5G: Looking Behind the Curtain
Signal Transmission & Reception

Part 1

01-01: Early Wireless Communications 0G to 3G

01-02: Transitioning to 4G and 5G

01-03: Signal Routing 3G to 4G/5G

Part 2:
Modulation, Constellations and Orthogonal Multiplexing

02-01: Review: 4G & 5G

02-02: 4G/5G Packet Spectral Technologies

02-03: Orthogonal Frequency Division Multiplexing (OFDM)

02-04: 5G Modulation

02-05: MIMO: Multiple-Input Multiple-Output

02-06: Next Generation 6G: $\approx$ 2030

Looking Behind the 5G Curtain
Signal Transmission & Reception Techniques

Part 2:
Modulation, Constellations and Orthogonal Multiplexing

02-01: Review: 4G & 5G

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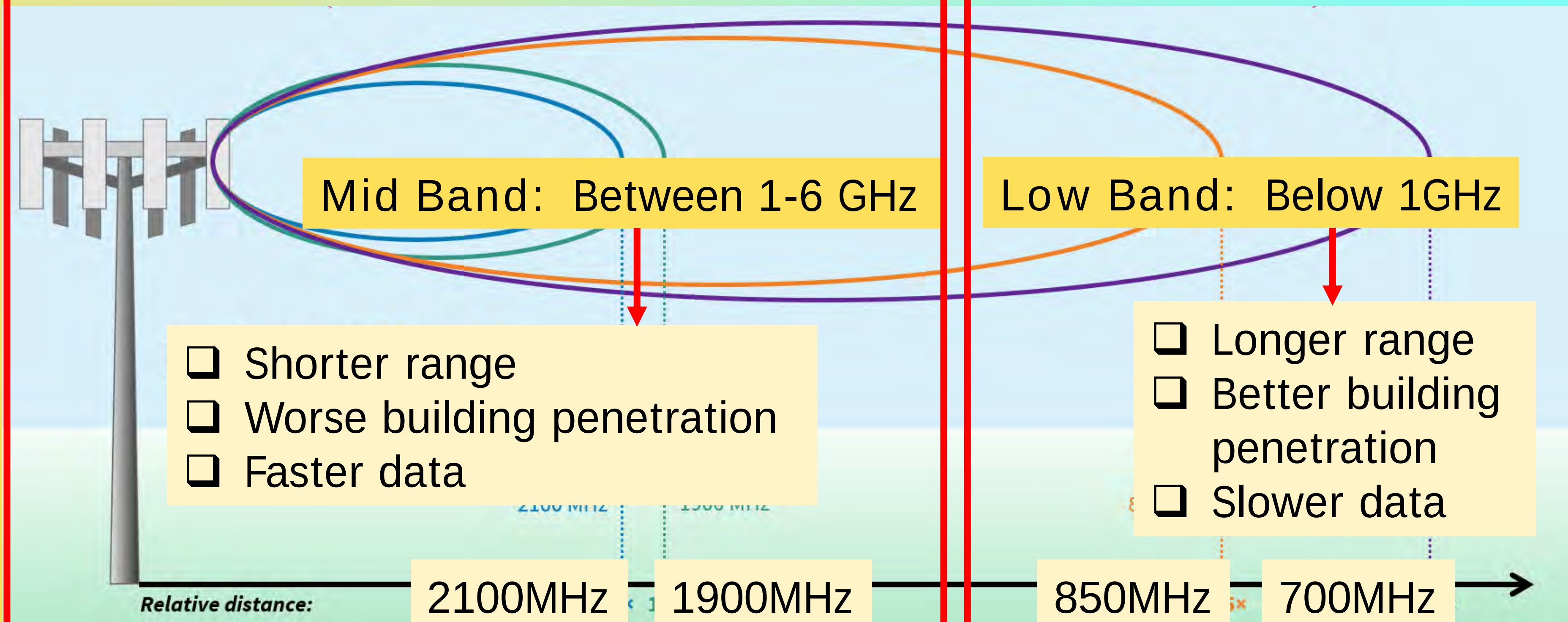
5G NR

NR is New Radio

FR1: < 6GHz

FR2: 24Ghz to 100GHz
Typically, 24 to 30GHz 6GHz

24GHz → 100GHz



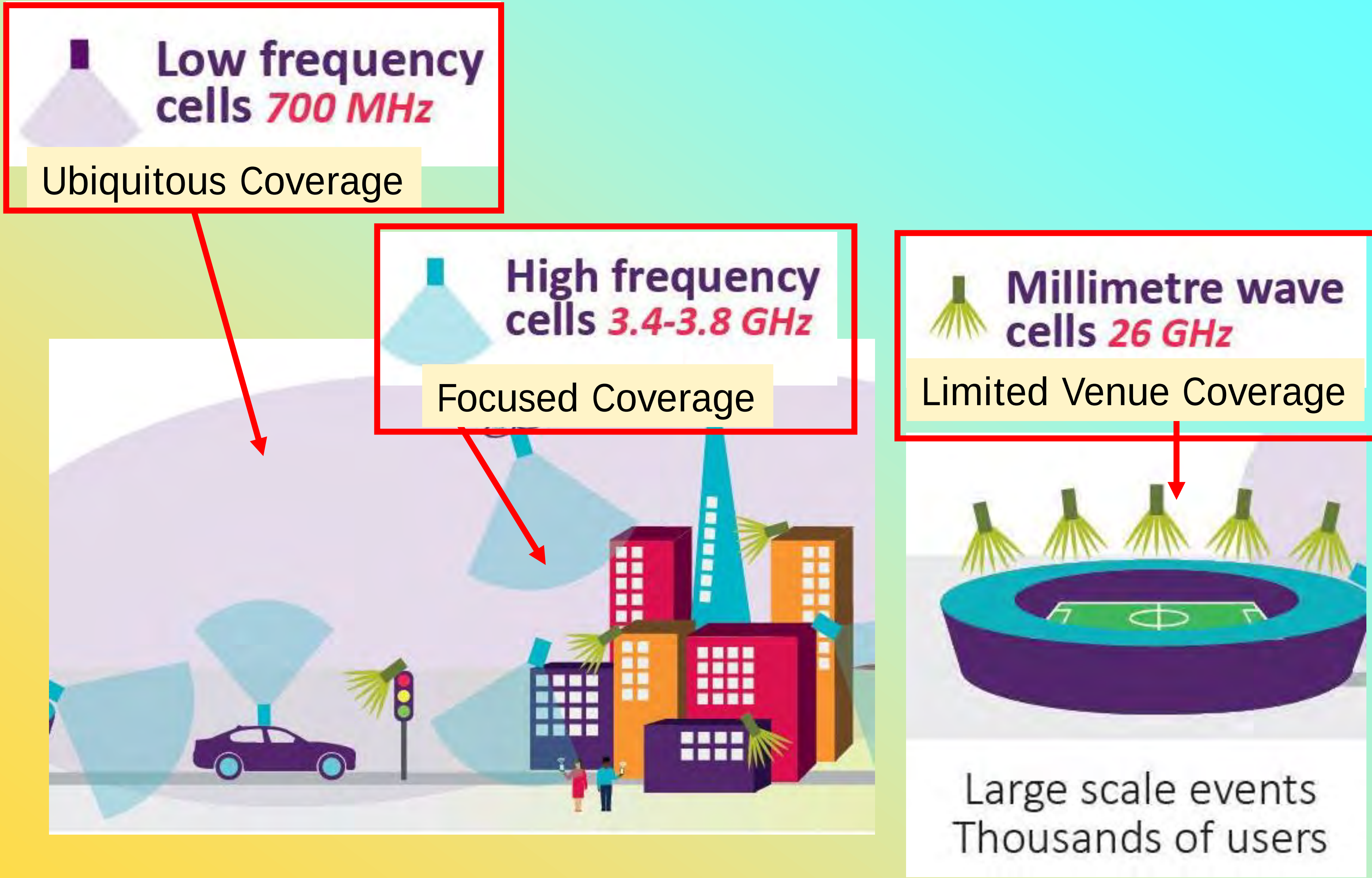
Mid Band: Between 1-6 GHz

- ❑ Shorter range
- ❑ Worse building penetration
- ❑ Faster data

Low Band: Below 1GHz

- ❑ Longer range
- ❑ Better building penetration
- ❑ Slower data

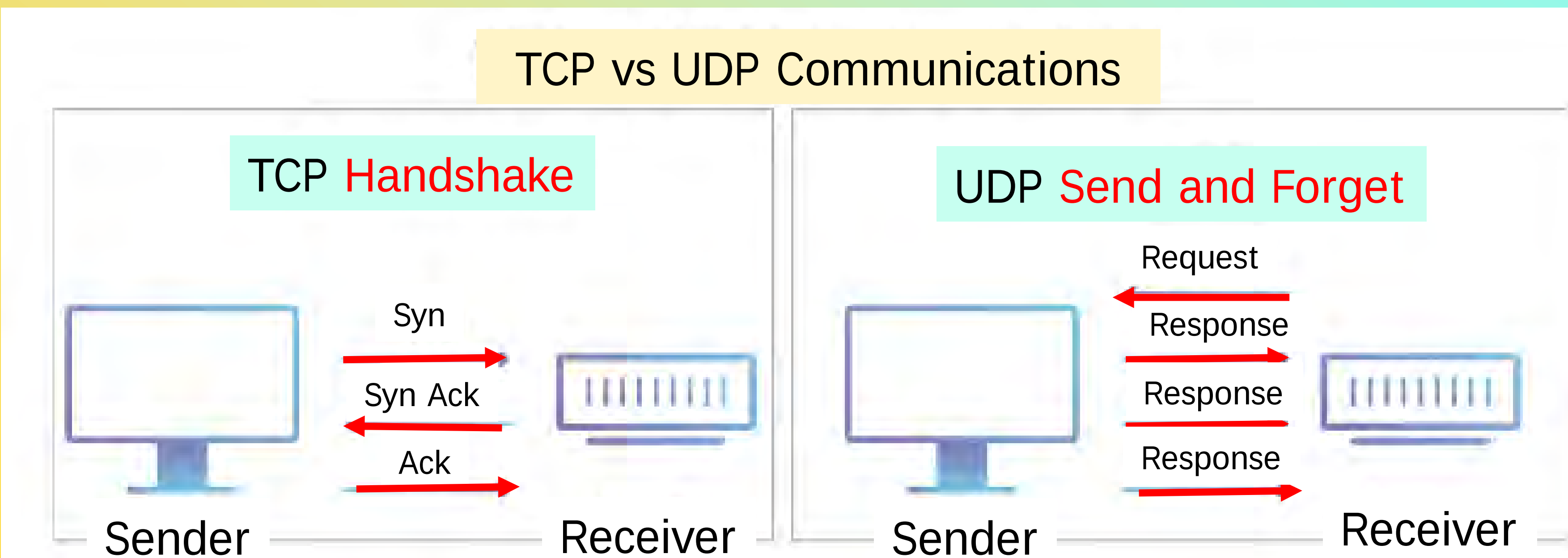
Relative Distance	2100MHz	1900MHz	850MHz	700MHz
	1x	1.1x	2.5x	3x


Low frequency cells 700 MHz
Ubiquitous Coverage
High frequency cells 3.4-3.8 GHz
Focused Coverage
Millimetre wave cells 26 GHz
Limited Venue Coverage
Large scale events
Thousands of users

Internet Transport Protocols

- TCP: Transmission Control Protocol
  - reliable, in-order delivery
  - congestion control
  - flow control
  - connection setup

- UDP: User Datagram Protocol
  - Unreliable
  - Unordered delivery
  - Faster Service
  - Satellite Communications
    - Always used UDP
    - Request through a Geosynchronous Satellite ≈ 250ms --



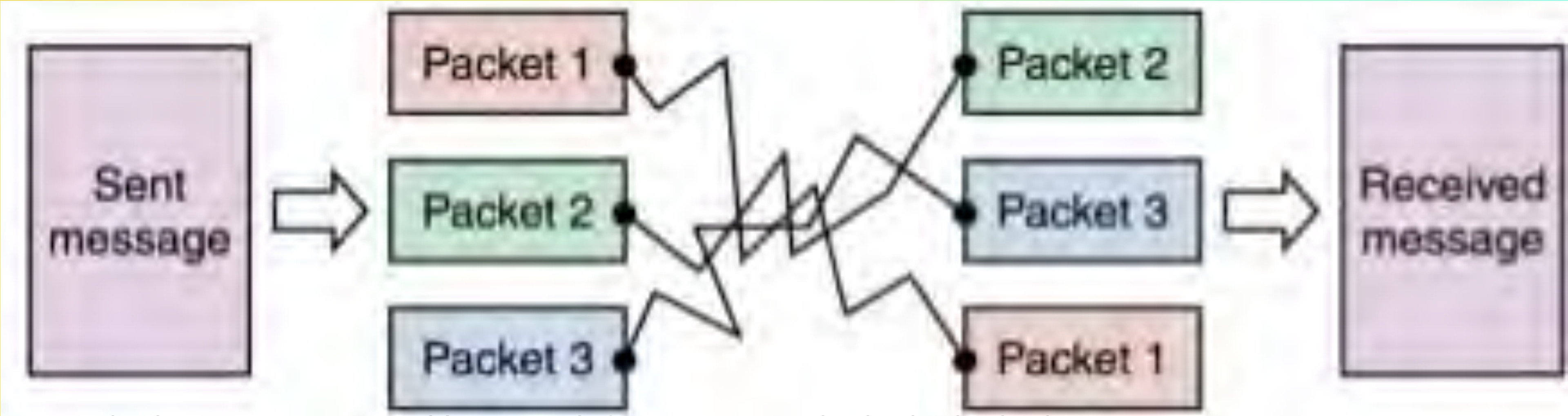
Packet Switching Technologies

Basic idea:

- Data is separated into a large number of parallel narrow-band subcarriers
  - Previously: TCP: Transmission Control Protocol
    - Single wide-band carrier to transport information
    - Channel was opened
    - Data receipt was confirmed
- Developed for 4G, Enhanced for 5G (UDP: User Datagram Protocol)
- Data is separated into a large number of parallel narrow-band subcarriers
- Subcarrier bandwidth: 15kHz to 60kHz
- Advantages of UDP: User Datagram Protocol
- Deals with multi-path interference
- Robust against narrow-band interference
- Efficient utilizes available bandwidth --

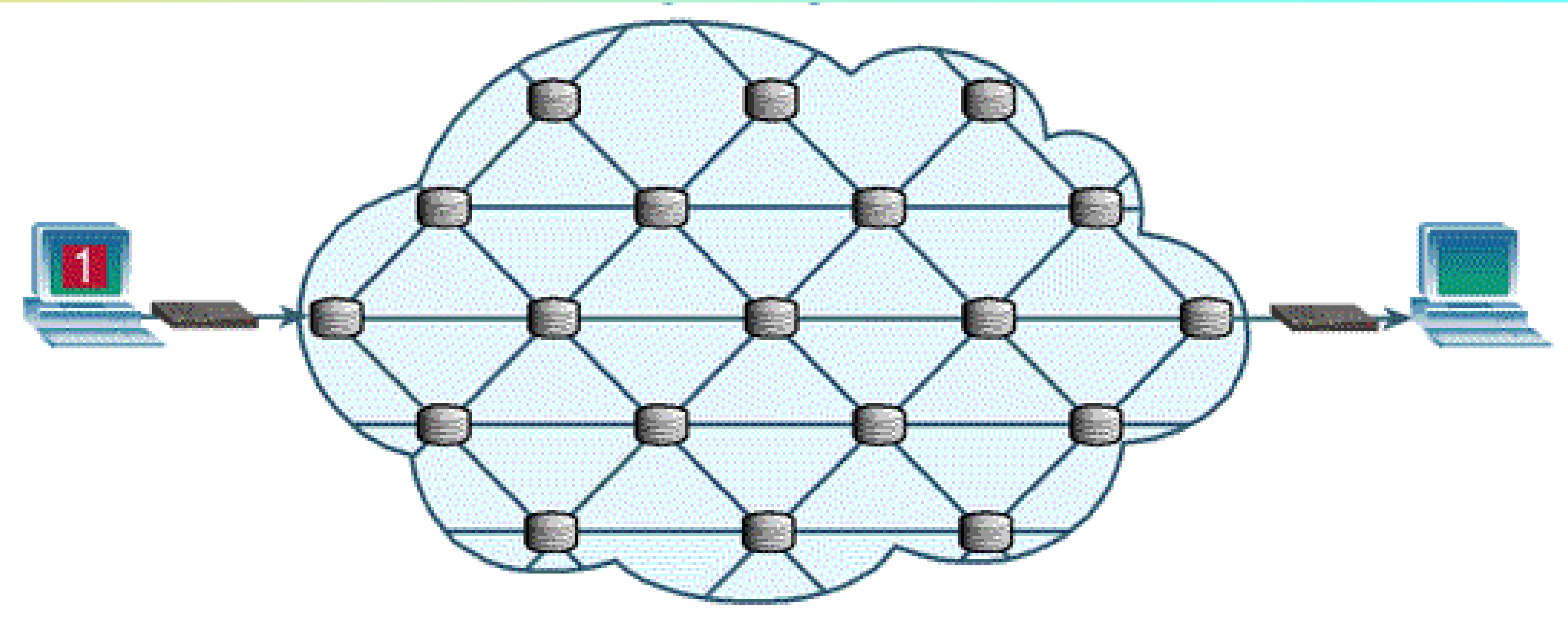
Packet Switching Review: 4G to 5G

- Message gets broken into small data packets
  - Typically 15kHz (4G) ➔ 15kHz to 60kHz (5G)
- Packets are sent out from the computer
- Travel around the network
  - Seeks the most efficient route
  - Based on circuit availability
  - Not necessarily shortest route --



Packet Routing

Each packet may take a different route through WAN (Wide Area Network)



- ❑ Data Packets are received out of order
- ❑ Data Packets are combined and reordered at the Destination--

Packet Synchronizing

Packet is sent with a 'header address'

- Lists final destination
- Describes the sequence for reassembly at the destination
- Receiving computer puts packets in the correct order
- How many packets should be arriving

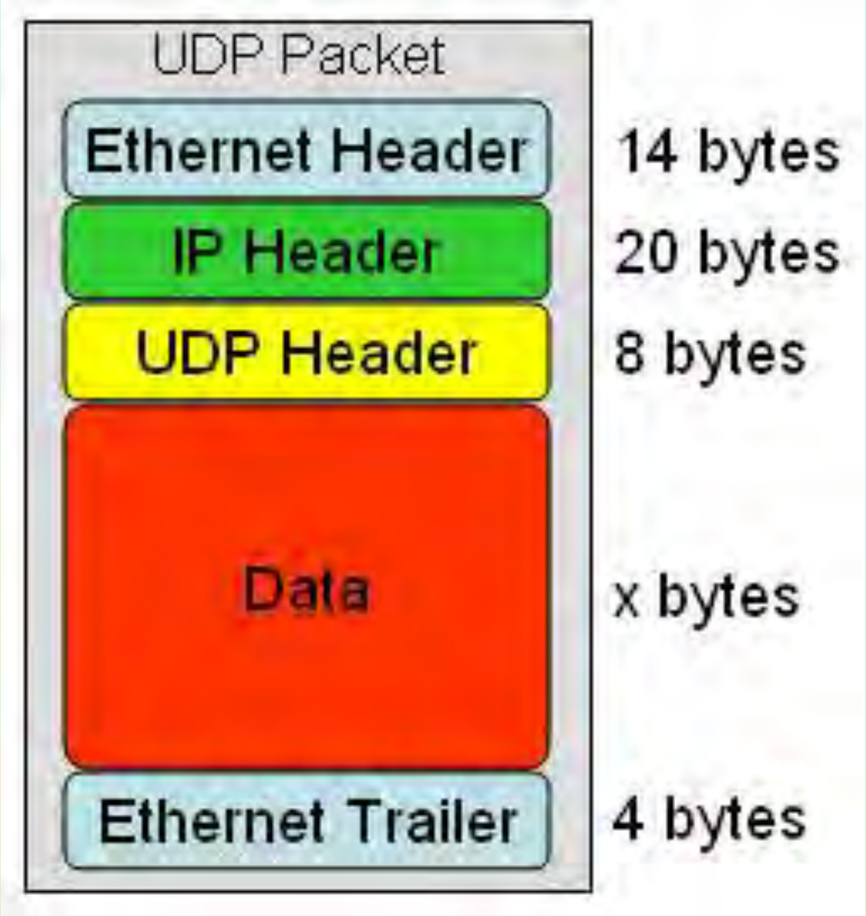
Packets at interim Nodes

- Packets are received
- Stored briefly (buffered)
- Past on to the next node

If a packet fails to arrive

- Computer asks for the missing packet to be resent --

UDP: User Datagram Protocol
IP: Internet Protocol



Packet Switching: Advantages/Disadvantages

Advantages

- Security
- Bandwidth: Used to full potential
- Devices of different speeds can communicate
- Not affected by line failure (redirects signal)
- Availability – no waiting for a direct connection to become available
- During a crisis or disaster, e-mails and texts can still be sent

Disadvantages

- Under heavy use there can be a delay (slow Internet Connection)
  - Actual Data Rates are a function of the number of users
- Data packets can get lost
- Data can become corrupted
- Can lose frames due to the way packets arrive out of sequence
- Protocols are imbedded in the Header for a reliable transfer
- Lost Data is recognized and re-requested --

Looking Behind the 5G Curtain
Signal Transmission & Reception Techniques

Part 2:
Modulation, Constellations and Orthogonal Multiplexing

02-02: 4G/5G Packet Spectral Technologies

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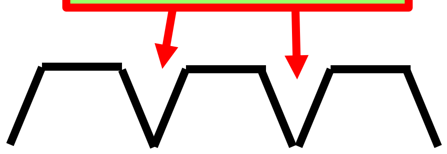
Transitioning to 4G

FDMA – Frequency Division Multiple Access

FDMA requires guard bands

Guard Bands



- User is allocated to a different carrier frequency
- Signals are available until channel is closed

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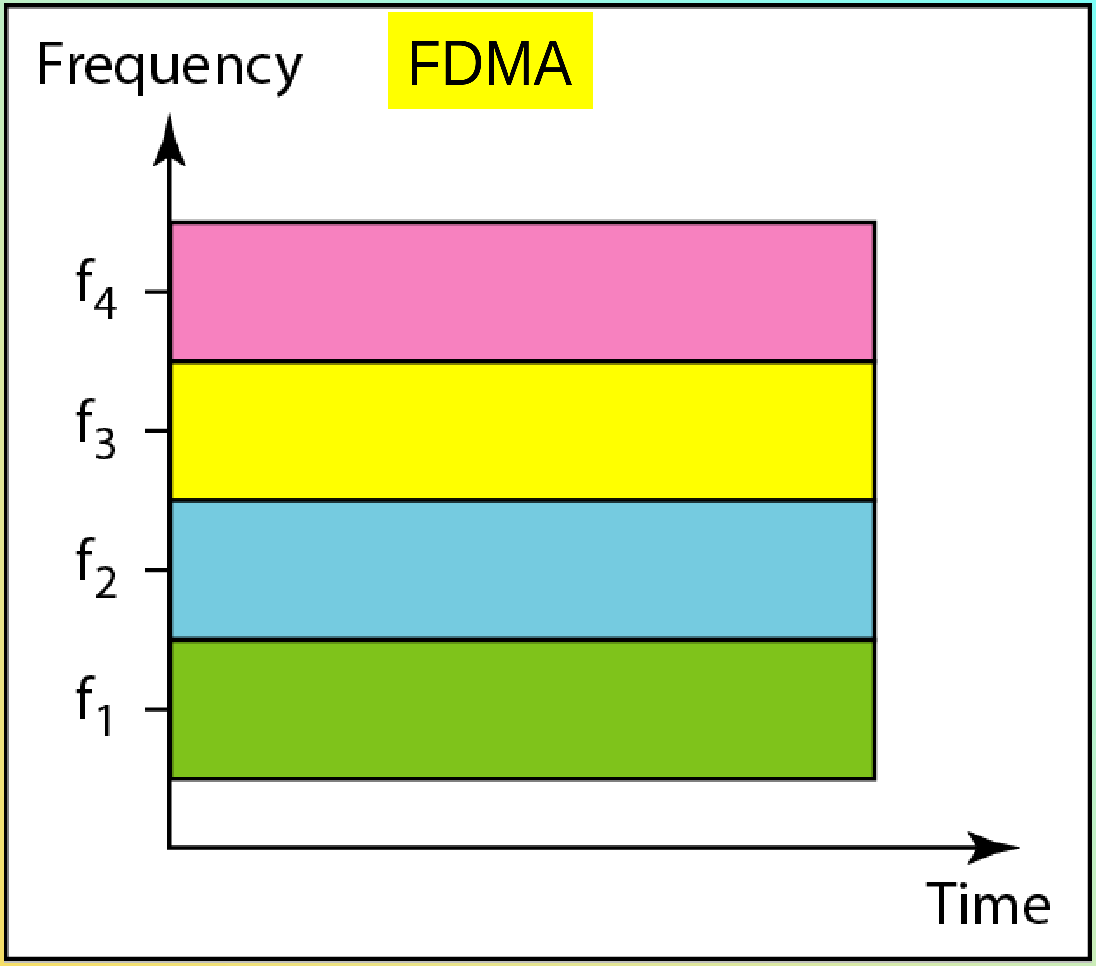
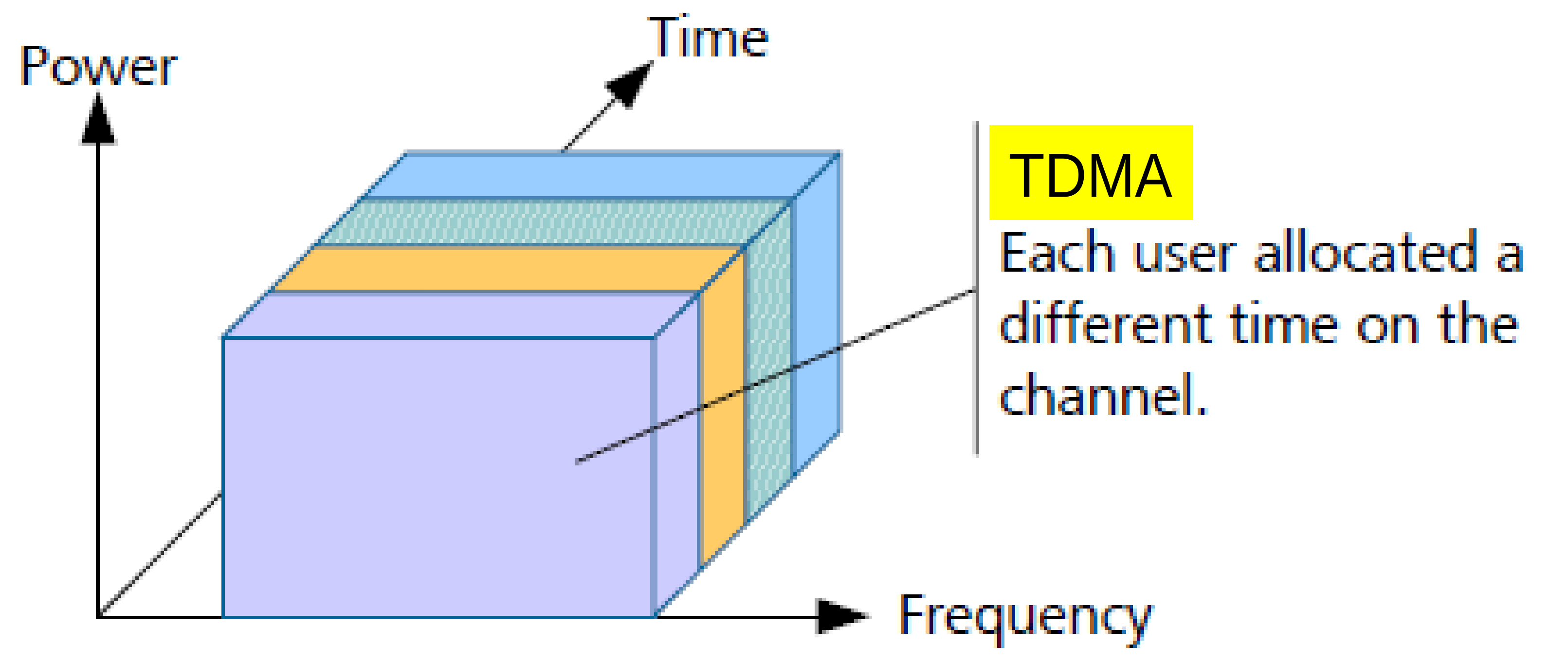


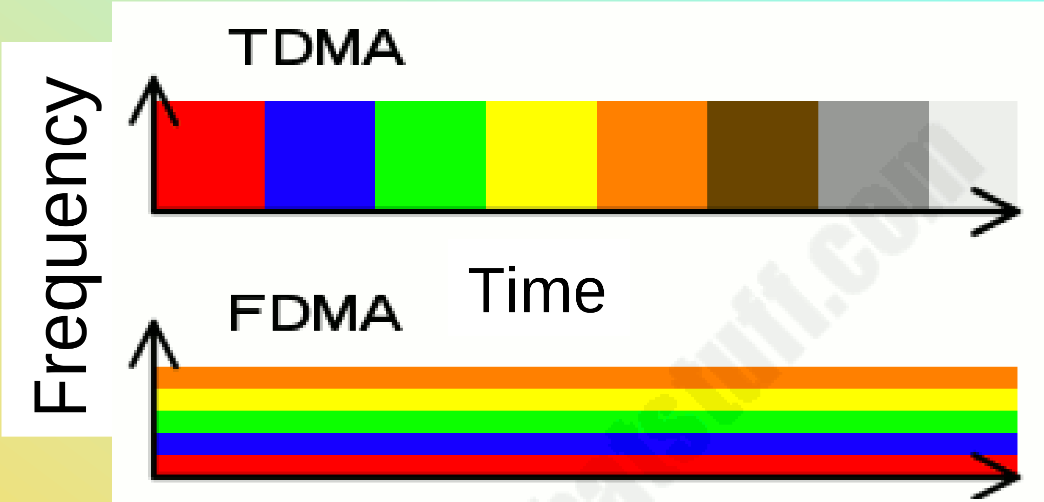
TDMA - Time Division Multiple Access

- User is allocated a time frame in the frequency band
- Infrastructure holds data until time frame is available

- Frequency bandwidths are wider than FDMA
- More flexible in allocating users
- Improved use for available Bandwidth
  - No Guard Band Required --

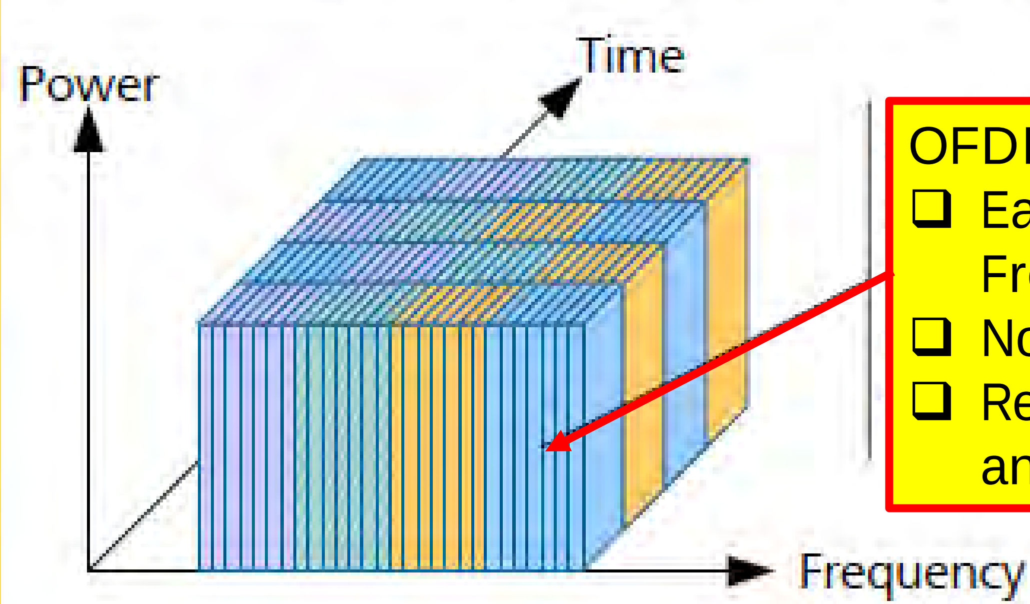


4G/5G Uses a Combination of FDMA and TDMA



TDMA: Allocated Time Slots
FDMA: Allocated Frequency Slots

Orthogonal Frequency Division Multiple Access (OFDMA)

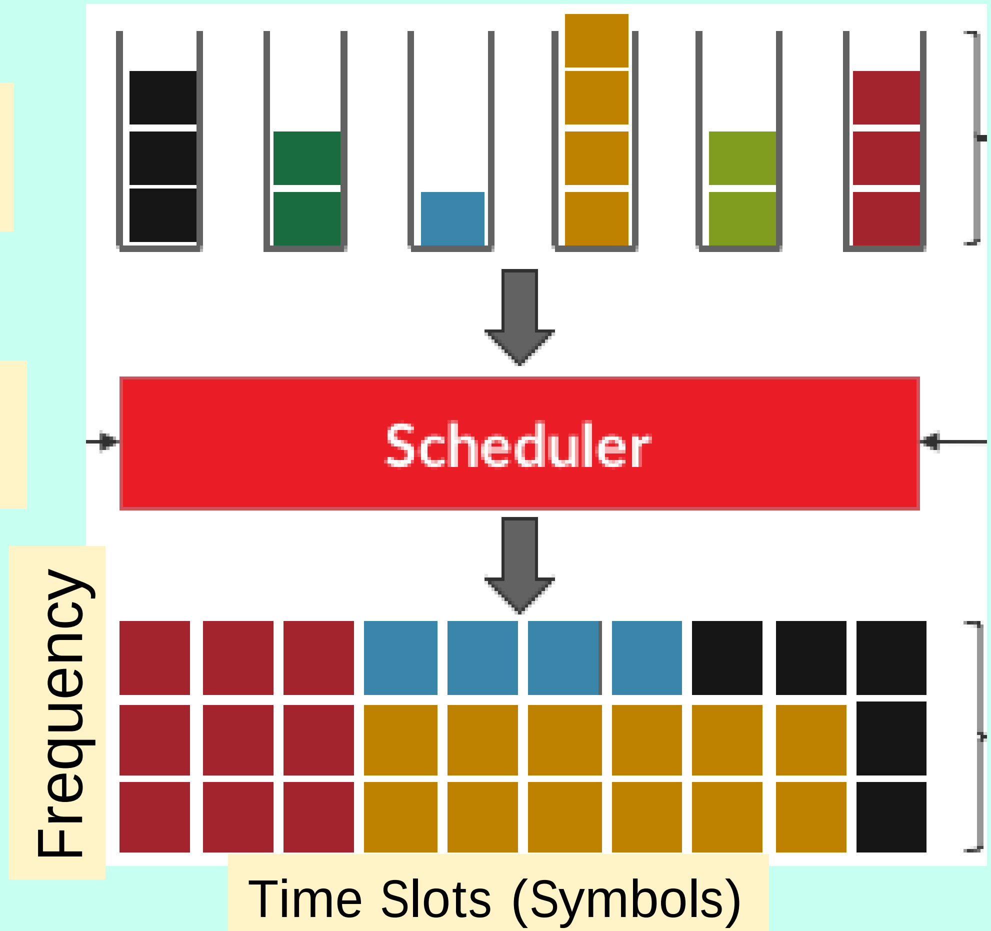


OFDMA:
- ❑ Each user is allocated a Frequency & Time Slot
- ❑ No dedicated resource
- ❑ Resources can vary in time and frequency --

User Data Stream

Scheduler allocates Resource Blocks to user data streams

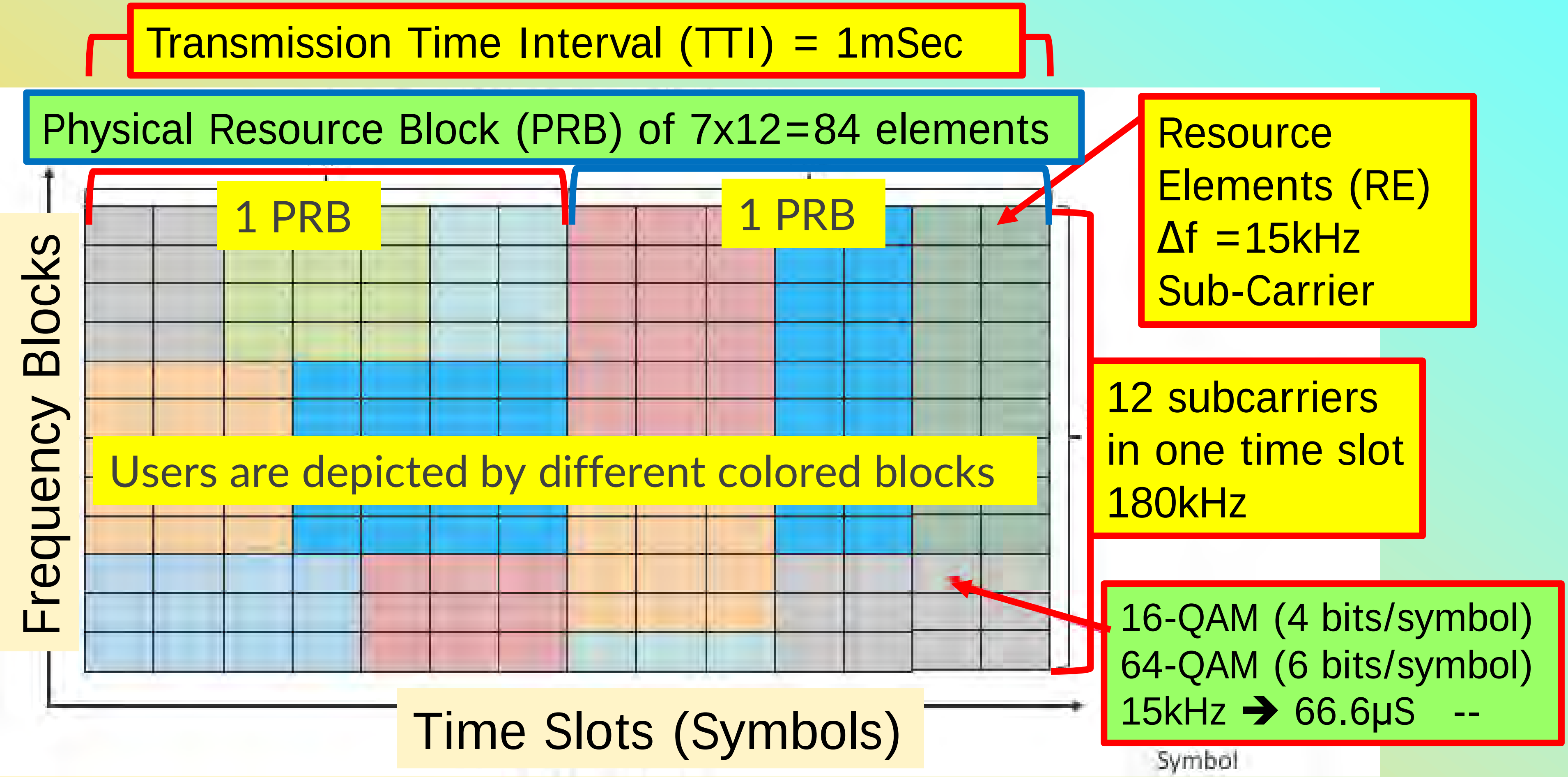
Allocated Resource Blocks



- Scheduler Program allocates Resource Blocks to user data streams based on
  - Quality of Service (QoS) requirements
    - Real-time business, such as voice, video, real-time games, etc.) bandwidth can be guaranteed --

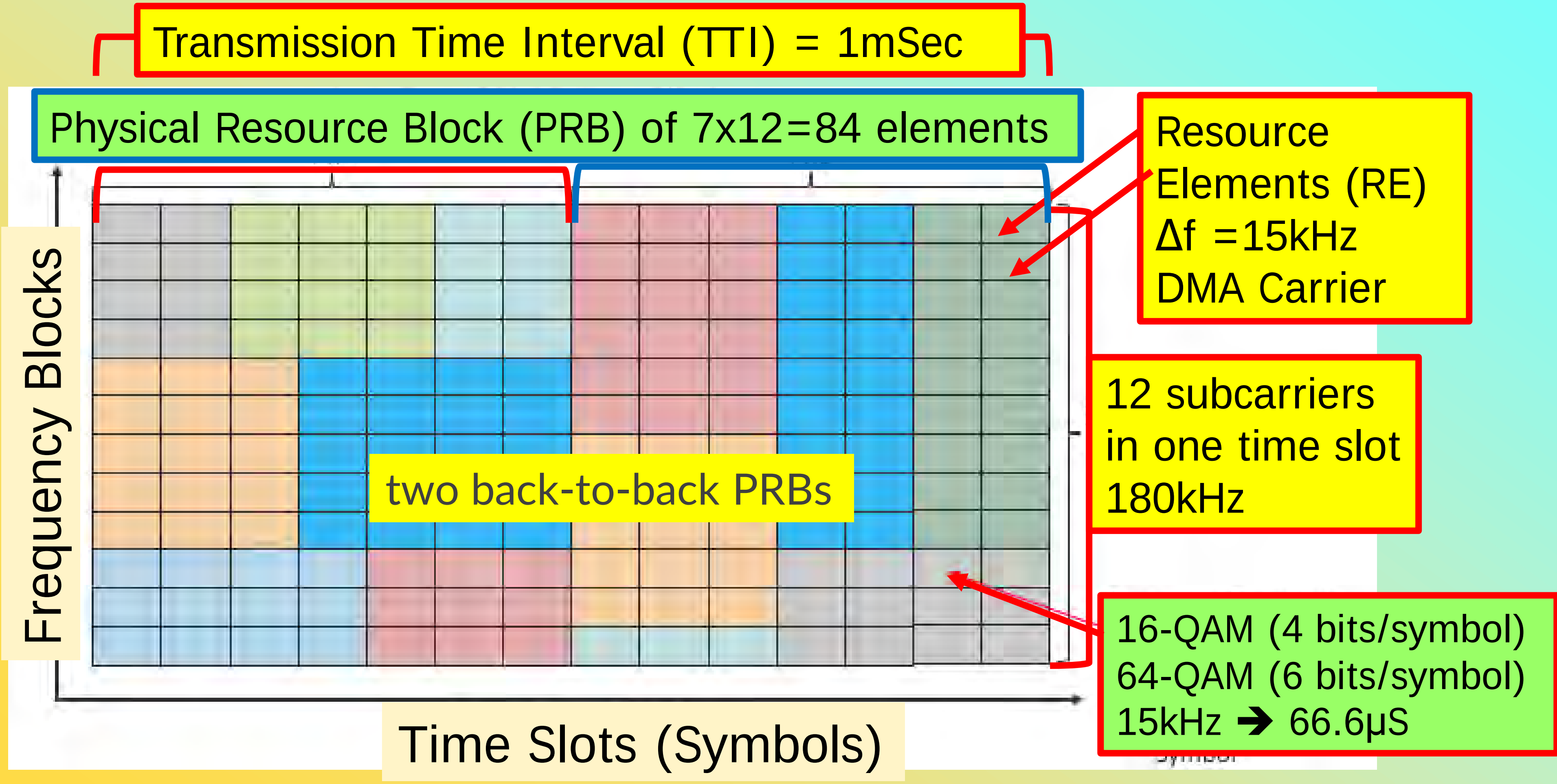
Multiplexing in 4G &5G Uses FDMA & TDMA

- Minimal schedulable unit, called a Resource Element (RE)
  - 4G: 15-kHz bandwidth around one subcarrier frequency
  - Number of bits / symbol is variable



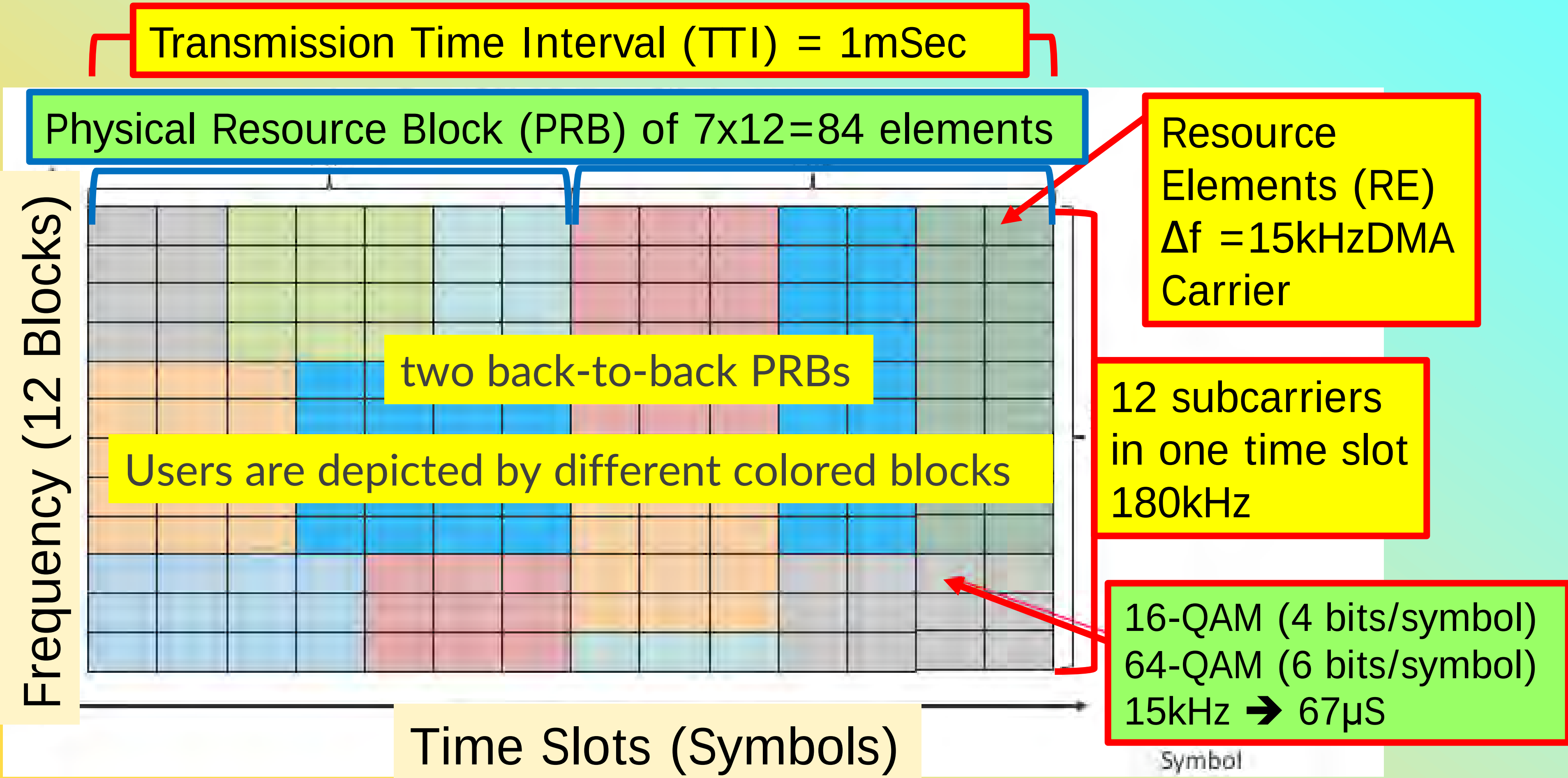
Scheduler (Software)

- Allocates a number of Resource Elements (RE) to each user
- Receives feedback from destination about the quality
- Selects the coding (bits/Symbol) per- Physical Resource Block (PRB) basis
- Scheduler uses feedback to allocate PRBs for the next TTI --



Physical Resource Block (PRB)

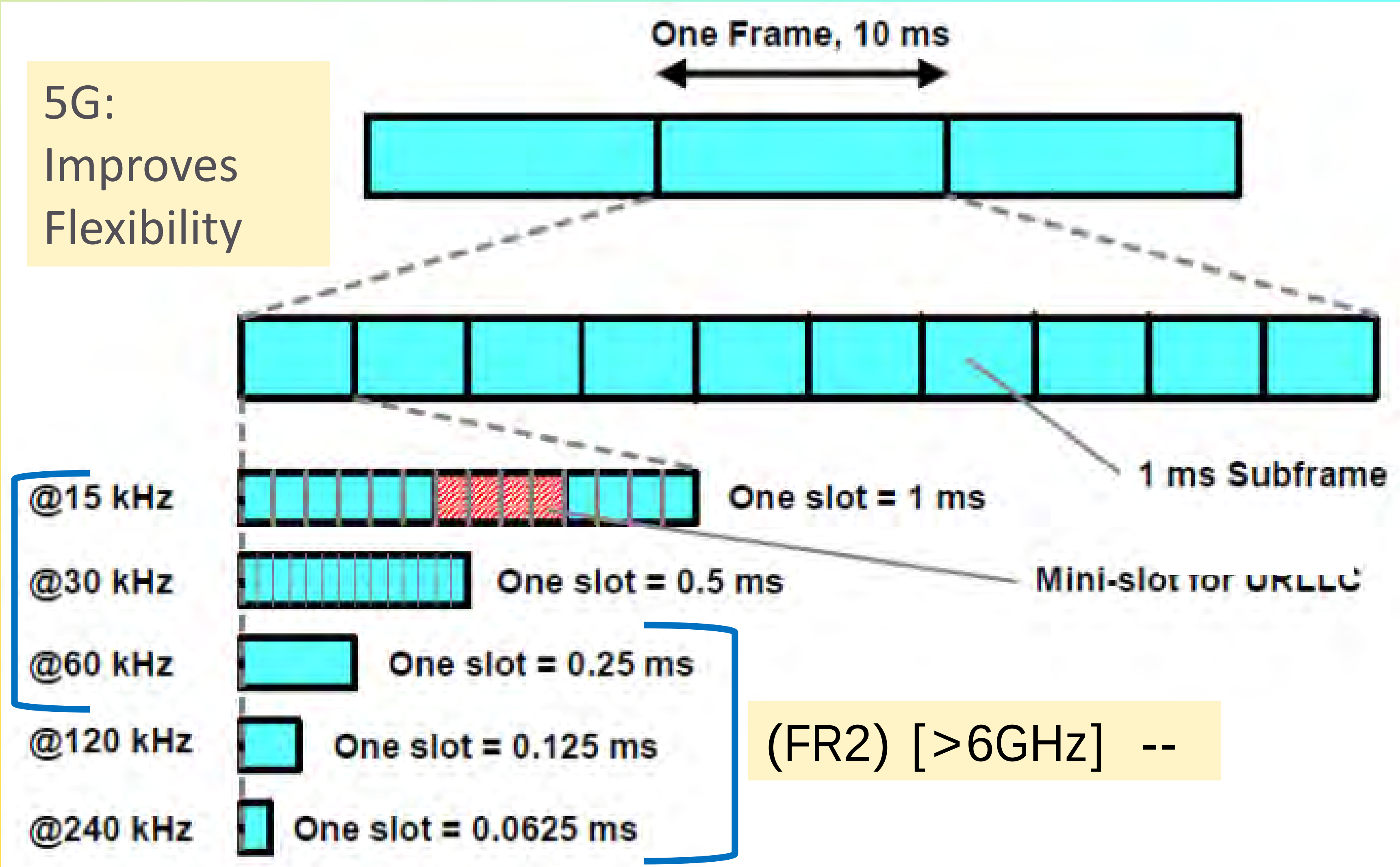
- Physical Resource Block (PRB) of 12 Carriers each 15kHz ➔ 180kHz BW
- 7 Time slots .066mS (1/15kHz) per slot ➔ ≈ 0.5mS for 1 Resource Block (PRB)
- Scheduler makes its decision to allocate PRBs for the next TTI (1mS) --



5G: Scheduler allocate Physical Resource Block (PRB) every (1 ms)

Telephone calls get a priority

- ❑ Each frame is 10 ms, each subframe is 1 mS
  - ❑ Ten subframes to a frame --



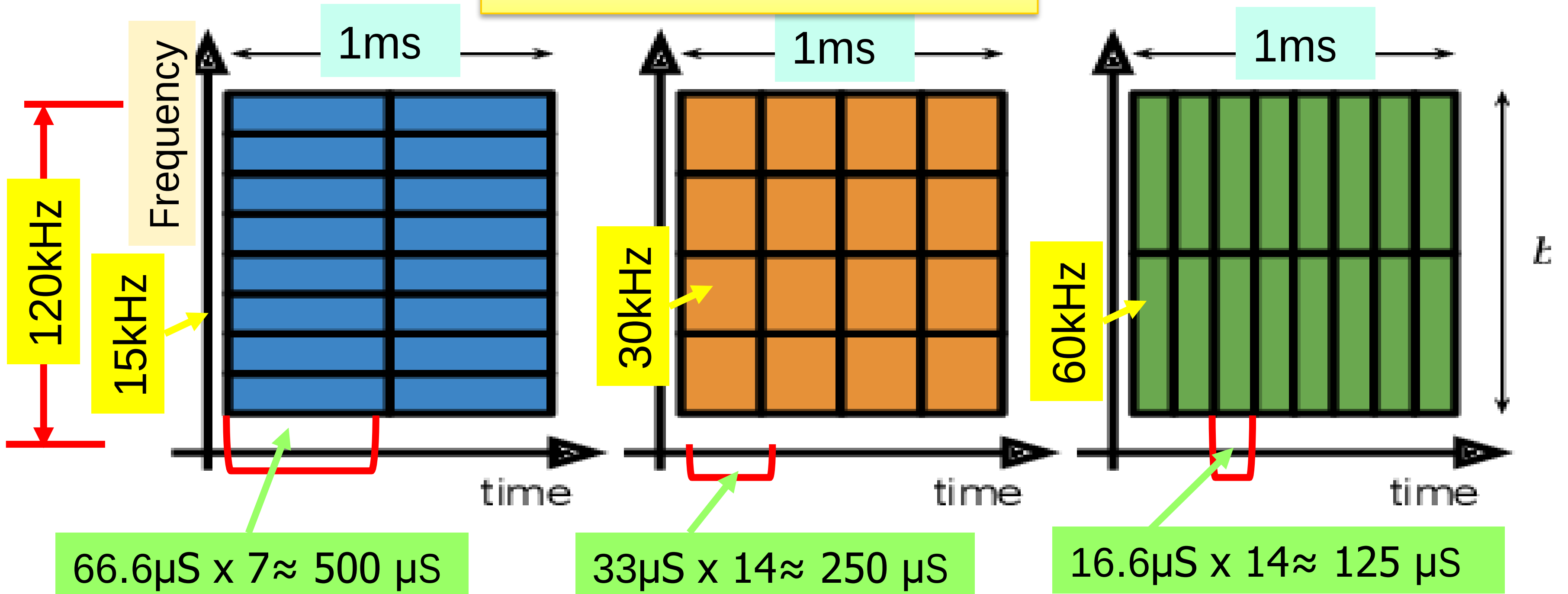
(FR1) [<6GHz]

5G: Improves Flexibility

Subframe : 1mS

Subcarrier spacing	# slots per subframe	Slot length
15 kHz	1	$1ms/2^0$=1 ms
30 kHz	2	$1ms/2^1$=500us
60 kHz	4	$1ms/2^2$=250 us
120 kHz	8	$1ms/2^3$=125µs

Wider Bandwidths →



5G
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Part 2:
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02-03: Orthogonal Frequency Division Multiplexing (OFDM)

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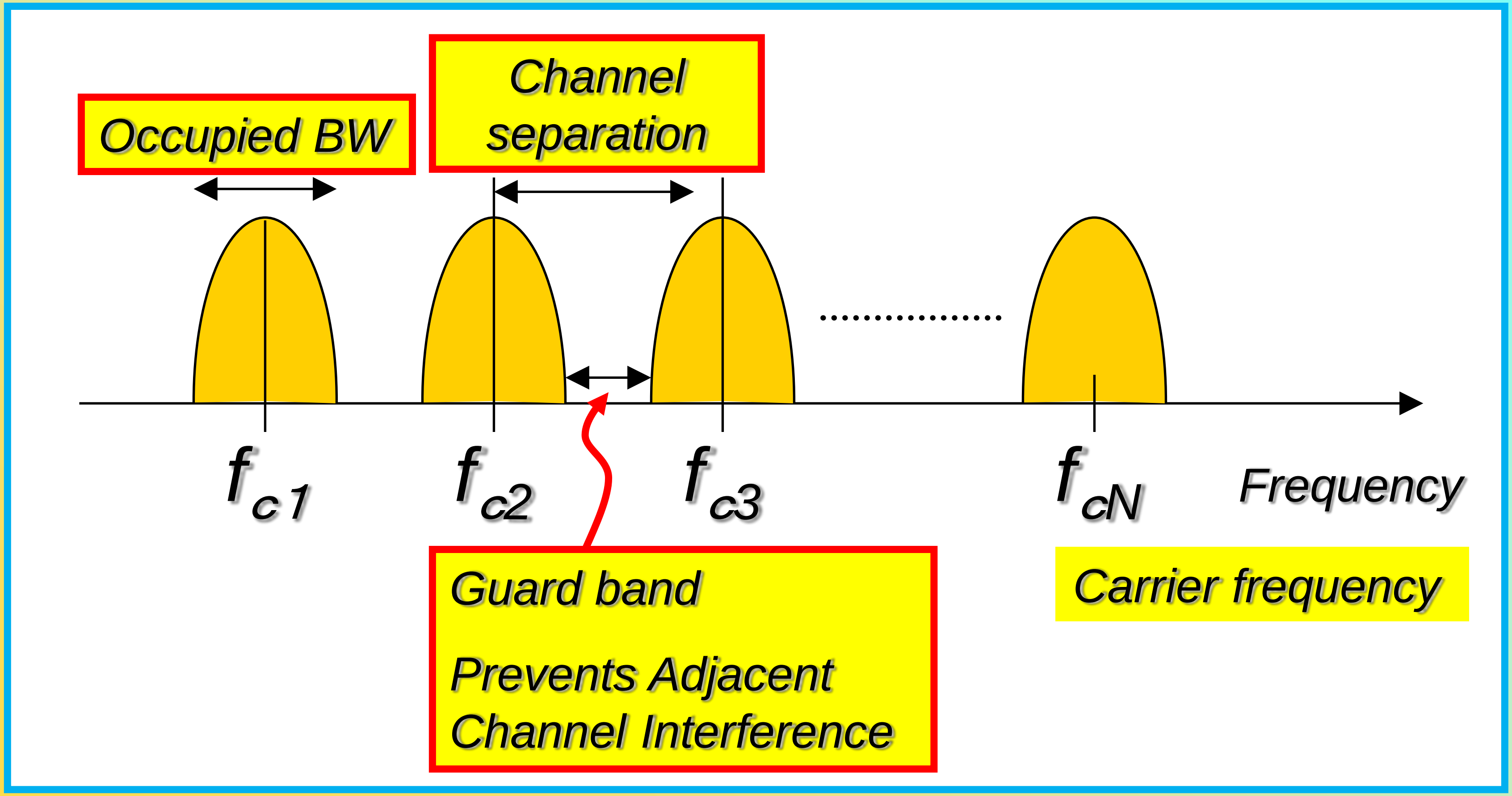
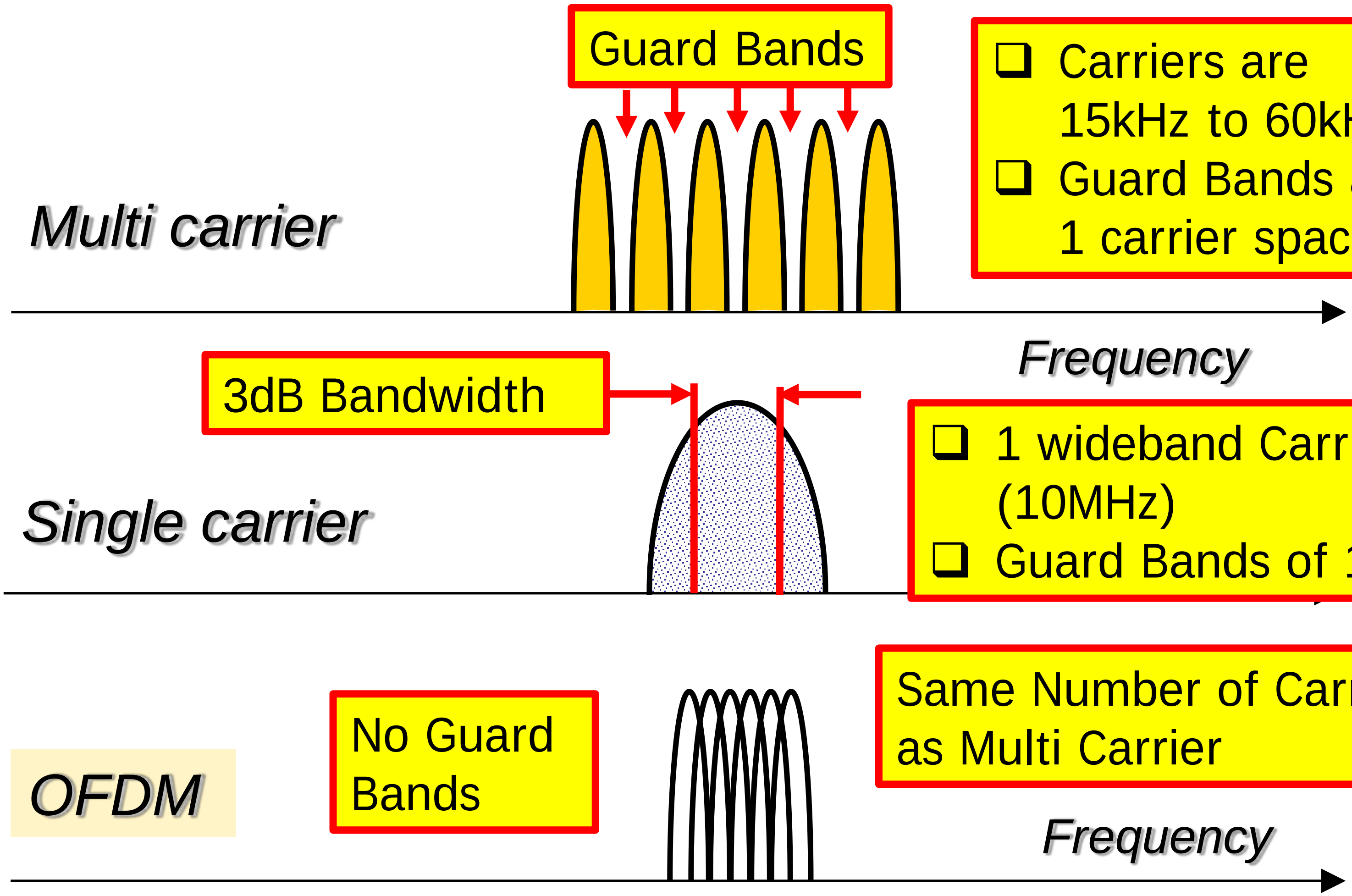
Conventional Frequency Division Multiple Access (FDMA)

- Separate carrier frequency for individual transmission --



Spectrum Comparison
Multi Carrier, Single Carrier & OFDM

OFDM: Orthogonal Frequency-Division Multiplexing



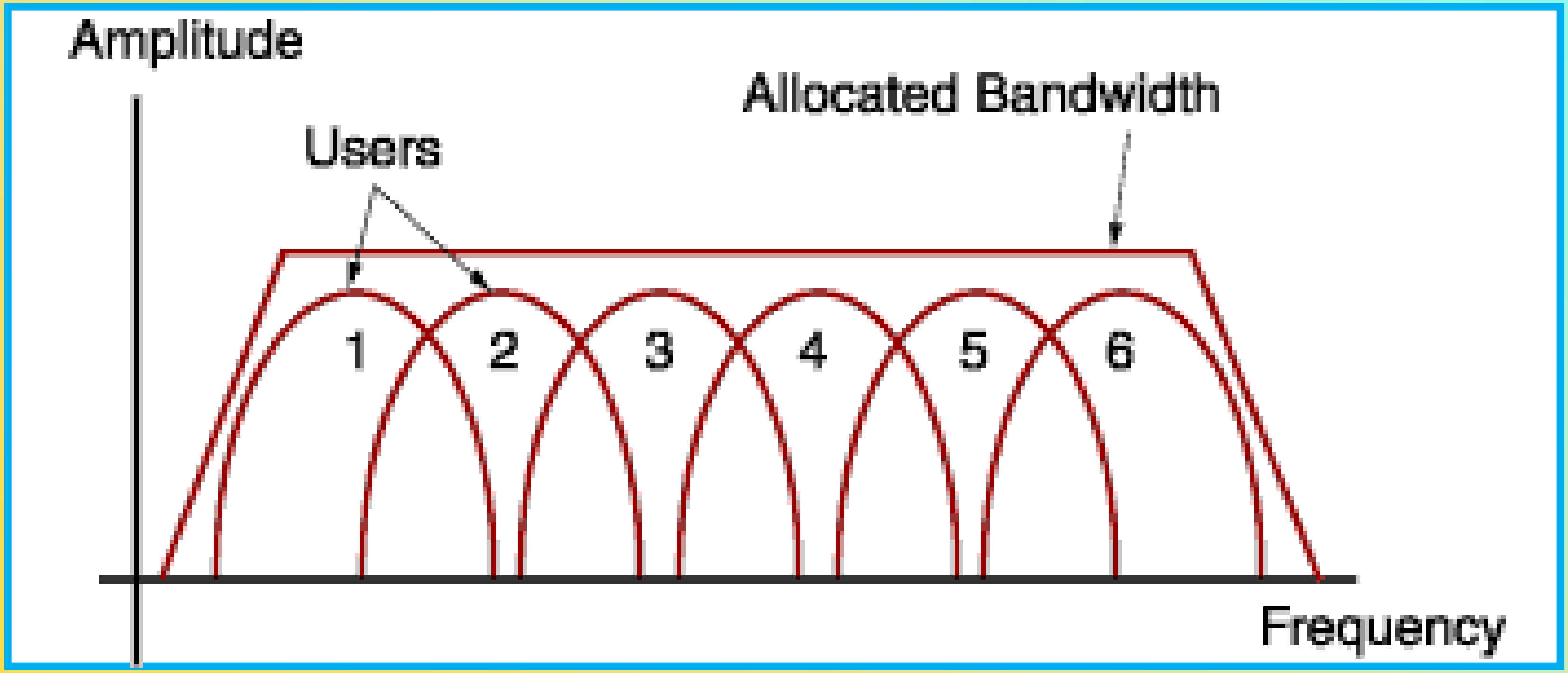
- Carriers are 15kHz to 60kHz
- Guard Bands are 1 carrier spacing

- 1 wideband Carrier (10MHz)
- Guard Bands of 10MHz

Same Number of Carriers as Multi Carrier

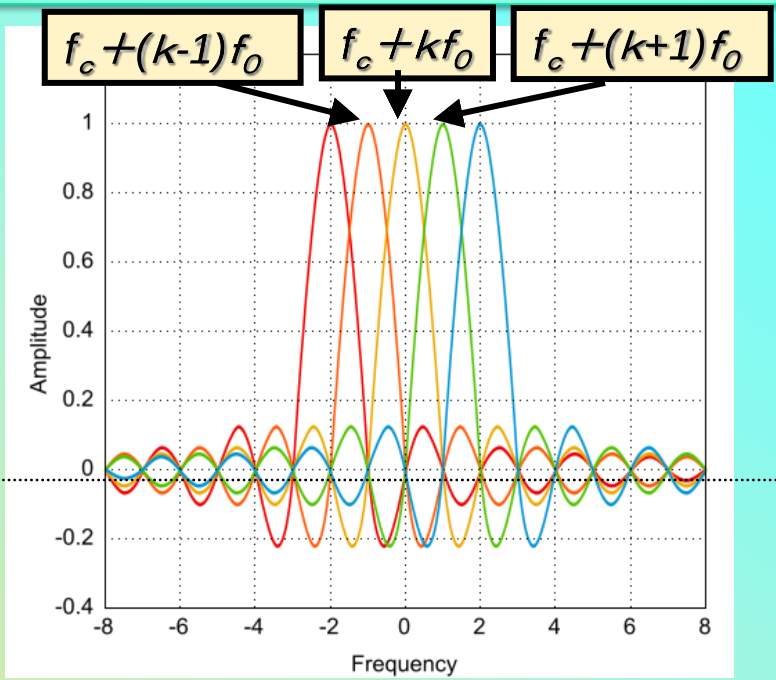
Implementation of OFDM

- OFDM is Based on use of
  - Fast Fourier Transforms (FFT): Receiver
  - Inverse Fast Fourier Transforms (IFFT): Transmitter
- Adjacent bands are Frequency orthogonal
  - 3D Movie Glasses use Orthogonal Polarization --

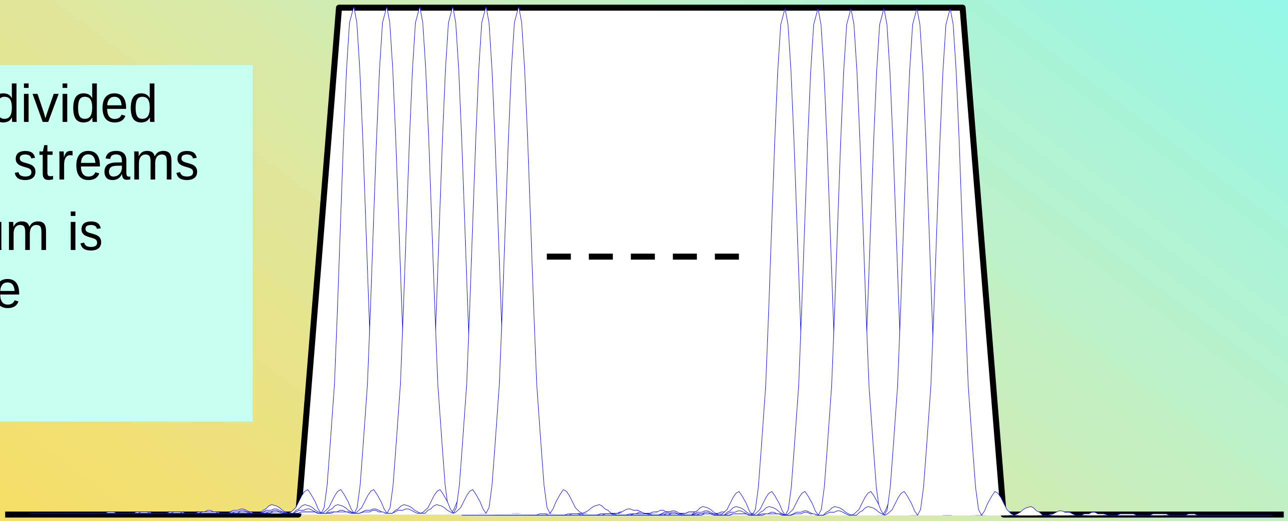


OFDM Power Spectrum

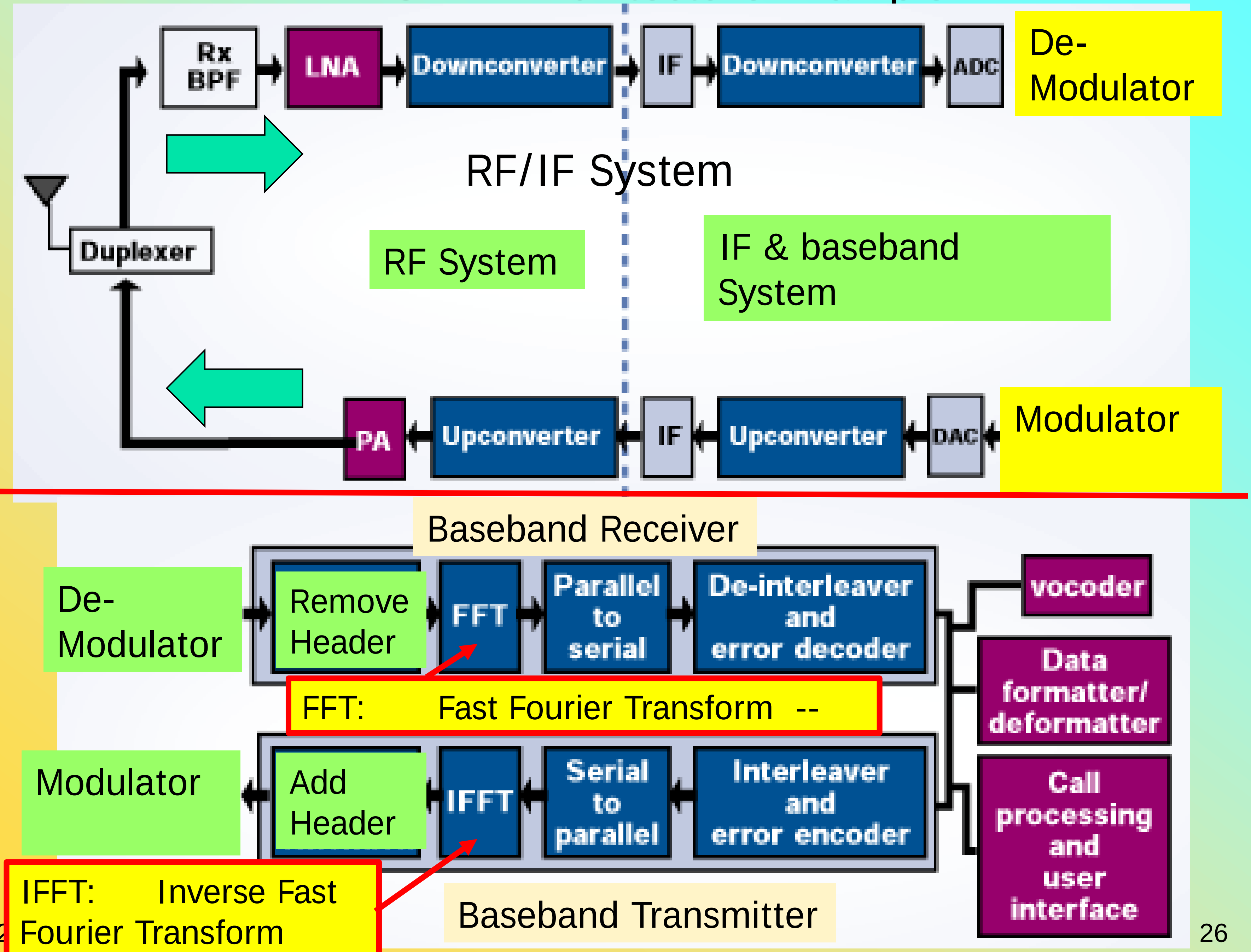
- OFDM carriers are densely packed
- Adjacent carriers are orthogonal
- Peak of one carrier occurs at null of the next carrier
- OFDM system is bandwidth efficient.



- High-speed data is divided into multiple slower streams
- Total Power spectrum is almost square shape
- No guard bands --



OFDM Architecture Example



5G
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Part 2:
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02-04: 5G Modulation

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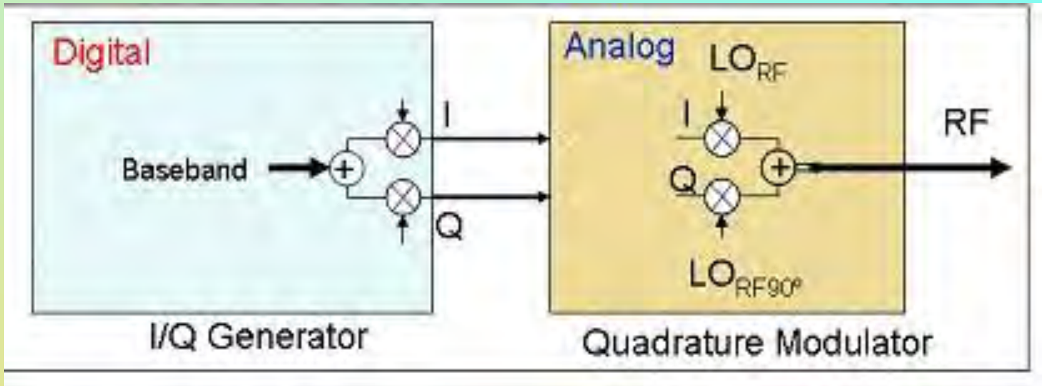
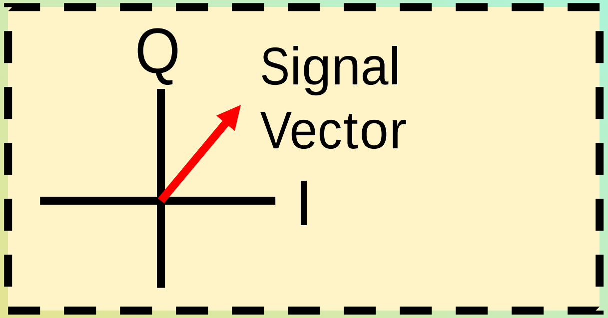
Waveforms & Modulation:

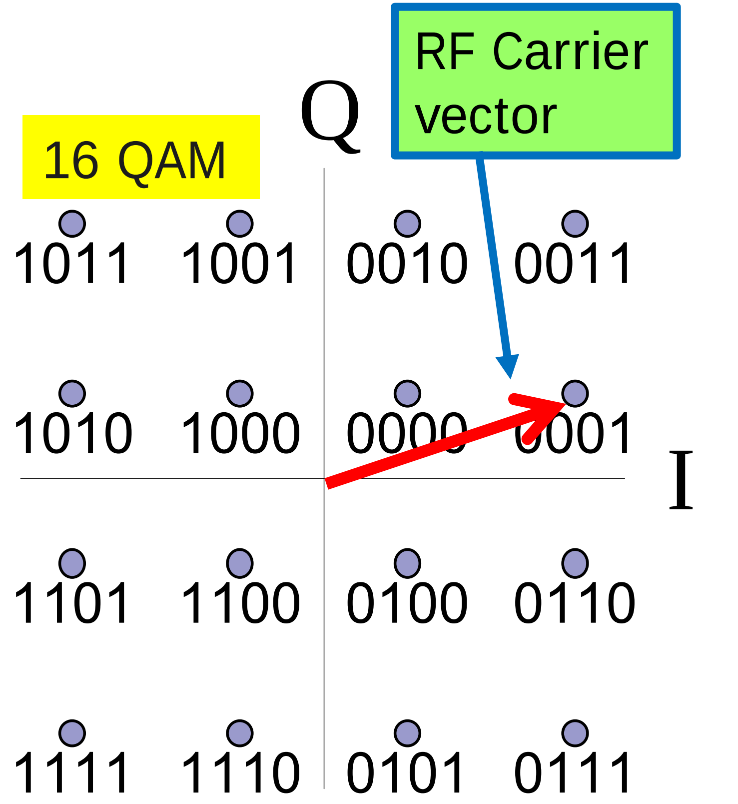
- 4G and 5G based around
  - Dividing data into small packets
  - OFDM densely populates the subcarriers
  - Subcarrier Modulation: Vector Modulation
- Vector Modulation formats dependent upon the quality of the link
  - More complex modulation requires higher S/N
  - Users see higher data rates
- Currently used:
  - Quadrature Amplitude Modulation (QAM)
  - 4QAM: 2 bits/symbol
  - 16QAM: 4 bits/symbol
  - 64QAM: 6 bits/symbol
- Experimental:
  - 256QAM: 8 bits/symbol
  - 1024QAM: 10 bits/symbol --





Vector Modulation

- Digital Communications has almost universally replaced Analog Communications
  - Analog requires higher S/N than digital
- Digital Transmission via Vector Modulation
  - RF Carrier is a vector
    - Amplitude
    - Phase information
  - Vector location defines a symbol
- A Symbol is a collection of Bits (1's & 0's)

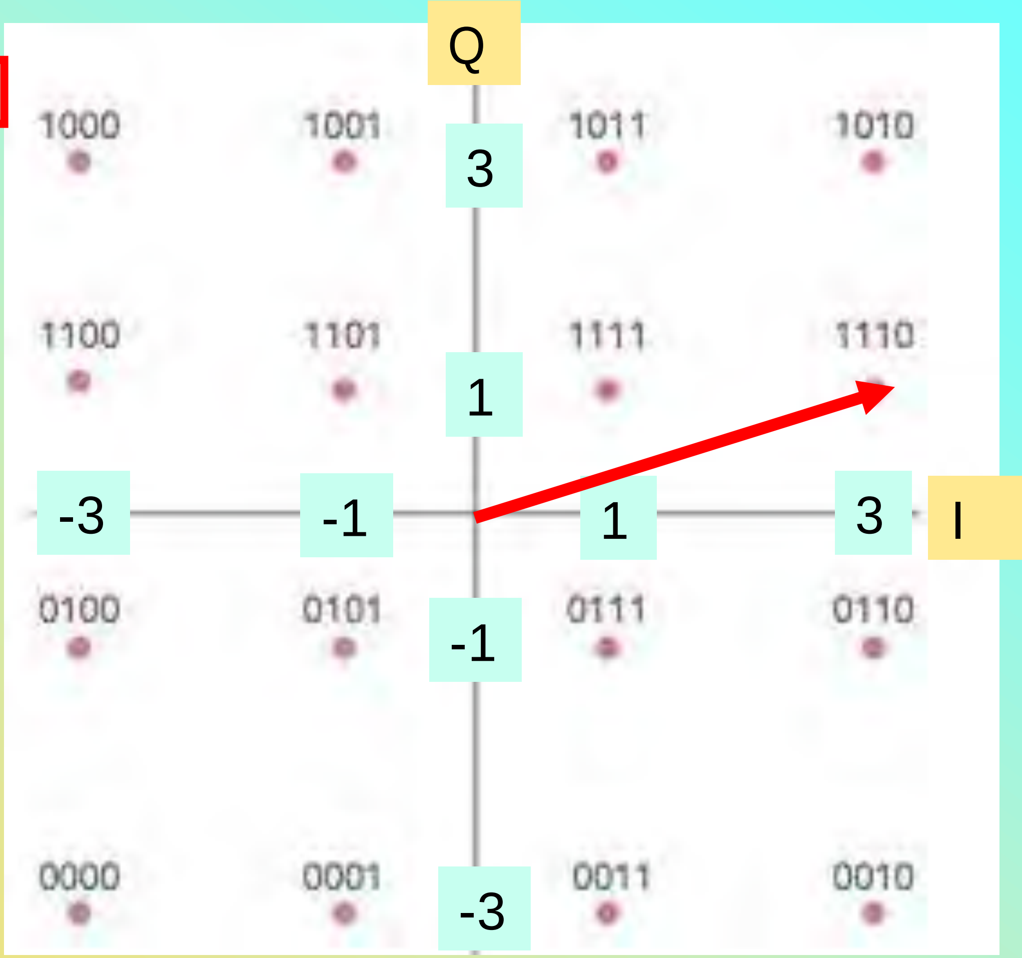


- ➢ Constellation of points
- ➢ 16 Positions
- ➢ 4 bits per position --

5G Modulation Techniques

Symbol	Q	I	Phase	Amp	Rel Amp
1110	1	3	18.4	3.16	0.75
1111	1	1	45.0	1.41	0.33
1010	3	3	45.0	4.24	1.00
1011	3	1	71.6	3.16	0.75
1001	3	-1	108.4	3.16	0.75
1101	1	-1	135.0	1.41	0.33
1000	3	-3	135.0	4.24	1.00
1100	1	-3	161.6	3.16	0.75
0100	-1	-3	198.4	3.16	0.75
0000	-3	-3	225.0	4.24	1.00
0101	-1	-1	225.0	1.41	0.33
0001	-3	-1	251.6	3.16	0.75
0011	-3	1	288.4	3.16	0.75
0111	-1	1	315.0	1.41	0.33
0010	-3	3	315.0	4.24	1.00
0110	-1	3	341.6	3.16	0.75

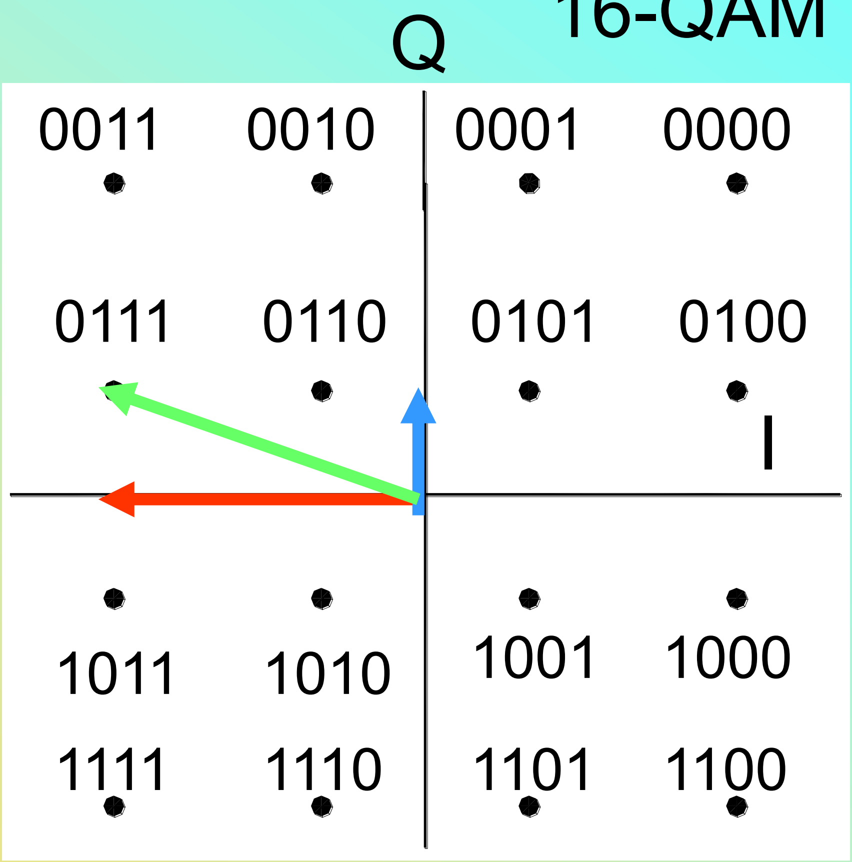
16-QAM modulation



Gray Code

- Encoding of numbers so that adjacent numbers have a single digit differing by 1
- Enhances the ability to correct data without retransmission
  - Forward Error Correction (FEC) --

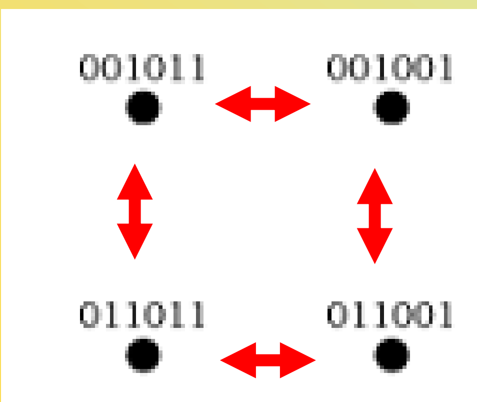
16-QAM

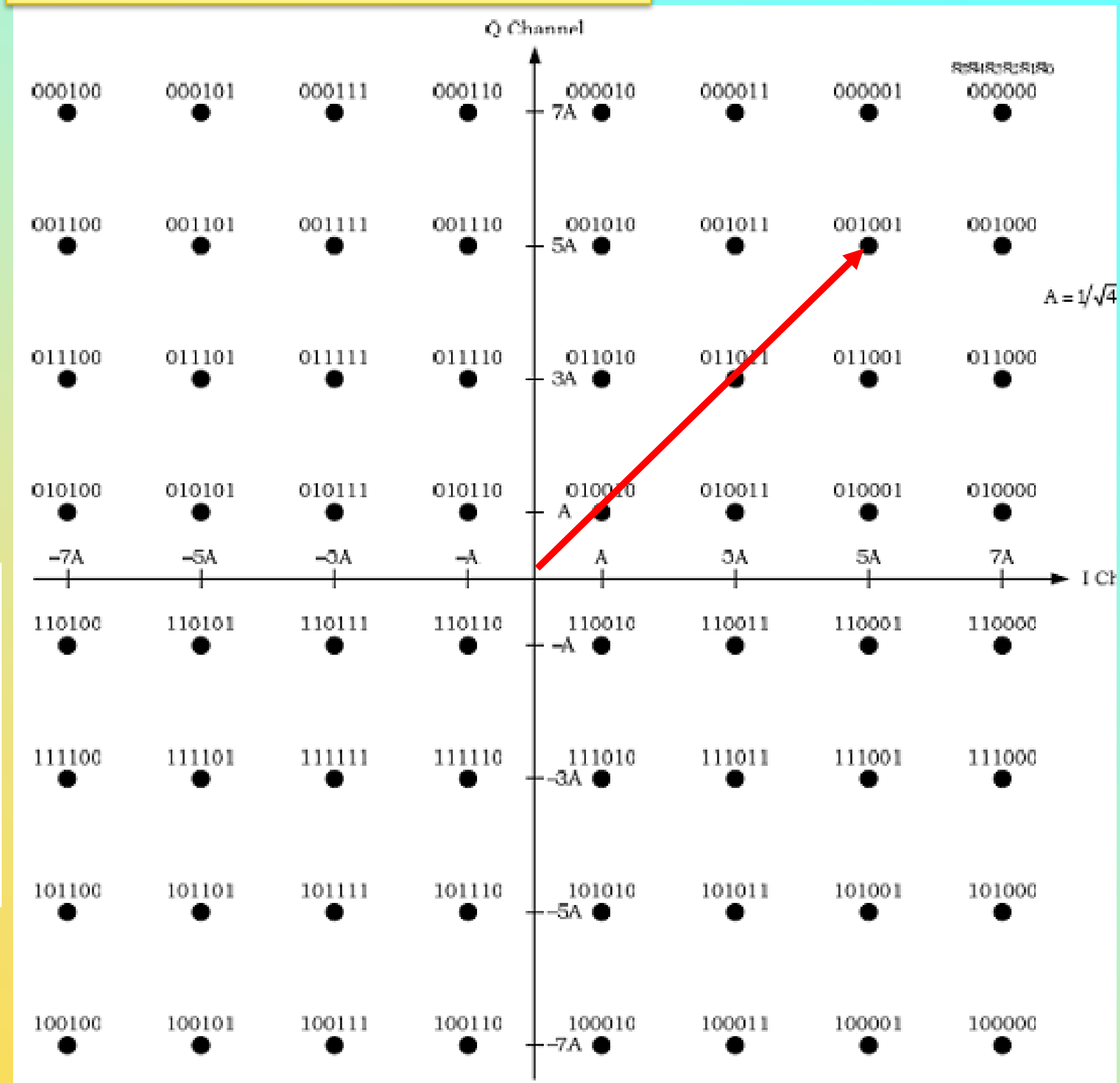


Transmitted 16-QAM Data, 4 bits/symbol

64QAM 6 Bits per symbol

Note:
Gray Code



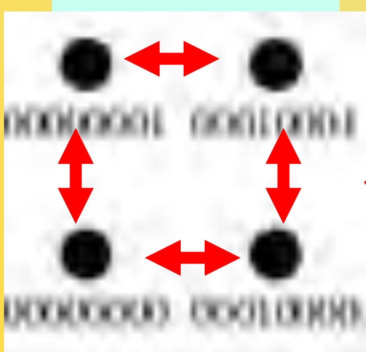


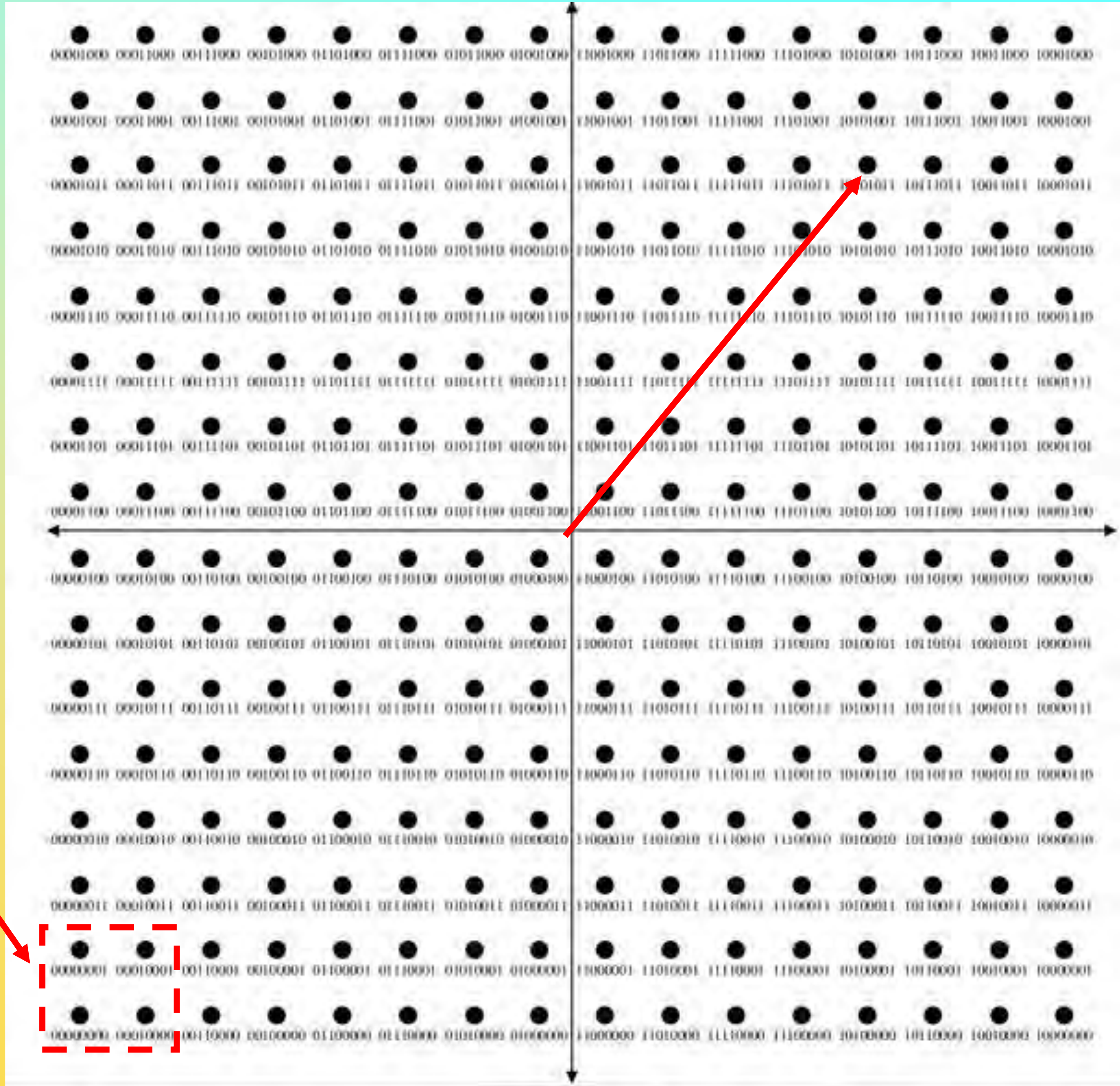
256QAM

8 Bits/Symbol

Vector Phase and amplitude errors are more of an issue

Note Gray Code

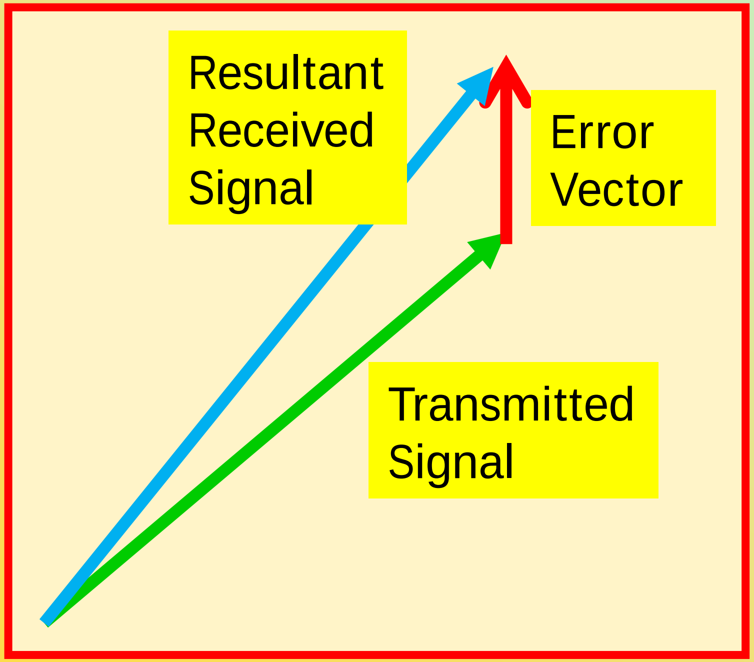


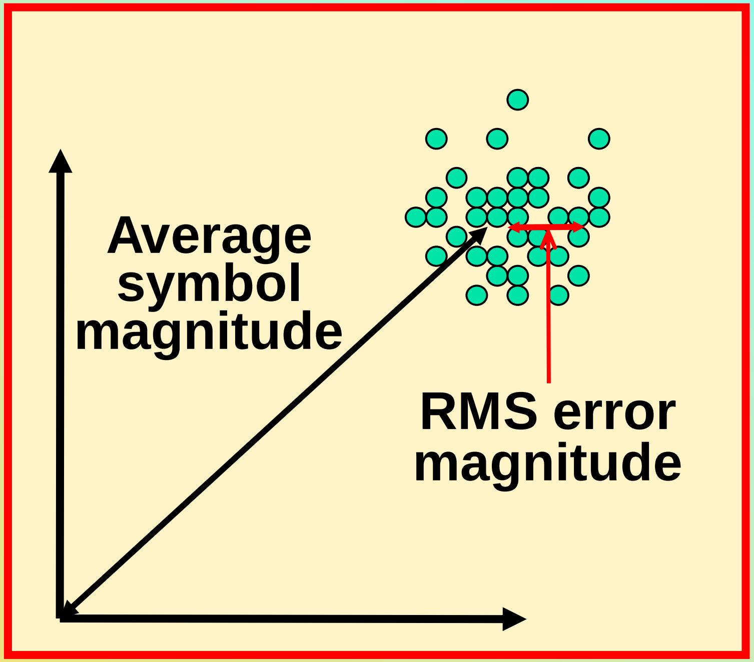


12/27/2022

Error Vectors

- Vector Errors (EV) distort the original signal
- EVM, (Error Vector Measurements) common term for defining vector distortion
- Can cause the resultant vector to point to the wrong symbol --



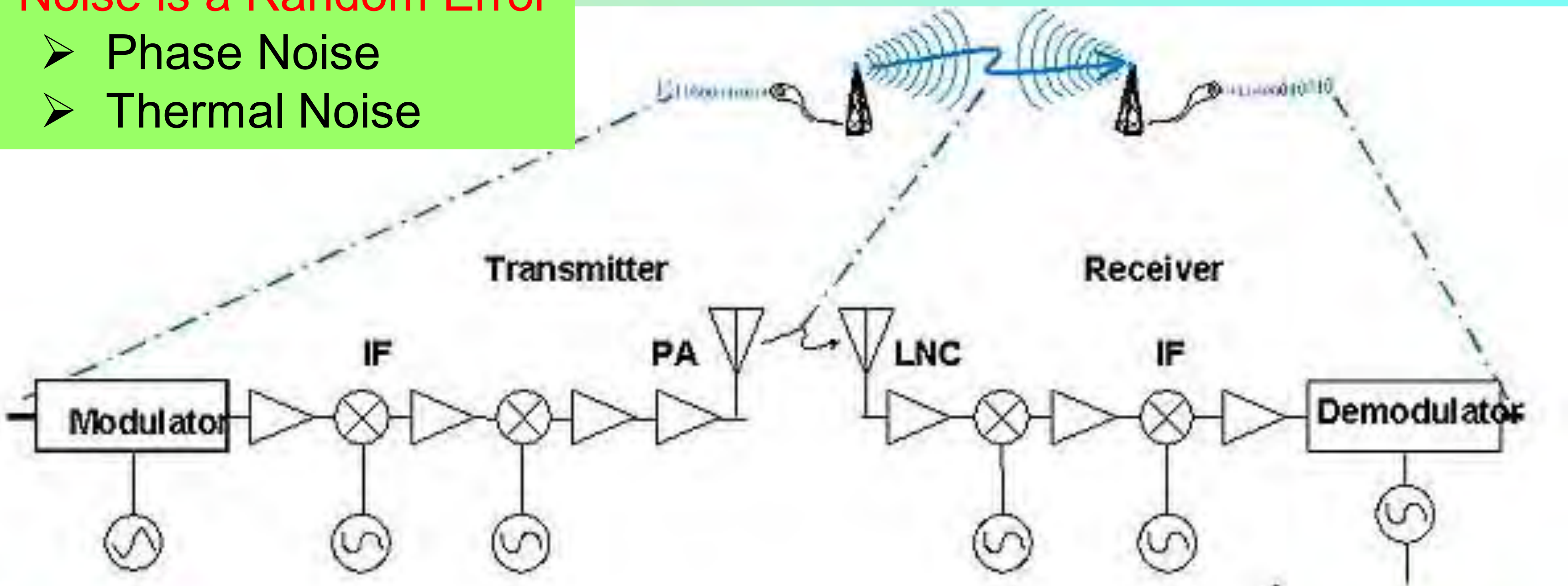


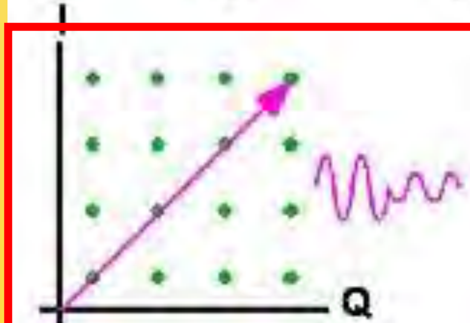
System Diagram: Decision Regions

- Two classes of Vector Errors
  - Deterministic
  - Random

- Deterministic Errors
  - Channel Linearity
  - Gain Ripple
  - Group Delay Distortion, Etc. --

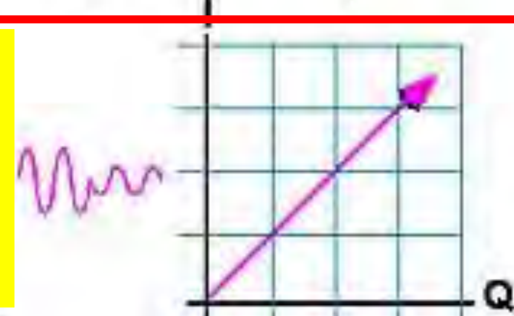
- Noise is a Random Error
  - Phase Noise
  - Thermal Noise





Vector is Transmitted on a point

Vector is Received in a decision region

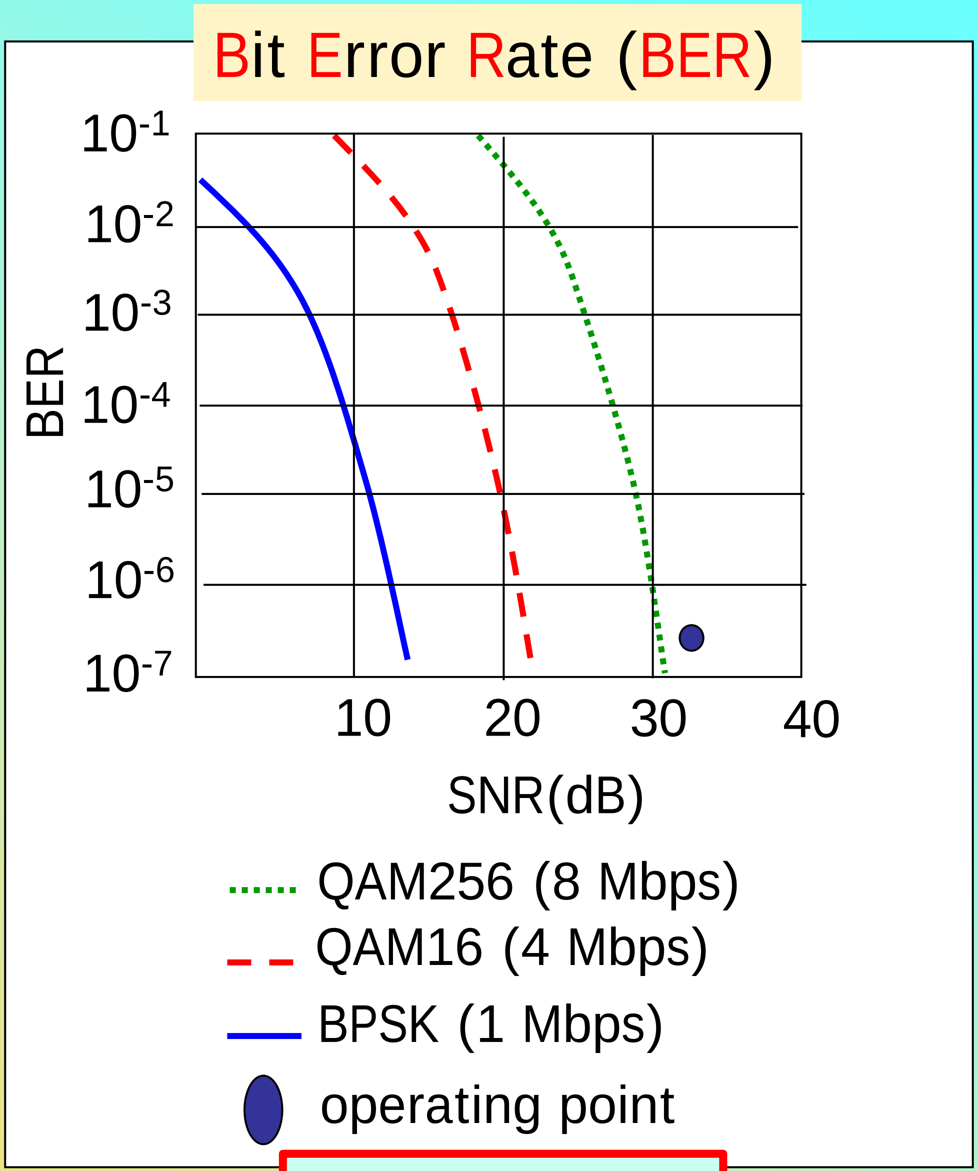


Rate adaptation

- Signal decreases ⇩
- S/N decreases ⇩
- BER Increases ⇧

1. Lower Constellation complexity
2. Decreases BER at the same S/N ⇩

1. Decreasing Bandwidth
2. Lowers Noise
3. Increases S/N
4. Decreases BER



No standard BER

Error Detection code

Simplest Form of Error detection codes uses Parity Checks

- Parity bit added to a block of data
- Parity Words added to the end of a block of words
- Even parity
  - Added a bit ensures an even number of 1's
- Odd parity
  - Added a bit ensures an odd number of 1's
- Example, 7-bits of data [1110001] & 8-bit code
  - Even parity [11100010]
  - Odd parity [11100011]

Parity bit

Two-Dimensional Parity

Data	Even Parity Bits
0101001	1
1101001	0
1011110	1
0001110	1
0110100	1
1011111	0
1111011	0

Even Parity Byte

- 1^{st} dimensional parity
  - Add a Parity Bit
  - Add one bit to every byte (word)
    - Ensure an even/odd number of 1's
- 2^{nd} dimensional parity
  - Add a Parity word
  - Add an extra byte (word) to every block
  - Bits in the Parity word
  - Ensure even/odd number of 1's in the respective column --

Forward Error Correction (FEC)

- Simplest Form of two-dimensional parity checks

Two-dimensional parity-check code (Even #1s)

							Parity Bits
1	1	0	0	1	1	1	1
1	0	1	1	1	0	1	1
0	1	1	1	0	0	1	0
0	1	0	1	0	0	1	1
0	1	0	1	0	1	0	1

Parity Word

Bit Error

Parity Error

							Parity Bits
1	1	0	0	1	1	1	1
1	0	0	1	1	0	1	1
0	1	1	1	0	0	1	0
0	1	0	1	0	0	1	1
0	1	0	1	0	1	0	1

Parity Word

Parity Error

(Even #1s)

- **Horizontal & Vertical Parity Finds & Corrects a single error --**

Forward Error Correction

							Parity Bits
1	1	0	0	1	1	1	1
1	0	$\boxed{1}$	1	$\boxed{1}$	0	1	1
0	1	1	1	0	0	1	0
0	1	0	1	0	0	1	1
0	1	0	1	0	1	0	1

Parity Word

Even #1s

2 Bit Errors in 1 word

No Parity Error

							Parity Bits
1	1	0	0	1	1	1	1
1	0	0	1	0	0	1	1
0	1	1	1	0	0	1	0
0	1	0	1	0	0	1	1
0	1	0	1	0	1	0	1

Parity Error

Parity Word

Even #1s

- Multiple errors in one word
  - Not found in the word parity
  - Found in the Block Parity Word
  - Error is detected but not corrected (Can't find the Error Word)
- Pr(1 error) = 10^{-6} (1 Errors in 1 Million Bits)
- Pr(2 errors) = 10^{-12} (1 Errors in 1 Trillion Bits)
- Two errors in 1 block: Error is known but can't be corrected
  - Request data sent again --

Block Code Design Considerations

- More check words ➔ higher probability of finding multiple errors
  - Transmission inefficiency increases Codes are designated by how many parity words are attaches
- Example: ¾ code
- Number ¾ means 4 words are transmitted 3 words are data
- Lower the fraction ➔ more parity words ➔ more error correction
- Example: Block code design
  - ½ rate code half the data rate
  - ½ code: 2 words sent for every (1) data word sent
- Parity bits added to each word
  - Decreases the efficiency of each word
  - Smaller words catch more errors
    - Less efficient •

5G
Looking Behind the Curtain
Signal Transmission & Reception

Part 2:
Modulation, Constellations and Orthogonal Multiplexing

02-05: MIMO: Multiple-Input Multiple-Output

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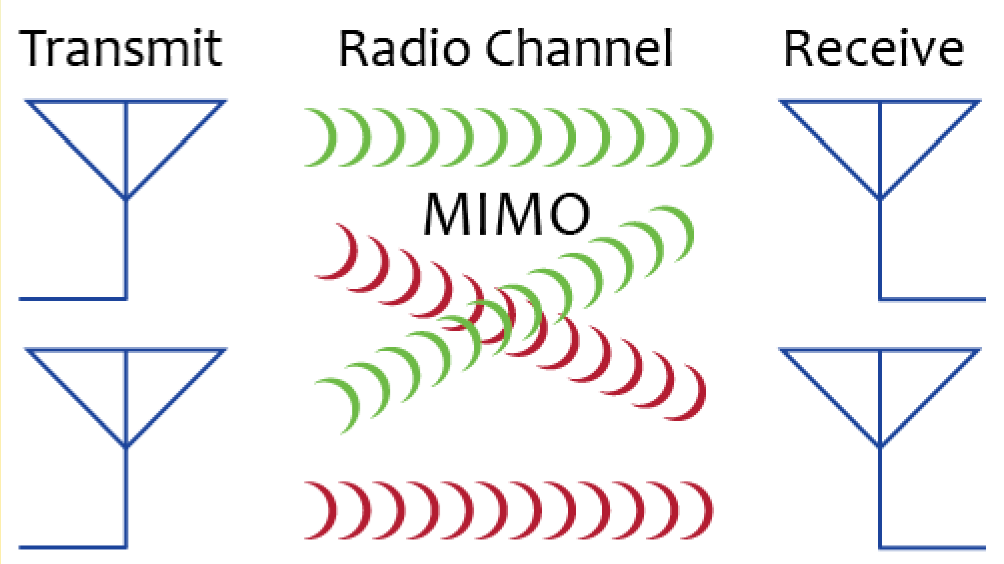
MIMO: Multiple-Input Multiple-Output

- MIMO is an antenna technology utilizing multipath signal propagation
  - Multipaths can be used for
    - Redundancy
    - Resolve multipath reflection issues
    - Spatial Frequency Reuse

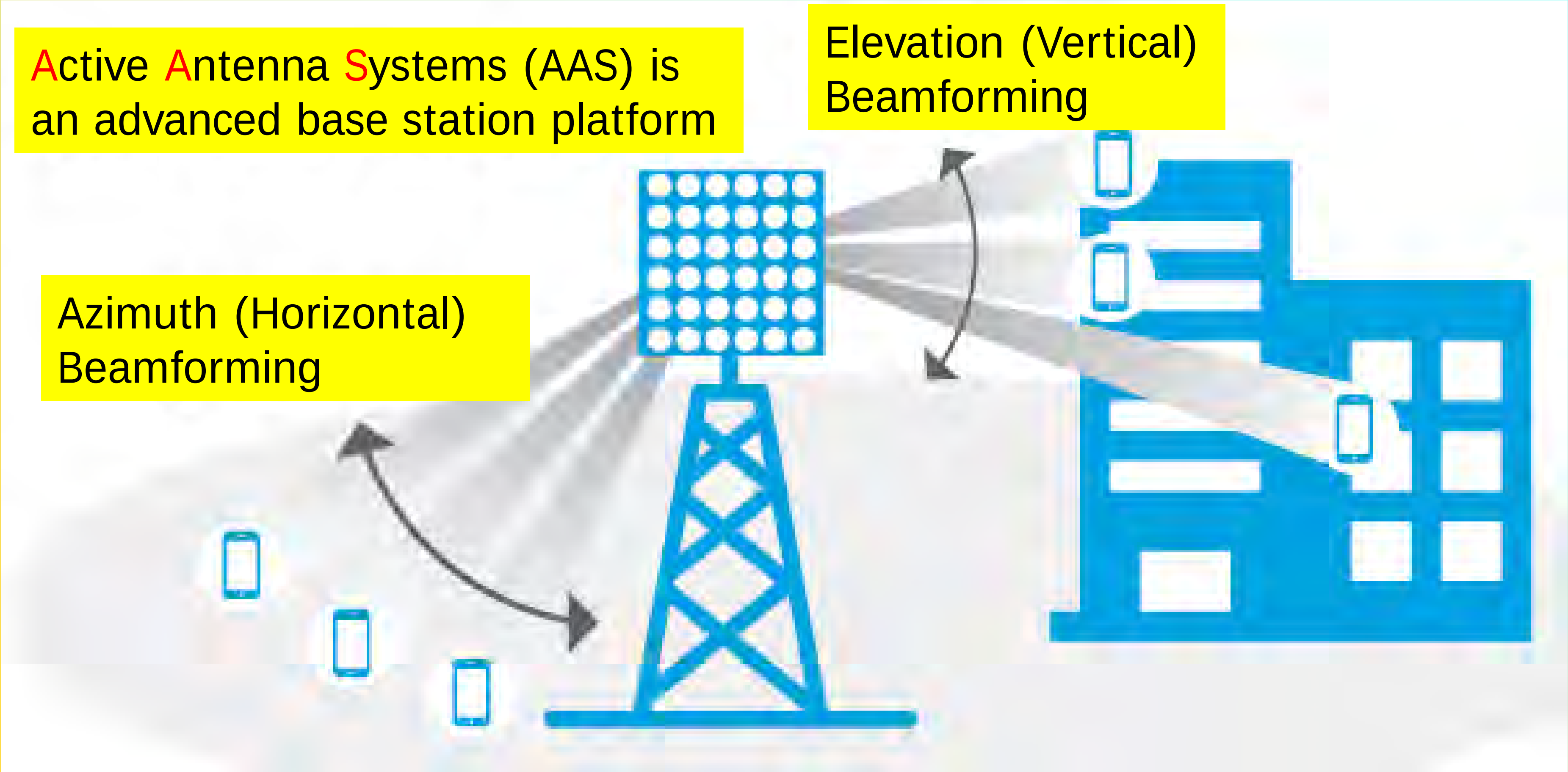


- Transmitter and receiver have more than one antenna
  - Utilizing the different paths
  - Selects path based for improvements in
    - Data rate
    - Signal to noise (BER)
- Scheduler determines which antenna will most effectively reach each receiver

Note: Scheduler is a software program

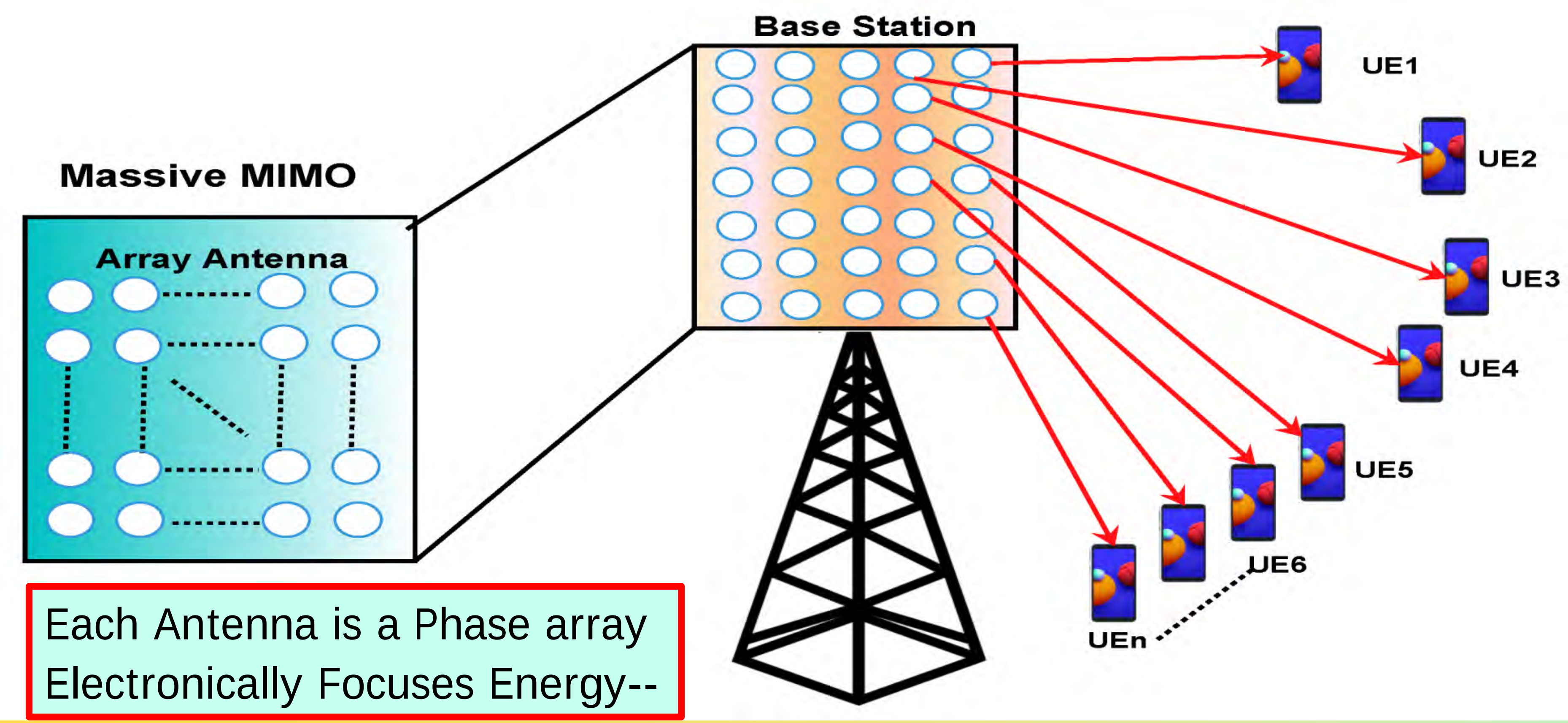
Massive MIMO: Beam Forming in the FR2 Band

- Massive MIMO scales to many antennas
- Vertical and Horizontal beam forming
  - Used for FR2 Frequencies: Small antenna size
- Uses Phase Array technology in the phone to focus beam



Geographic region divided into Cells

- Phase Array Antenna Focuses Energy
- Large Numbers of users served simultaneously
- Shrinking cell size increases capacity



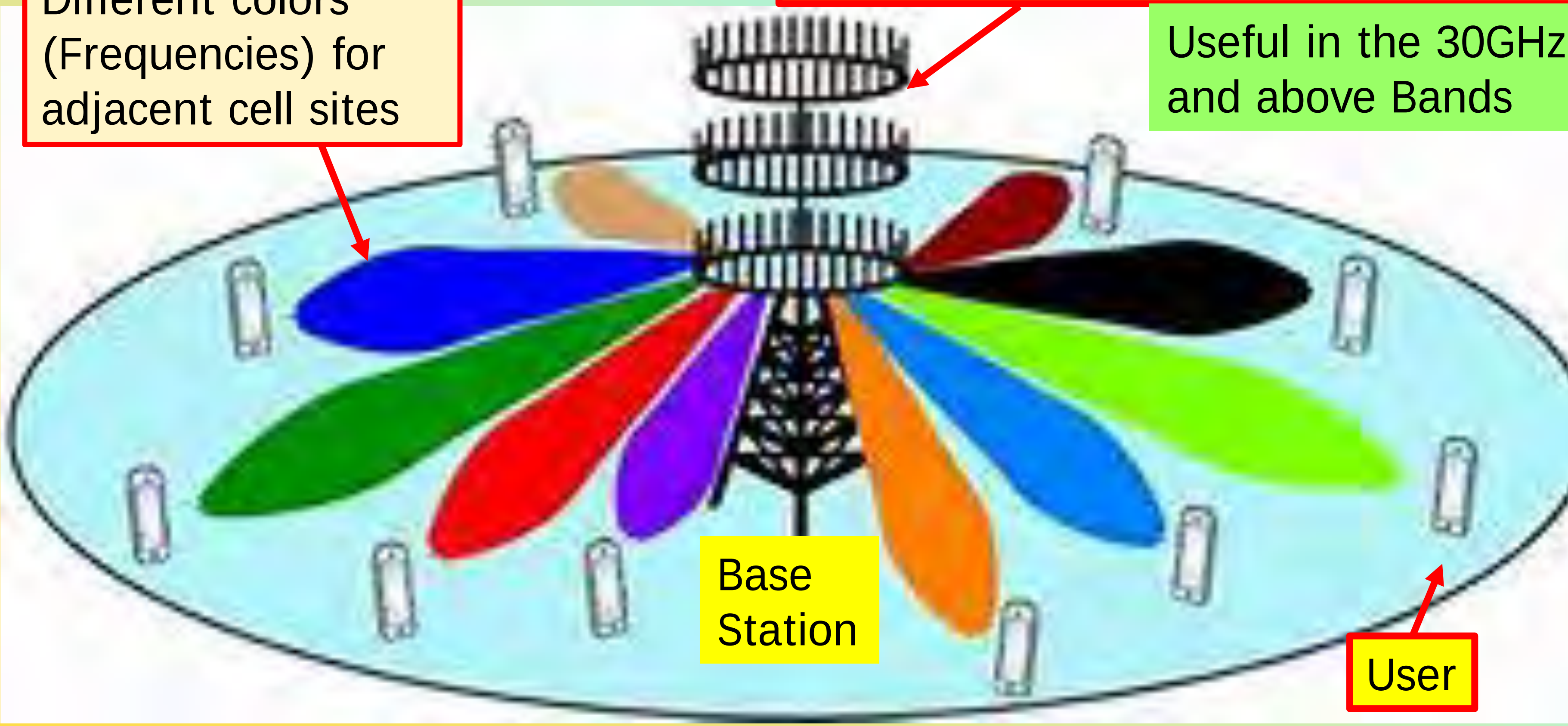
Each Antenna is a Phase array
Electronically Focuses Energy--

Massive MIMO
Frequency Reuse

Large Antenna Array at the base station
- Enhances the throughput
- Support a large number of users
- Spatial reuse
- Massive number of antennas: Typically > 100

Note:
Different colors (Frequencies) for adjacent cell sites

Useful in the 30GHz and above Bands



5G
Looking Behind the Curtain
Signal Transmission & Reception

02-06: Next Generation 6G: ≈ 2030

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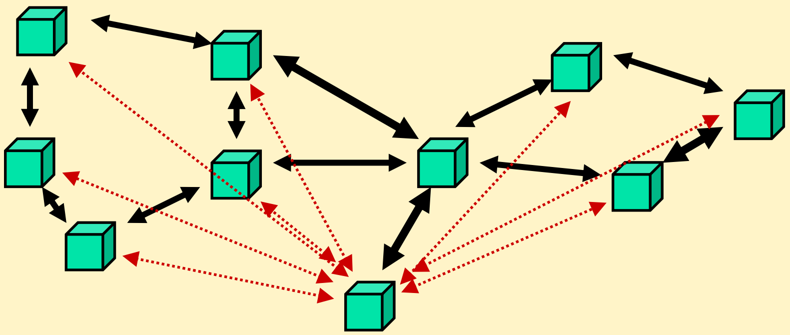
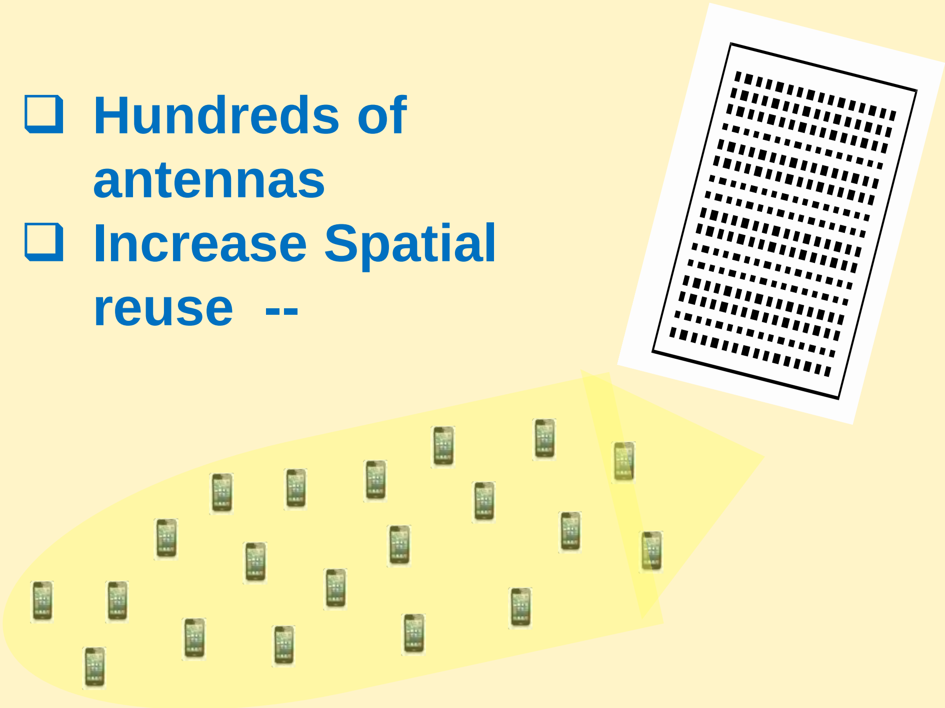
6G In Development

- 5G is still being rolled out
- 6G networks are expected to be
  - Faster
  - Increased bandwidth
- Planned for 2030

- Direct User-to-User communications
- Needed for self driving autos

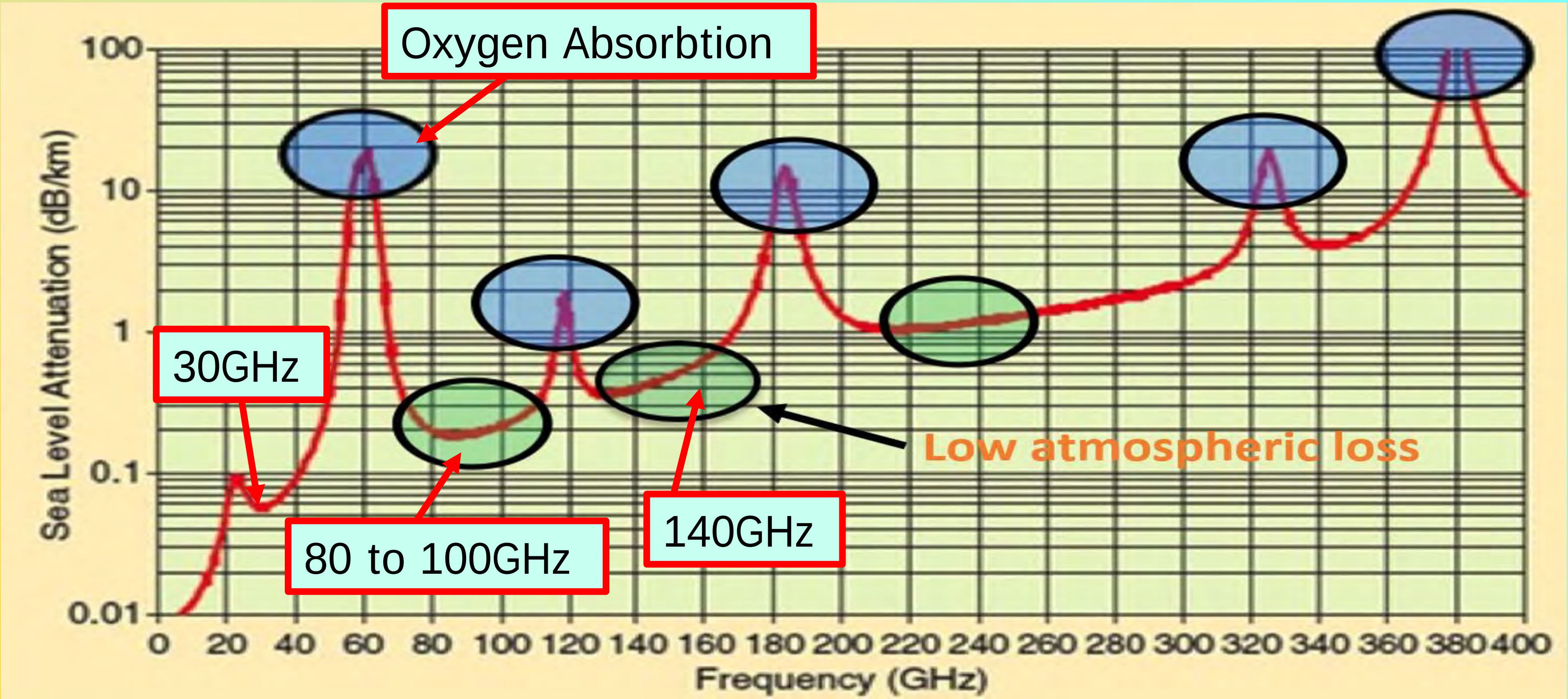


- **Hundreds of antennas**
- **Increase Spatial reuse --**



Frequencies from 100 GHz to 3 THz

- ❑ Extreme focus on Short-range Communication
- ❑ Extremely High Radio Density
- ❑ Flexible decentralized operation
  - ❑ Peer-to-Peer



End of Lecture
Part 2