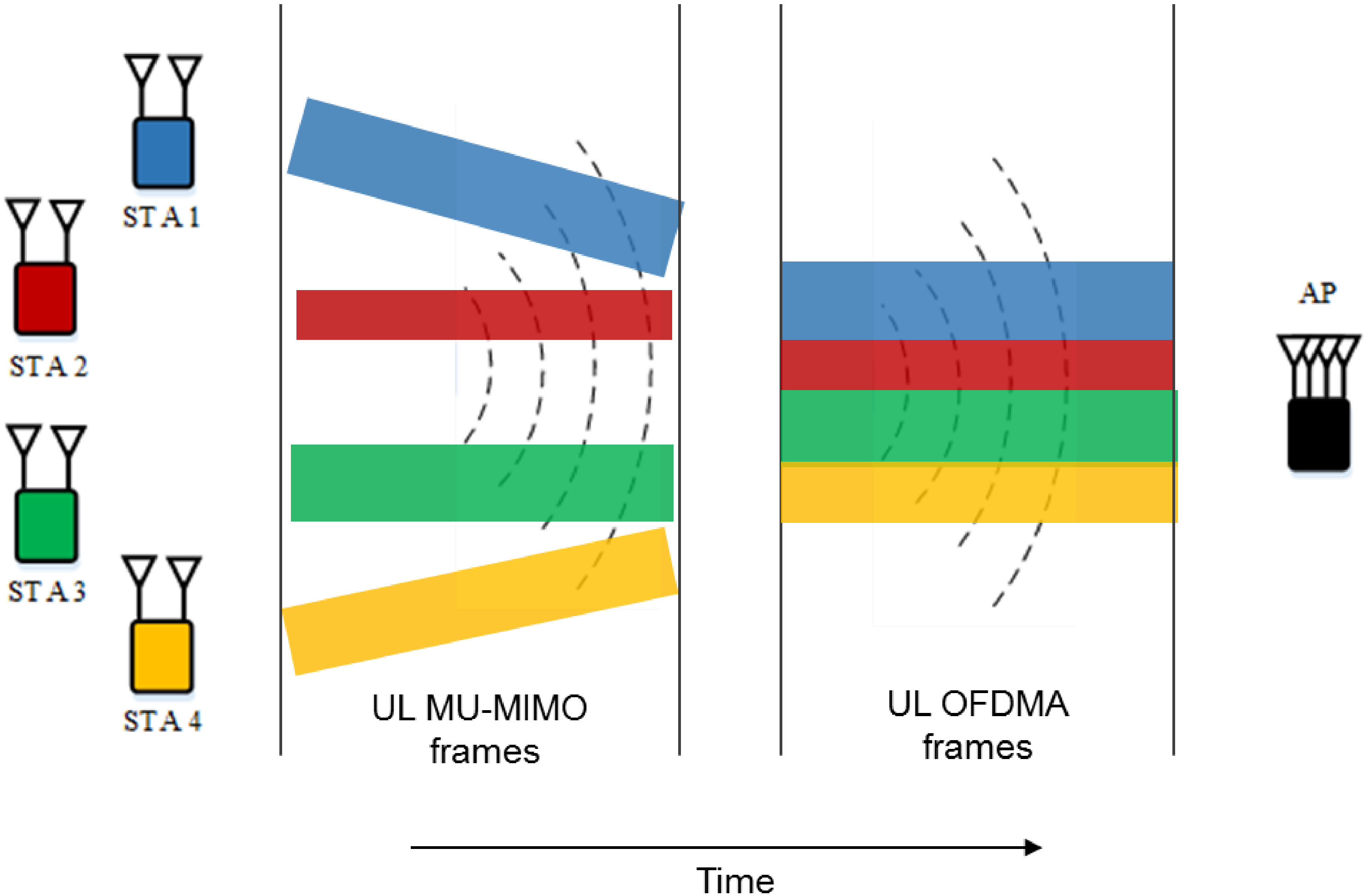
MIMO (Multiple Input Multiple Output)

SU/MU-MIMO

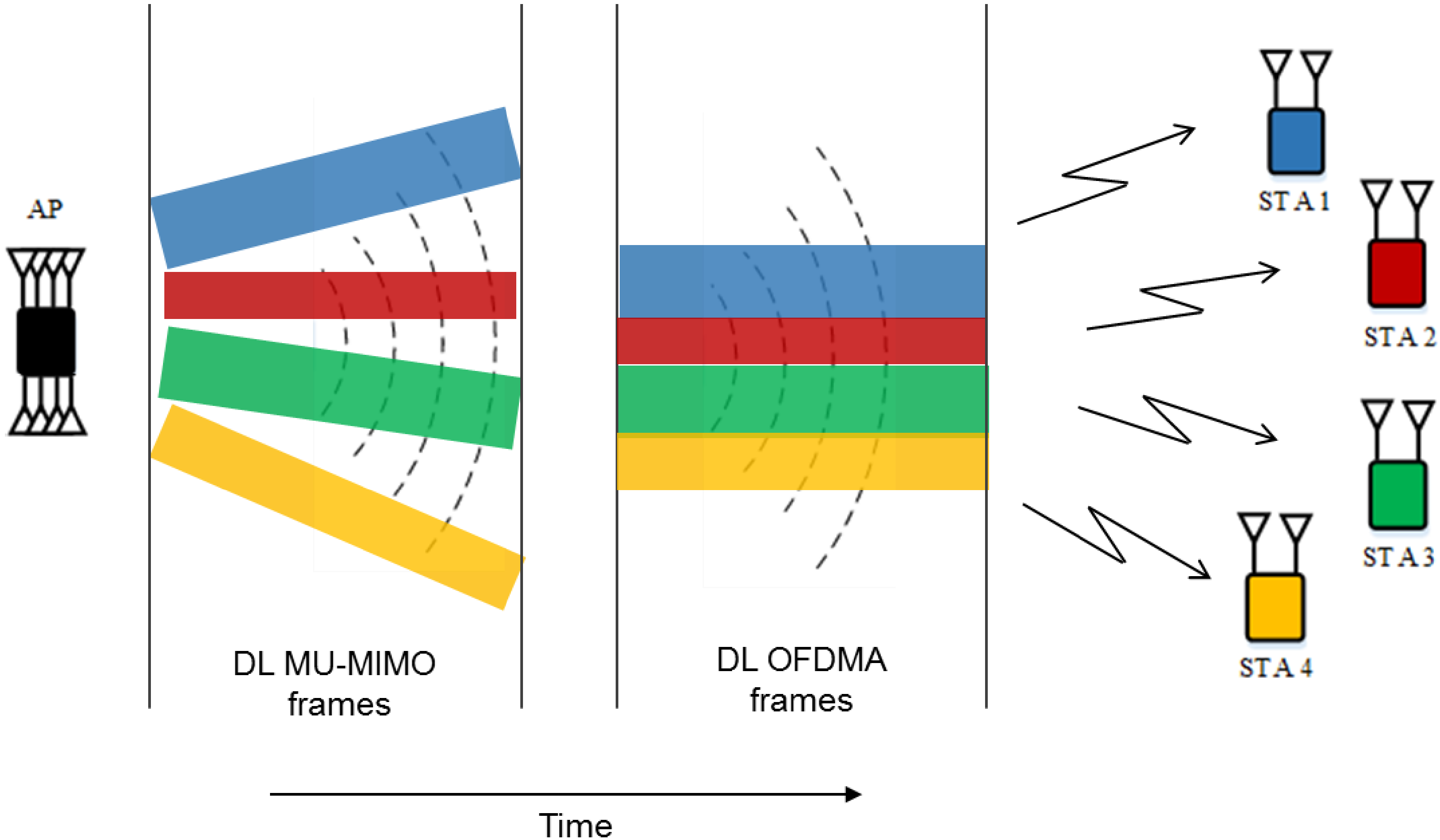


SU MIMO
Stream 1
Stream 2
Stream 3
3x3
802.11n
Access Point
802.11n
Client
MU MIMO
Stream 1
Stream 2
Stream 3
3x3
802.11ac
Access Point
Client 1
Client 2
Client 3
802.11ac
Client Devices

UL MU-MIMO



DL MU-MIMO



MIMO in 802.11n

MCS index	Modulation	Coding rate	Antennas	20 MHz Mbps	40 MHz Mbps
0	BPSK	1/2	1	6.5	13.5
1	QPSK	1/2	1	13	27
2	QPSK	3/4	1	19.5	40.5
3	16-QAM	1/2	1	26	54
4	16-QAM	3/4	1	39	81
5	64-QAM	2/3	1	52	108
6	64-QAM	3/4	1	58.5	121.5
7	64-QAM	5/6	1	65	135

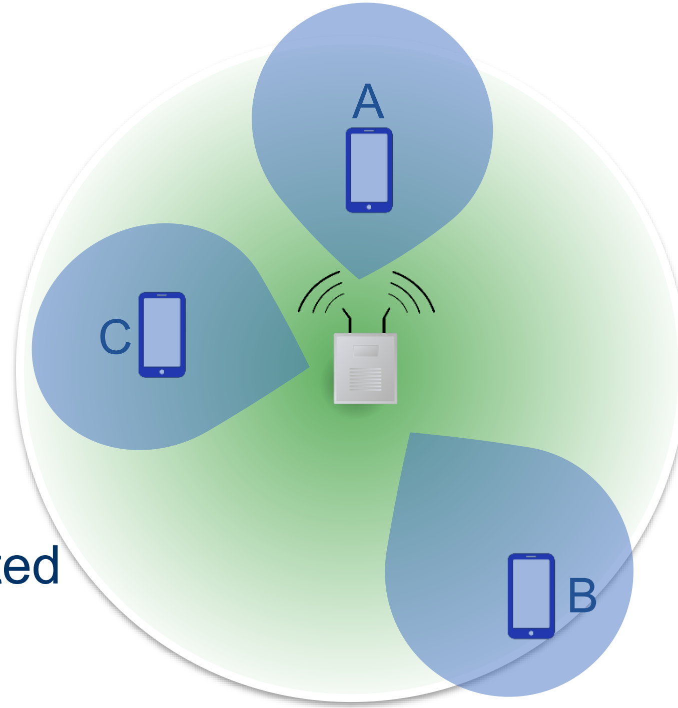
MCS index	Modulation	Coding rate	Antennas	20 MHz Mbps	40 MHz Mbps
8	BPSK	1/2	2	13	27
9	QPSK	1/2	2	26	54
10	QPSK	3/4	2	39	81
11	16-QAM	1/2	2	52	108
12	16-QAM	3/4	2	78	162
13	64-QAM	2/3	2	104	216
14	64-QAM	3/4	2	117	243
15	64-QAM	5/6	2	130	270

MIMO in 802.11ac

MCS index	Modulation	Coding rate	160 MHz Data rate (Mbps)			
			1x1	2x2	4x4	8x8
0	BPSK	1/2	65	130	260	520
1	QPSK	1/2	130	260	520	1040
2	QPSK	3/4	195	390	780	1560
3	16-QAM	1/2	260	520	1040	2080
4	16-QAM	3/4	390	780	1560	3120
5	64-QAM	2/3	520	1040	2080	4160
6	64-QAM	3/4	585	1170	2340	4680
7	64-QAM	5/6	650	1300	2600	5200
8	256-QAM	3/4	780	1566	3120	6240
9	256-QAM	5/6	866.7	1733.3	3466.7	6933.3

Omni-directional antenna

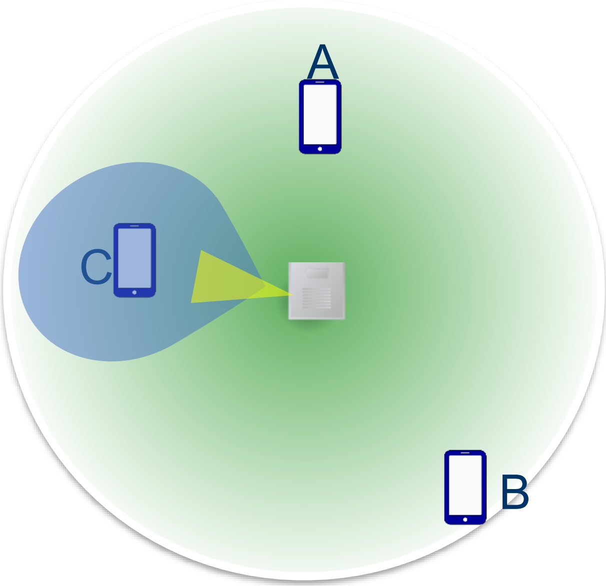
- Omni directional antenna
  - Commonly used in 802.11 WiFi networks
- Advantages
  - Coverage in all directions
  - Simpler hardware design
- Disadvantages
  - A large amount of radiated power is wasted



- Can we concentrate the radiated transmission energy towards the intended receivers?
  - Can increase SNR for intended receivers
  - Reduce interference to other devices

~~Omni-~~directional antenna

- Directional antenna
  - Widely used in special purpose applications

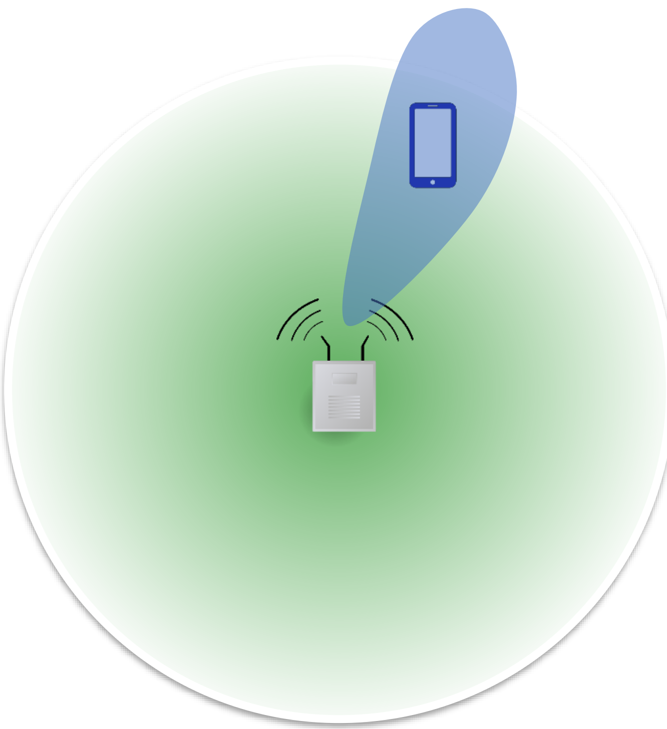


- Advantages
  - Higher signal strength in desired direction
  - Reduced interference to other devices
- Disadvantages
  - Coverage restricted to some direction
  - Costly - multiple antennas needed for omni coverage, capacity (similar to sectors used in cellular network base stations)

  - Solution – electronic beamforming

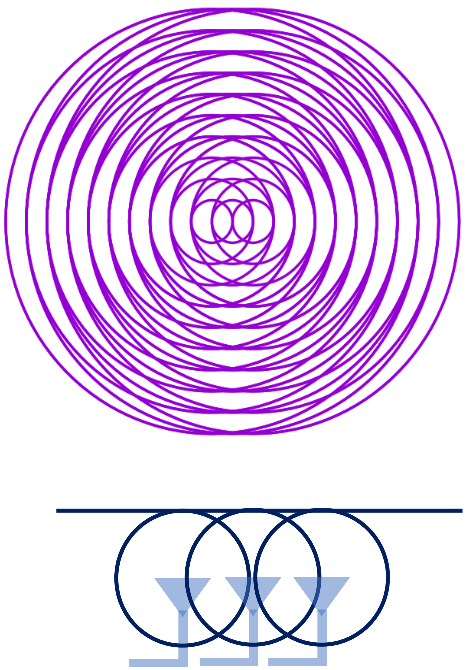
Beamforming

- Beamforming
  - Use omni-directional antennas to focus signal in specific direction
  - Exploit multiple antennas used for MIMO



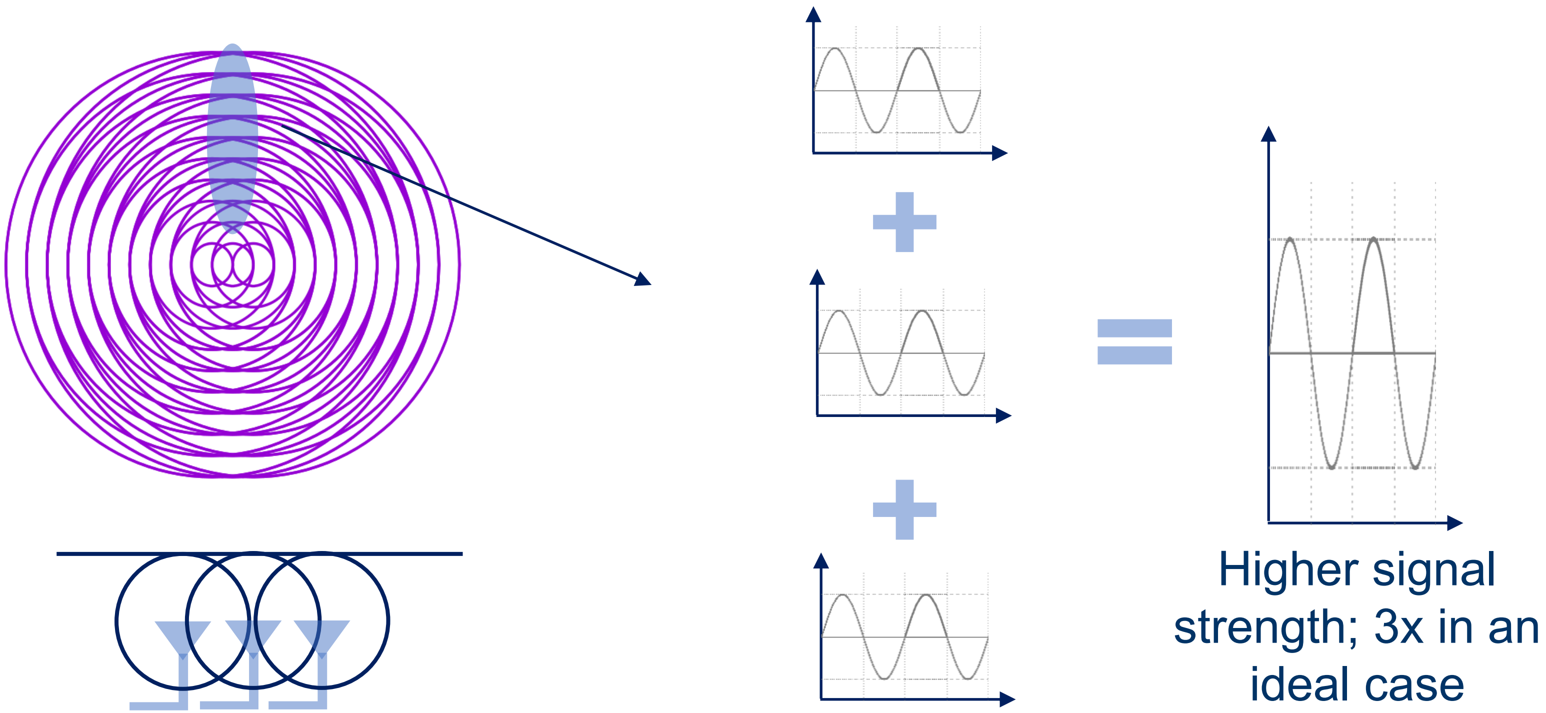
Beamforming

- Beamforming using multiple antenna



Beamforming

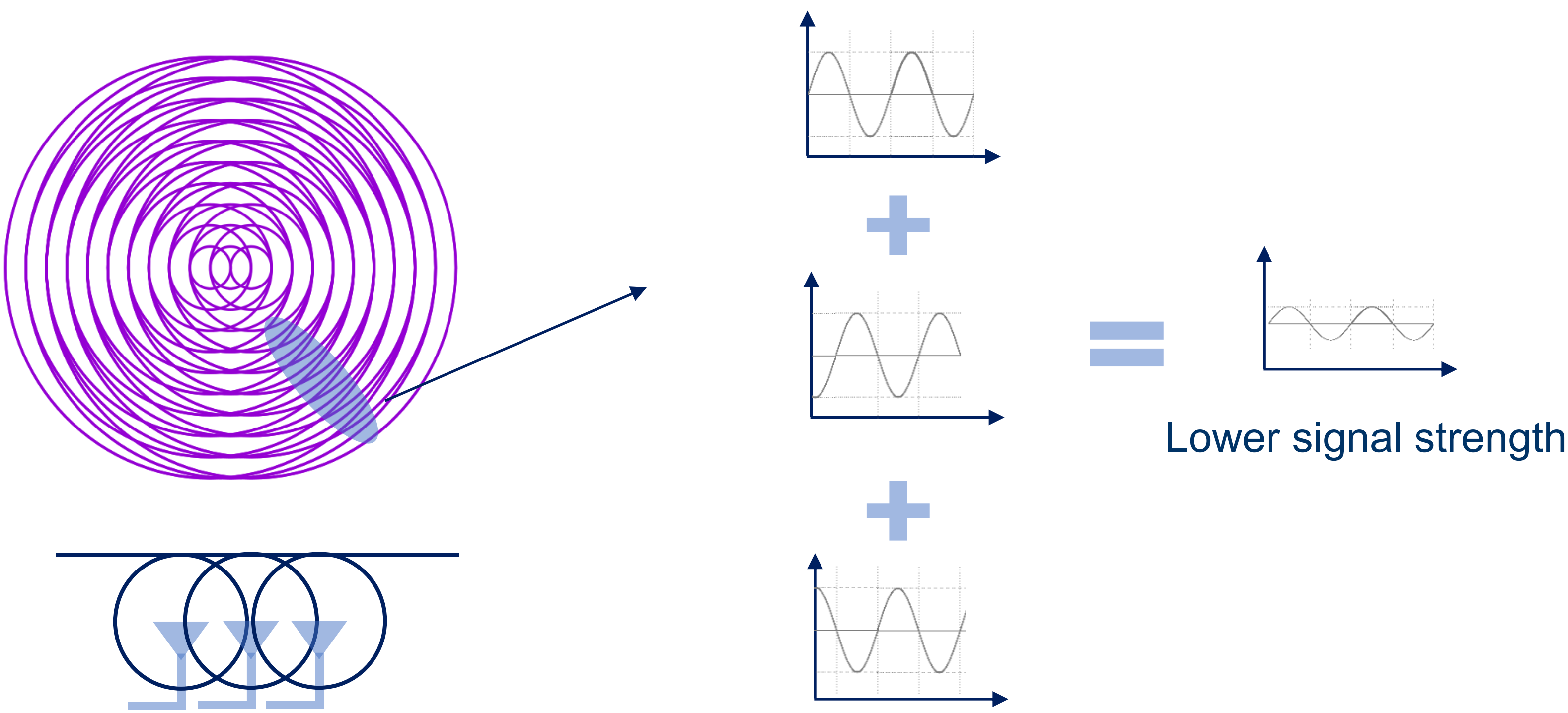
- Beamforming
  - Constructive interference
  - When signal meet in phase, resultant signal strength increases



Beamforming

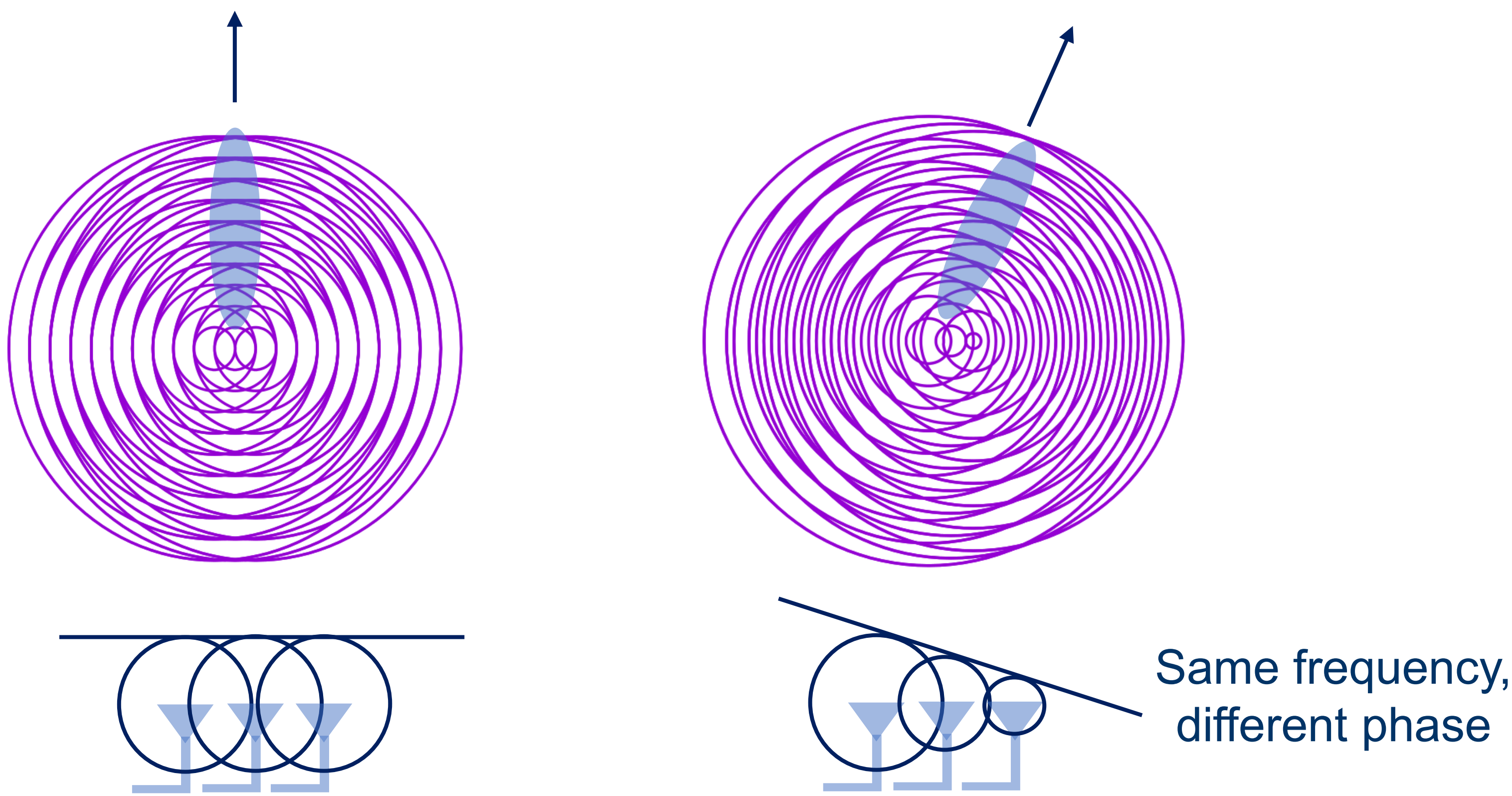
- Beamforming
  - Destructive interference
  - When signal meet out of phase, resultant signal strength weakens

Easier to achieve in higher frequencies, why?
In 5GHz 1wavelength = 6mm

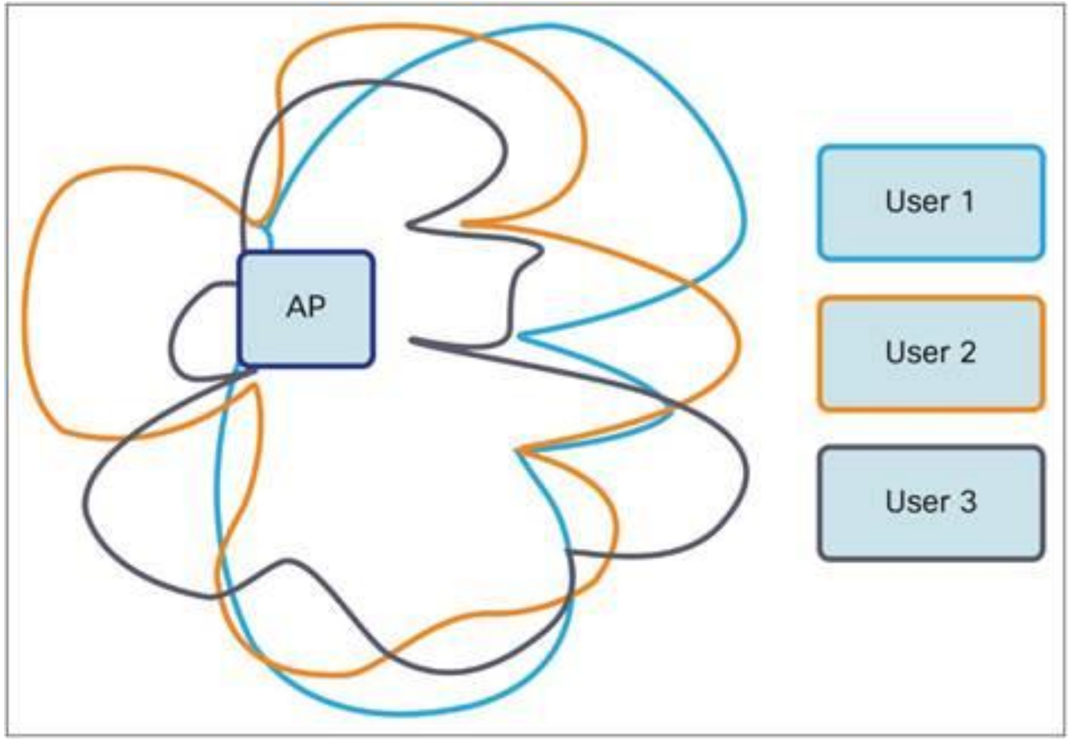


Beamforming

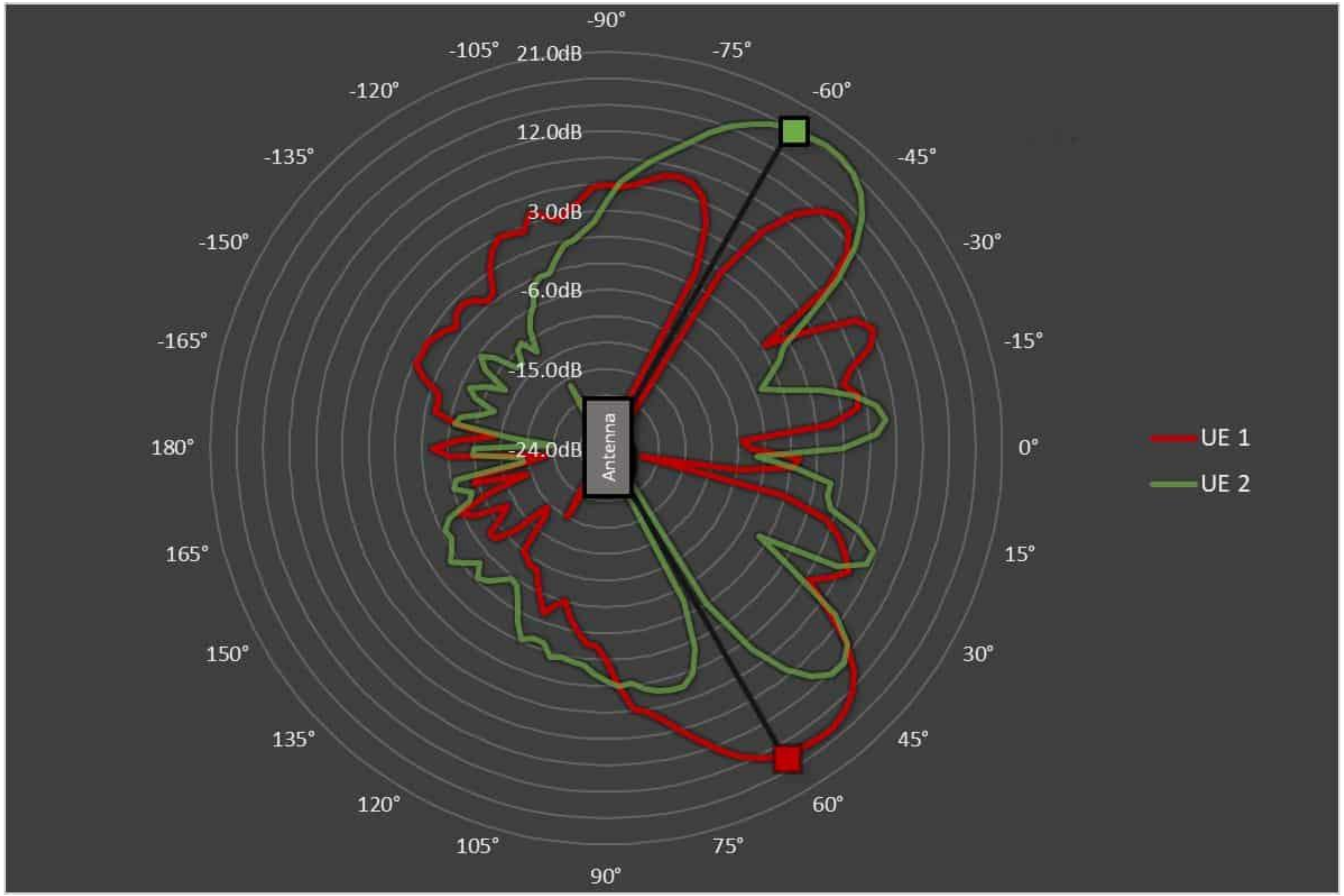
- Beamforming
  - Use omni-directional antennas to focus signal in a specific direction
  - Change the phase of signal emitting from different antenna
  - Intelligent phase modification can result in beams in desired direction



Beamforming

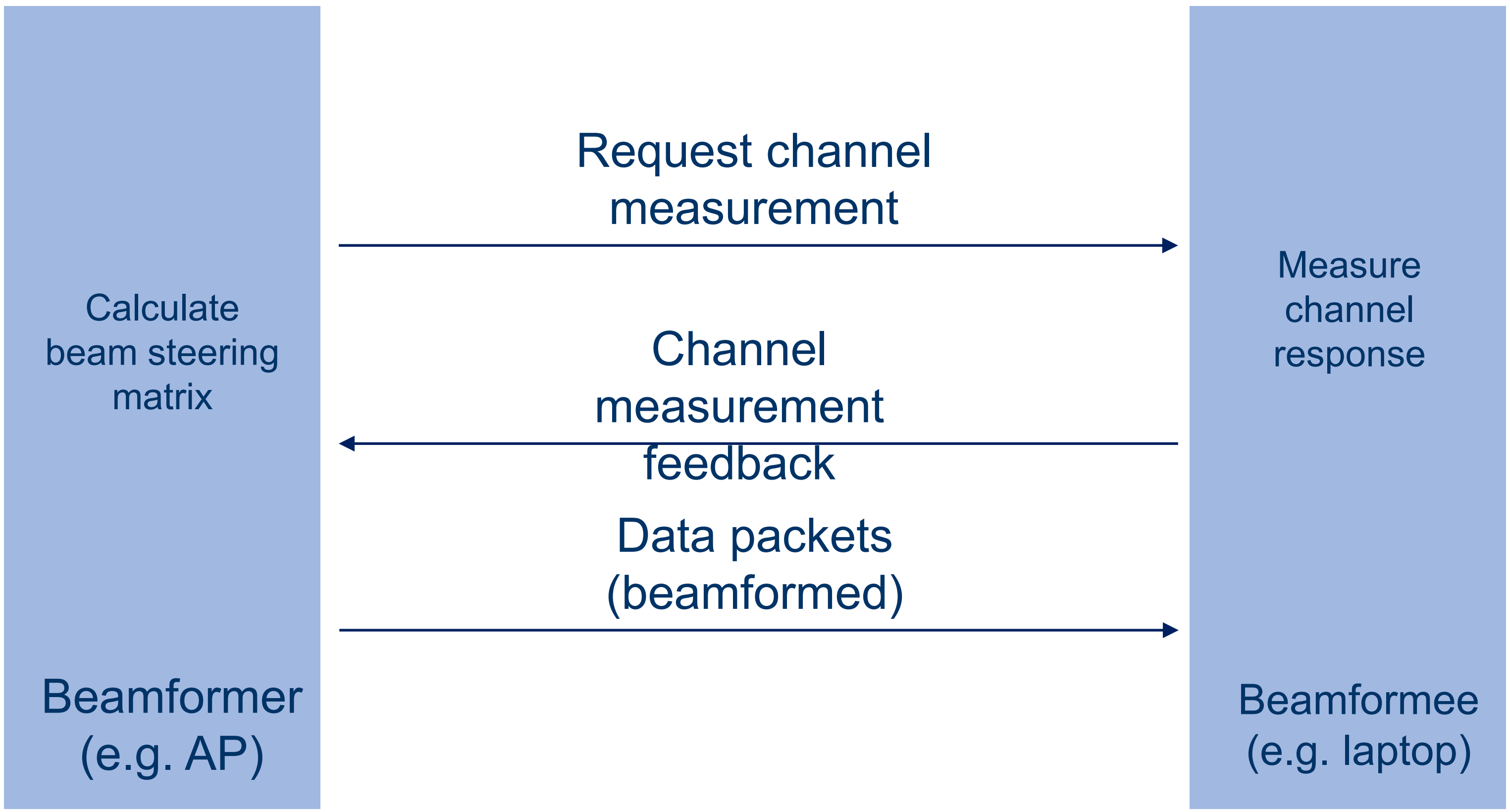


Beamforming



Beamforming

- Channel sounding procedure
  - Explicit feedback
  - Beamformer asks the beamformee to provide a feedback of channel measurement



Channel matrix

Feedback matrix

Number of subcarriers	×	Number of Tx antenna	×	Number of Rx antenna

- Channel State Information (CSI)
  - Also used as feedback for MIMO spatial multiplexing
  - Challenge – the CSI matrix can be very large in size, especially for wider channel widths (e.g. 160 MHz)
  - Frequent feedback necessary for accurate beamforming – high overhead

The quest for high speed wireless

- Applications driving the growth

Sync and go

High definition (4K and beyond) video streaming

Tether less interfaces
Wireless USB, PCI buses, HDMI

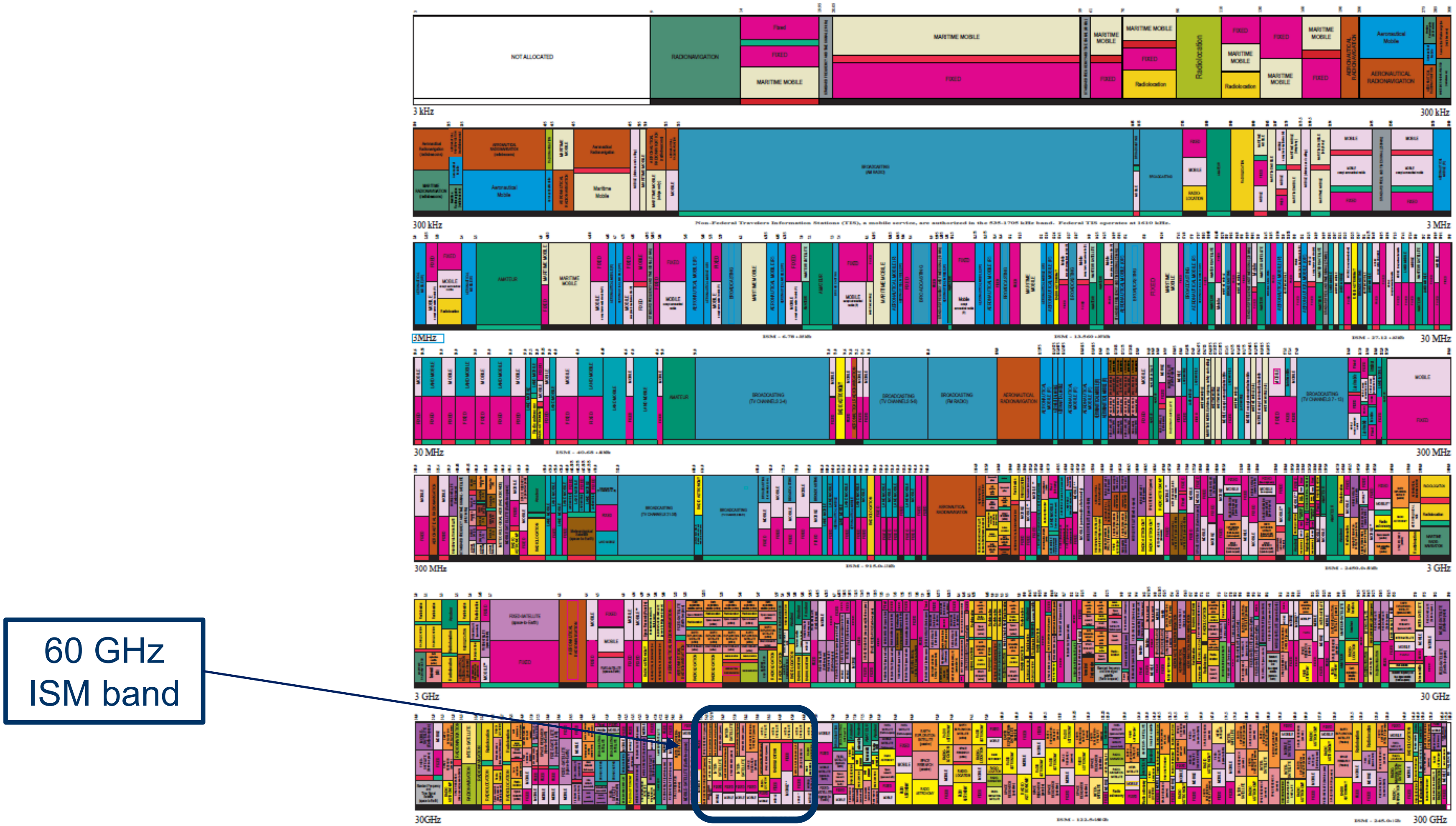
Wireless docking, screen mirroring

The quest for high speed wireless

- Virtual reality

https://www.youtube.com/watch?v=Oxfj-qoV5KE

Search for more bandwidth



Search for more bandwidth

- How can we create wireless networks that can provide multi-gigabit per second data rate?
  - Per link speed should be > 3 Gbps

Millimeter wave wireless networks

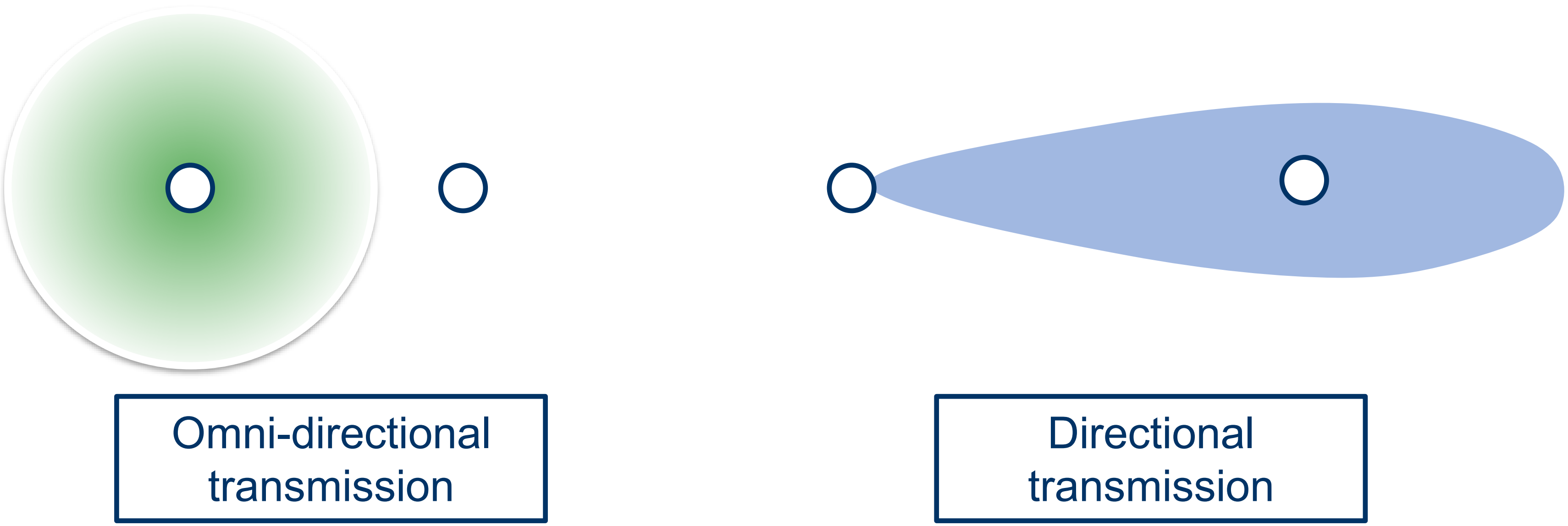
Current WiFi operates in 2.4 and 5 GHz

Major millimeter wave spectrum bands

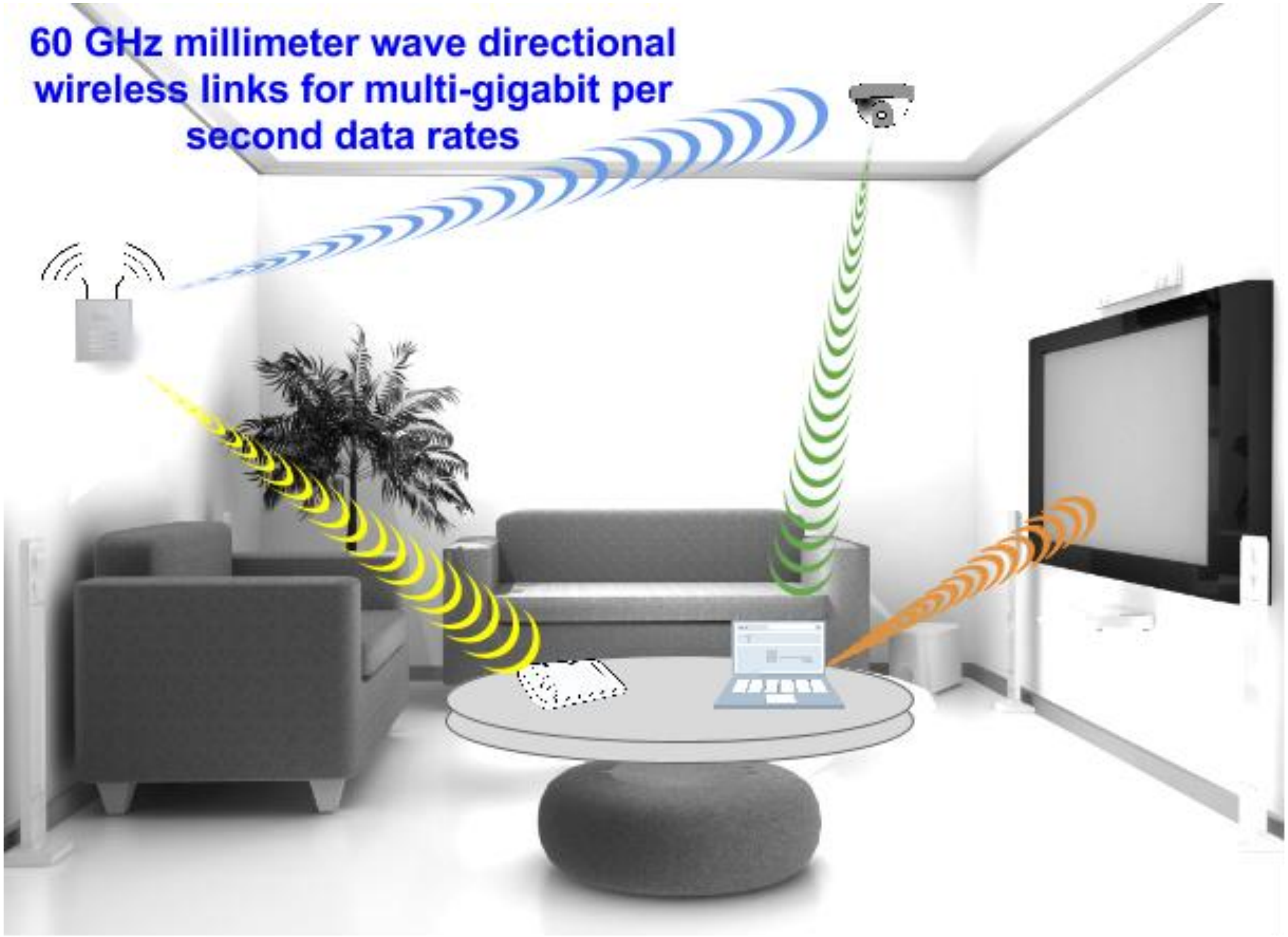
Spectrum bands	Bandwidth	
28 GHz	1.3 GHz	
39 GHz	1.4 GHz	
60 GHz	14 GHz	ISM
74 GHz	5 GHz	
84 GHz	5 GHz	

60 GHz path loss

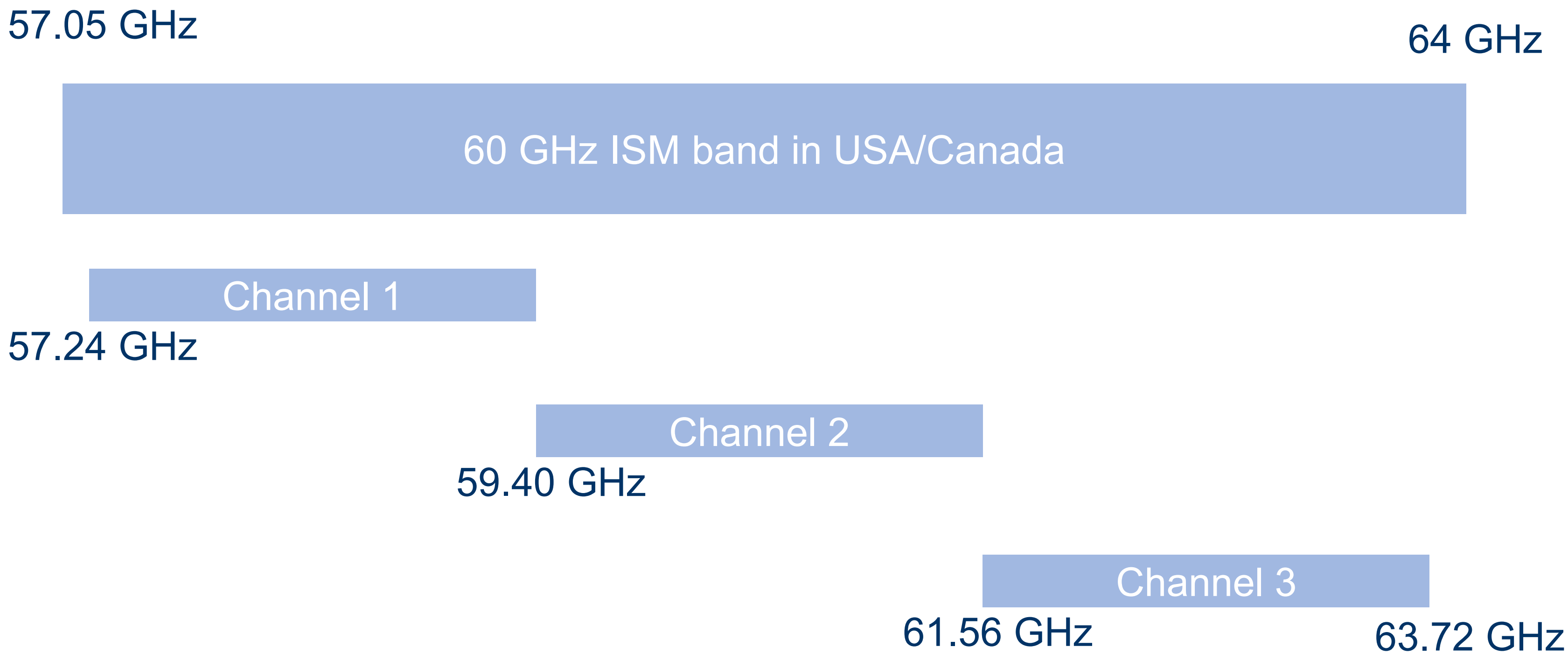
- How to deal with such high path loss?
  - Directionality – concentrate the radiated energy in one direction



60 GHz Network

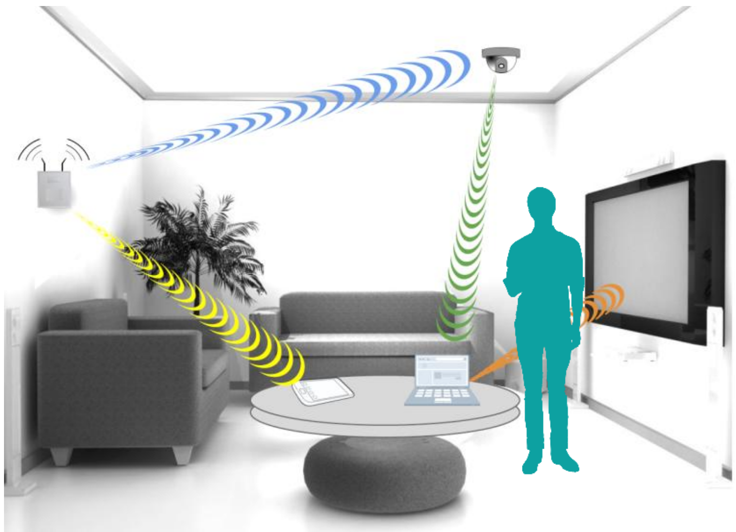


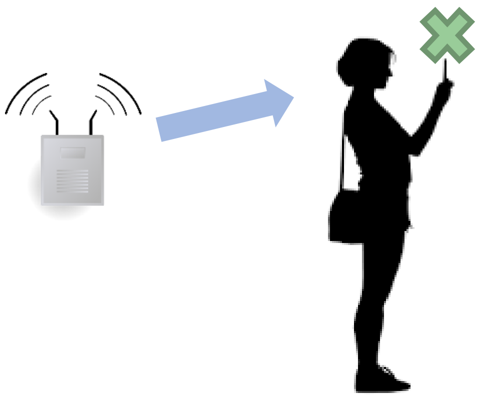
802.11ad frequency bands



Human blockage

- 60 GHz networks
  - Human mobility – results in unpredictable blockage of links

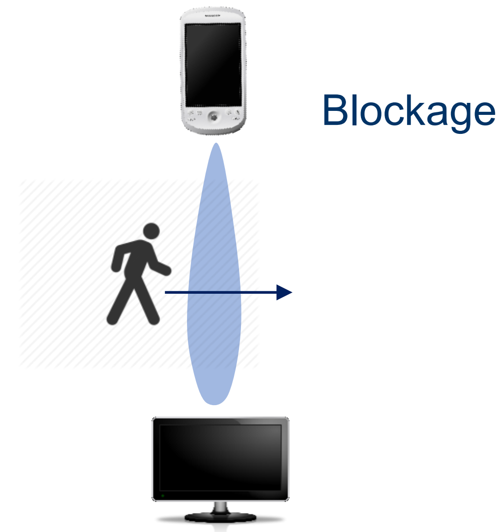




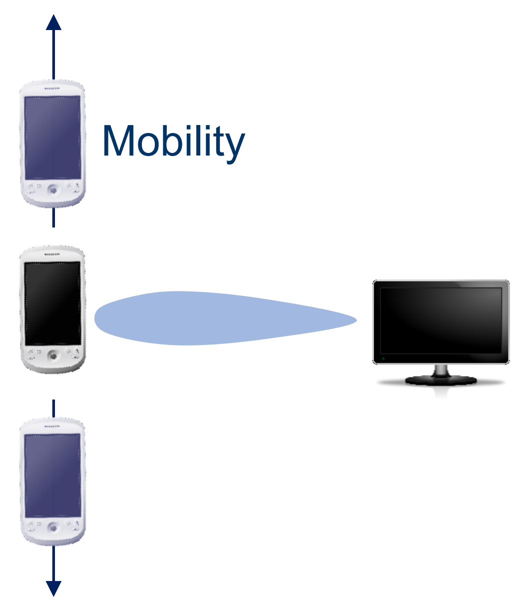
Self blockage - human body blocks link to mobile device
- specifically a challenge for mobile devices

Blockage and mobility

- Two important open challenges
  - Blockage and mobility



- Blockage
  - Commonly caused by human mobility over Tx, Rx path
  - Human body blockage can result in complete link outage, especially when narrow beamwidth is in use



- Mobility
  - One or both endpoints of a 60 GHz link are mobile
  - Requires constant tracking of mobile endpoints
  - Beam steering – change beam direction based on observed direction

Two possible solutions