5G: Looking Behind the Curtain:
Signal Transmission & Reception Techniques

Part 1

Topic 01:	Early Wireless Communications 0G to 3G
Topic 02:	Transitioning to 4G and 5G
Topic 03:	Signal Routing 3G to 4G/5G

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Howard Hausman received his MSEE degree from Polytechnic University/Tandon School of Engineering, NYU where he was an Adjunct Professor. He is currently President/CEO of RF Microwave Consulting Services and an Adjunct Professor at Hofstra University. Formerly Mr. Hausman was CTO and VP of Engineering, before being appointed President/CEO of MITEQ Inc., a world renown microwave engineering company with approximately 500 employees. He has designed hardware, wrote papers and lectured on microwave systems and components for Satellite Communications, Space Systems, Radar and Reconnaissance systems. Howard Hausman is a recipient of an NYU Distinguished Alumni Award, the IEEE LI Alex Gruenwald Award "For outstanding contributions to enhance the knowledge of the IEEE LI Section members", and a NASA Award for work on the Mars Landing System. Mr. Hausman is currently the Chairman of the IEEE LI Communications Society and was selected to review papers for the IEEE MIT Undergraduate Research Conference. Mr. Hausman was awarded a patent "Measuring Satellite Linearity From Earth Using A Low Duty Cycle Pulsed Microwave Signal". He also authored a Microwave Engineering textbook "Microwave Power Amplifier Design with MMIC Modules" published by Artech House, Boston and London.

Microwave Power Amplifier Design With MMIC Modules

by Howard Hausman

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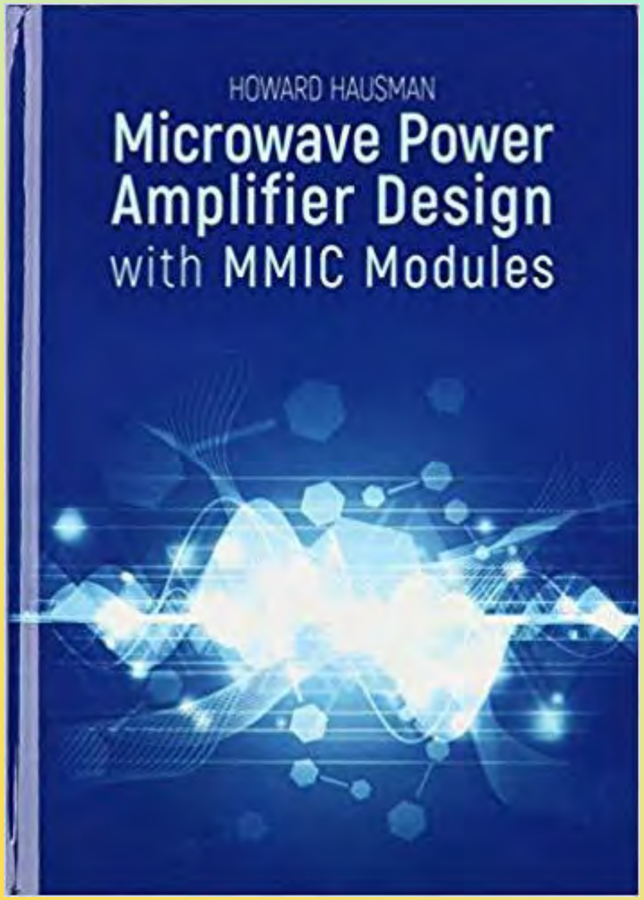

Published by Artech House
Boston, MA & London, UK
Copyright: 2018 / Pages: 384
ISBN: 9781630813468

Part One: Useful Microwave Design Concepts -- Lumped Components in RF and Microwave Circuitry. Transmission Lines. S-Parameters. Microstrip Transmission Lines. Circuit Matching and VSWR. Noise in Microwave Circuits. Non-Linear Signal Distortion. System Cascade and Dynamic Range Analysis.

Part Two: Designing the Power Amplifier -- Defining the Output Power Requirements for a Communication Link and Other Wireless Systems. Parallel Amplifier Topology Enhancing SSPA Performance. MMIC Amplifier Modules for Use in Parallel Combining Circuits. Measuring and Matching the Impedance of High Power MMIC Amplifier Modules. Power Dividers and Combiners Used in Parallel Amplifier SSPAs. Power Amplifier Chain Analysis.

Part Three: Designing the Power Amplifier System -- RF Signal Monitoring Circuits. DC Power Interface with the RF Signal Path. SSPA DC Voltage and Current. Thermal Design and Reliability. Electromagnetic Interference (EMI).

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Part 2

Topic 04:	4G/5G Spectral Technologies
Topic 05:	Orthogonal Frequency Division Multiplexing (OFDM)
Topic 06:	MIMO: Multiple-Input Multiple-Output
Topic 07:	Vector Modulation
Topic 08:	Error Vector Modulation

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Topic 01: Early Wireless Communications 0G to 3G

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0G (Zero Generation Mobile System)

- Late 1940's
  - First radio telephone service was introduced
  - Designed for cars to the land-lines
- In the 1960's
  - Improved Mobile Telephone Service (IMTS)
  - Direct dialing from the mobile user --

1G Technology

- Introduced early 1990s
- Analog system
- Digital control link
  - Phone to cell site
- Advance Mobile Phone System (AMPS) Allows user to make voice calls in 1 country
- FDMA (Frequency Division Multiple Access) --

Shoe Box Size Phone

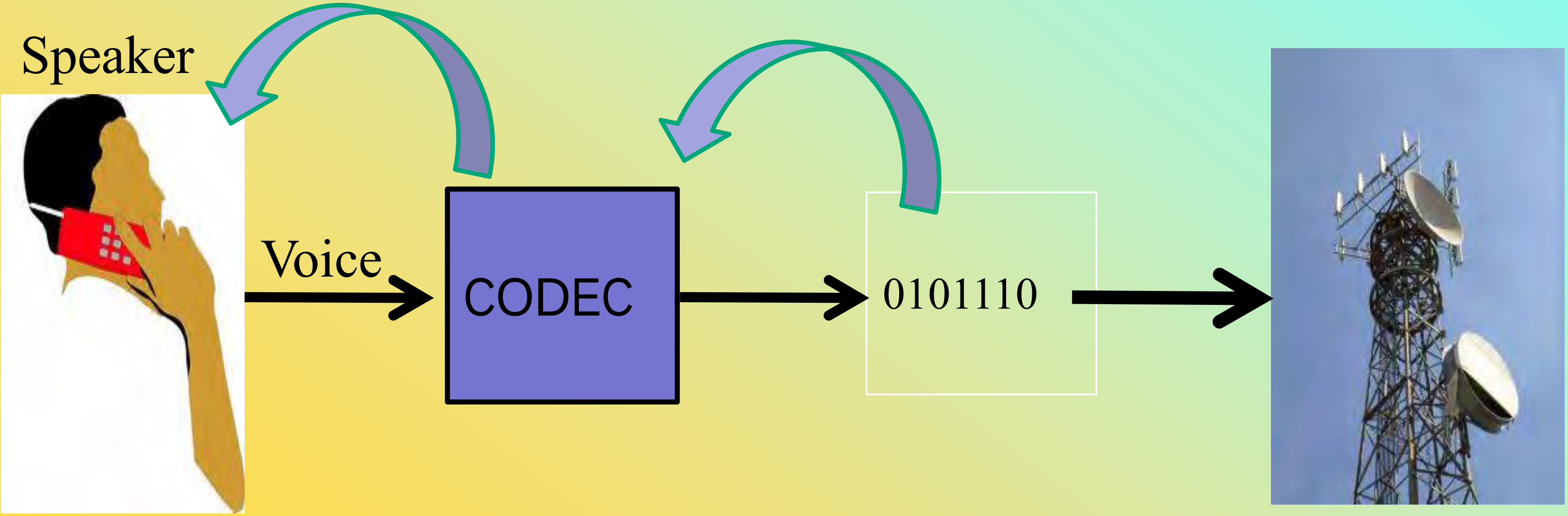
Region	Frequency (MHz)	Channel Spacing (kHz)	No. of Channels	Modulation	Data Rate (kbps)
USA	824-849 869-894	30	832	FM	10
Europe	890-915 935-980	25	1000	FM	8
UK	872-915 917-950	25	1240	FM	8

2G Technology

- Fielded in the late 1990s.
- Digital Voice transmission
- Speeds up to 64kbps.

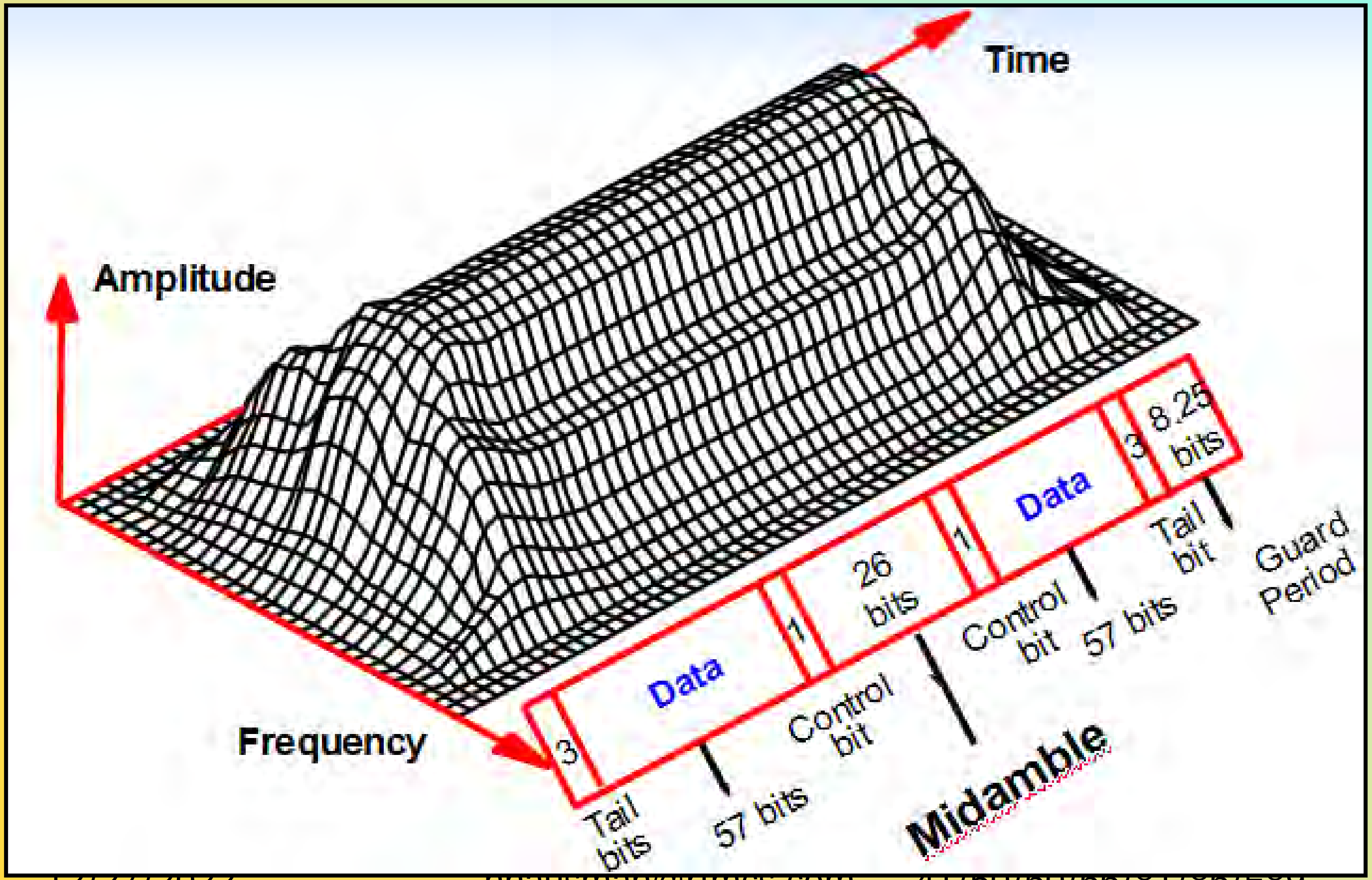
- Introduction of SMS –"Short Message Service"

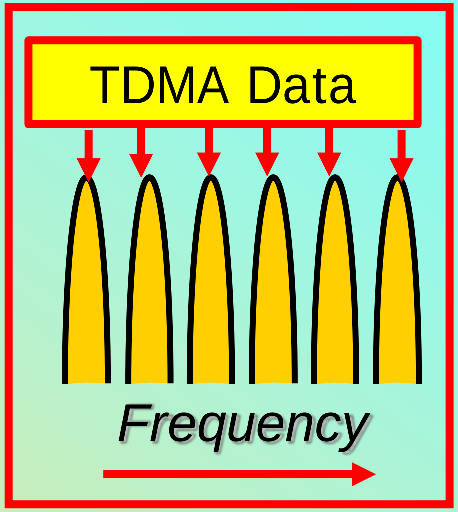
- Translated data from digital to analog and vice versa (CODEC)
  - Codings and Decoding digital data
- Voice ➔ Digital data can be compressed ➔ Analog Voice --



Common 2G Technology

- TDMA: Time Division Multiple Access
- GSM: Global System for Mobile communication
  - GSM was originated in Europe
  - Used in most of the world outside North America
  - GSM is a combination of FDMA and TDMA --





2.5G Technology: Implemented 1999

- Higher capacity packet data
- MMS: Multimedia Message Service)
  - 2G: Introduction SMS –"Short Message Service"

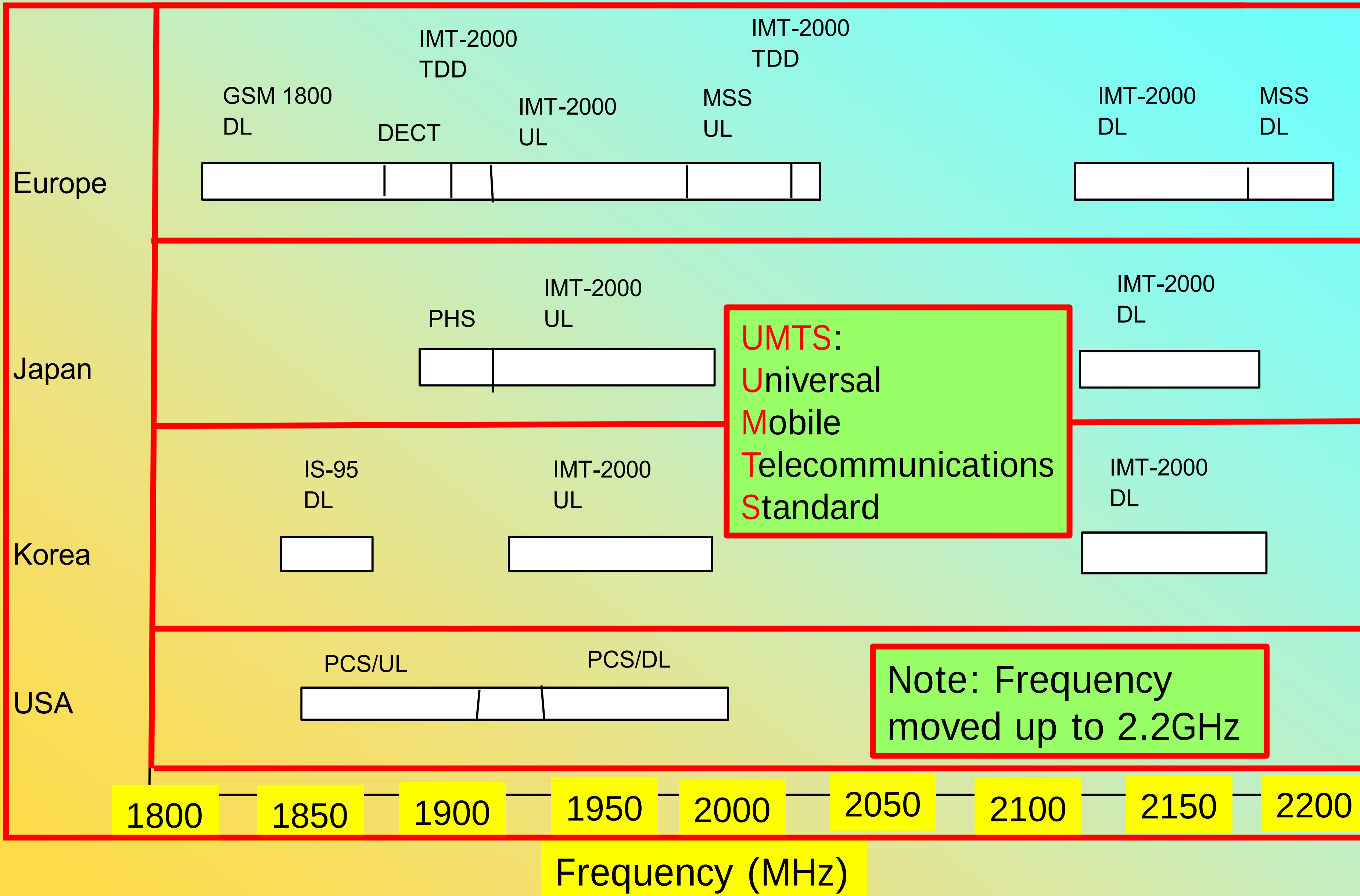
- EDGE: Enhanced Data for GSM Evolution
  - Global System for Mobile communication
- Data bandwidth: 384kbps
- TDMA and CDMA implemented
  - CDMA: Code Division Multiple Access
  - Spread Spectrum Communications
  - Signal overlap
  - Need a code to separate users --

3G Technology

- 3G wireless system
  - UMTS: Universal Mobile Telecommunications Standard
- Transmission speeds up to 2Mbps
- Introduction in 2001

- CDMA –Code Division Multiple Access
- E-mail, PDA, Internet, on-line shopping, banking, games, etc.
- Global roaming
  - Phones worked on multiple system --

UMTS: Universal Mobile Telecommunications Standard (3G)



Comparing 3G and 4G

Attribute	3G	4G
Major Characteristic	Predominantly voice Data as add-on	Converged data and Voice over IP (VoIP)
Network Architecture	Wide area Cell based	Integrated Wireless LAN (WiFi), Blue Tooth, Wide Area Networks (WAN)
Frequency Band	1.6 - 2.5 GHz	2 – 6 GHz
Component Design	Optimized antenna; multi-band adapters	Smart Switched multi-band antennas
Bandwidth	5 – 20 MHz	100+ MHz
Data Rate	385 Kbps - 2 Mbps	20 – 100 Mbps
Access	CDMA2000	CDMA or OFDM

OFDM: Orthogonal Frequency-Division Multiplexing

Moving to 4G Technology

- Wireless technology to 3G was an evolution from wired communication
- 4G moved wireless from the standard telephone structure to the Internet Protocol (IP) structure
- Scaling up to hundreds of megabits and even gigabit-level speeds.
- 4G was on a multi-release evolutionary path
  - Referred to as Long Term Evolution (LTE) --

Long Term Evolution (LTE)

- LTE uses Orthogonal Frequency Division Multiplex (OFDM) modulation
- Adopted as the generalized cell-phone communications service
- Uses multiple frequency bands
  - Not the same from carrier to carrier.
- Standard bandwidths of 1.4, 3, 5, 10, 15, and 20 MHz
  - 5- and 10-MHz widths are the most common --

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Topic 02: Transitioning to 4G and 5G

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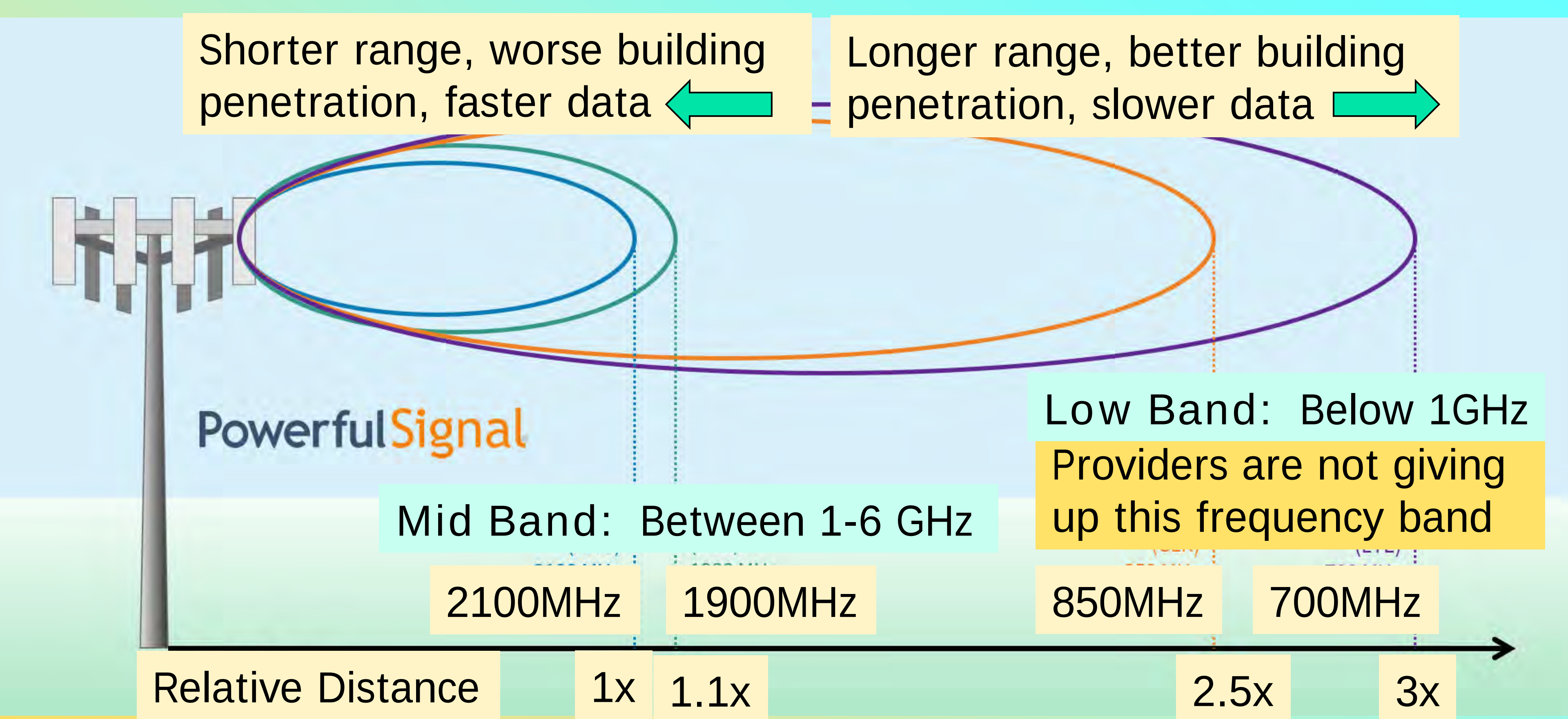
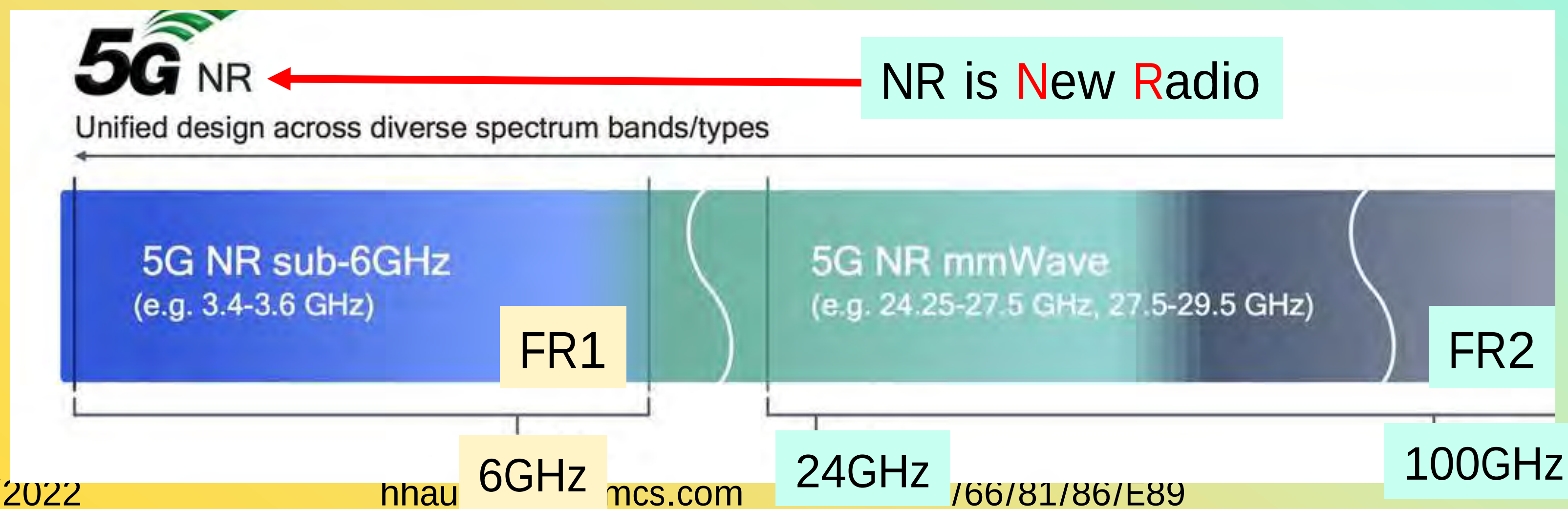
4G LTE Frequency Bands

4G LTE		Carriers			
Frequency (MHz)	**Band Number**	**Verizon**	**AT&T**	**T-Mobile**	**Sprint**
600	**71**			Yes	
L700	**12,17**		Yes	Yes	
L700	**29**		Yes		
U700	**13**	Yes			
800	**26**				Yes
850	**5**	Yes	Yes	Yes	
1700/2100	**4,66**	Yes	Yes	Yes	
1900	**2,25**	Yes	Yes	Yes	Yes
2300	**30**		Yes		
2500	**41**				Yes

Note: 5G devices also use 4G Freqeuncies


Shorter range, worse building penetration, faster data
Longer range, better building penetration, slower data
PowerfulSignal
Low Band: Below 1GHz
Providers are not giving up this frequency band
Mid Band: Between 1-6 GHz
2100MHz
1900MHz
850MHz
700MHz
Relative Distance
1x
1.1x
2.5x
3x


5G NR
NR is New Radio
Unified design across diverse spectrum bands/types
5G NR sub-6GHz
(e.g. 3.4-3.6 GHz)
FR1
5G NR mmWave
(e.g. 24.25-27.5 GHz, 27.5-29.5 GHz)
FR2
6GHz
24GHz
100GHz

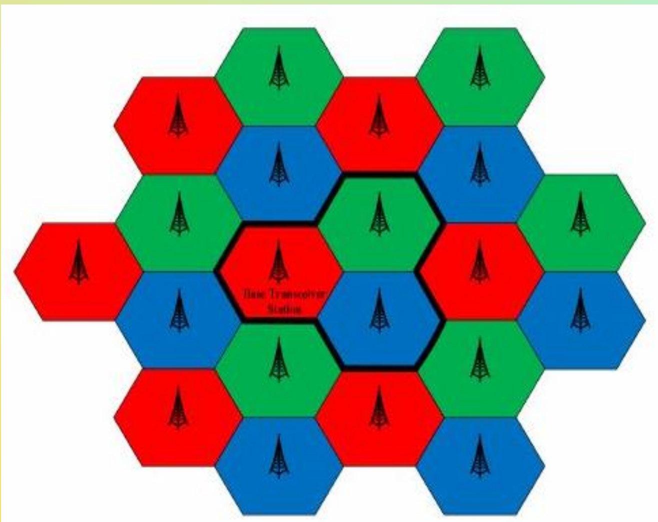
4G to 5G Technology

- 4G moved wireless from the standard telephone structure to the Internet Protocol (IP) structure
  - Direct Connection to Packet Switching
- 5G Below 6GHz (FR1) enhances 4G
  - Higher operating frequencies to over 4GHz
    - Higher Frequencies ➔ More bandwidth
  - Improves speed, coverage, applications and reliability
  - Smaller Antenna footprints
    - Spatial reuse
    - Divides geographical coverage into smaller segments
  - More complex modulation techniques
    - Higher level Quadrature Amplitude Modulation (QAM) constellations
- 5G above 6GHz (FR2) is a new concept --

Cellular Technology: Spatial Reuse

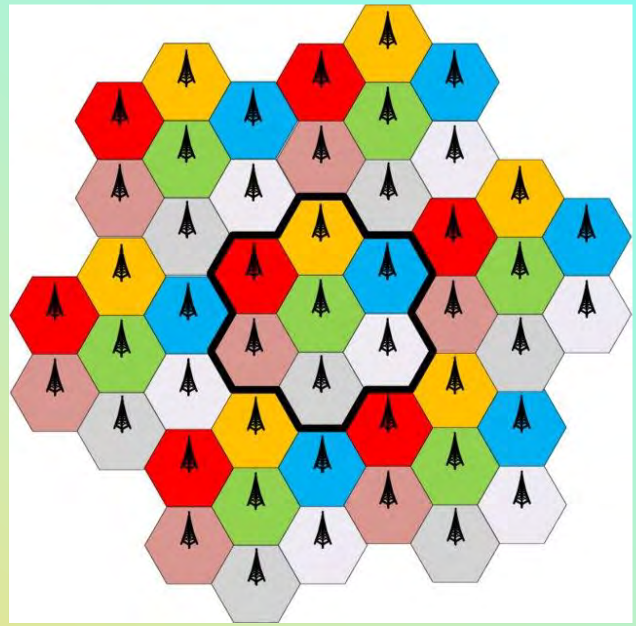
- Adjacent "cells" use different frequencies

Cells of different colors use different frequencies



Frequency reuse pattern with 3-cell clusters

Available Spectrum



- Frequency reuse pattern with 7-cell clusters
- Distance between frequencies are greater

5G Frequency Bands (FR1 & FR2)

Frequency Range	FR1 < 6 GHz	FR2 24 to 52.6 GHz
CBW	100 MHz	400 MHz

CBW: Carrier Bandwidth

SCS: Single Carrier Spacing

CHBW: Chanel Bandwidth

Frequency range	SCS (kHz)	Min CHBW (MHz)	Max RB	Max CHBW (MHz)
FR1	15 (4G)	5	270	50
	30	5	273	100
	60	10	135	100
FR2	60 (5G)	50	264	200
	120	50	264	400

Faster Data

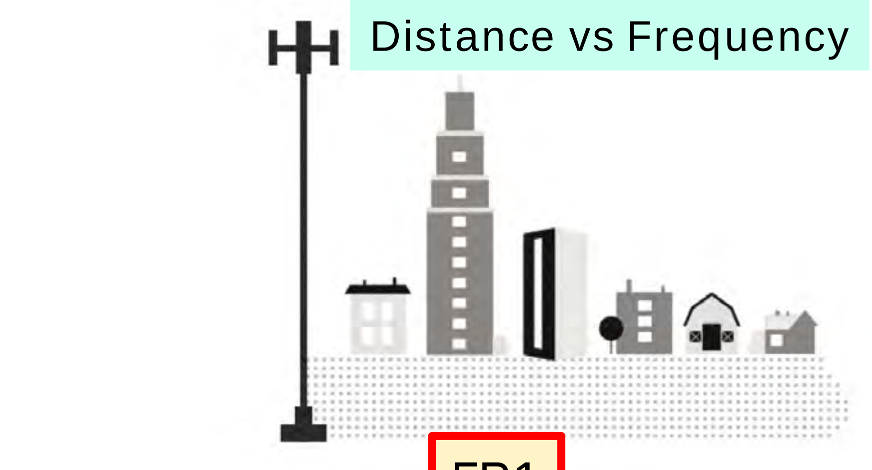
Flexibility

RB is Resource Block

5G is big on Acronyms

Higher Data rate

Note: FR2 increased BW



- Lower frequencies (700–800MHz) **penetrates** solid structures much better than high frequency (2500MHz+ range)
- Higher Frequencies have higher loss in free space

FR1

Low Band:
- Below 1GHz
- Greater Range
- Not effected by obstacles

Mid Band:
- Between 1-6 GHz
- Balance between speed and range

FR2

High Band:
- mmwave (24GHz–100GHz)
- Cover small area
- High Data Rates
- Can’t penetrate buildings

5G Frequency Bands

- **Verizon**

Band	Frequency	Band Type
n40	2.3GHz	Mid-band sub-6 GHz
n260	39GHz	mmWave
n261	28GHz	mmWave
n2, n5, n66	1900MHz, 850MHz, 1700-2100MHz	DSS with LTE

- **AT&T**

Band	Frequency	Band Type
n260	39GHz	mmWave
n5	850MHz	Low-band

- **T-Mobile**

Band	Frequency	Band Type
n41	2.5GHz	Mid-band sub-6GHz
n260	39GHz	mmWave
n261	28GHz	mmWave
n71	600MHz	Low-band

600MHz to 800MHz Bands are not going away

FR1 > GHz does not have widespread usage

Issues with 5G FR2 (>24GHz) mmWave Signals

- Currently, there are only a few carriers who are offering mmWave 5G to the masses
- Smaller the wavelength → More difficult for those signals to pass through obstacles such as
  - Trees
  - Walls
  - Buildings
- Antenna Gain is greater as frequency increases
  - Coverage Footprint decreases
- Transmit and receive using smaller antennas.
- Inter Site Distances (ISDs) range is few hundred meters
  - Same channel can be used repeatedly (Spatial Reuse)
  - Need Cell sights every block
- Applications in places like Restaurants, Sports Arenas and Shopping Malls --

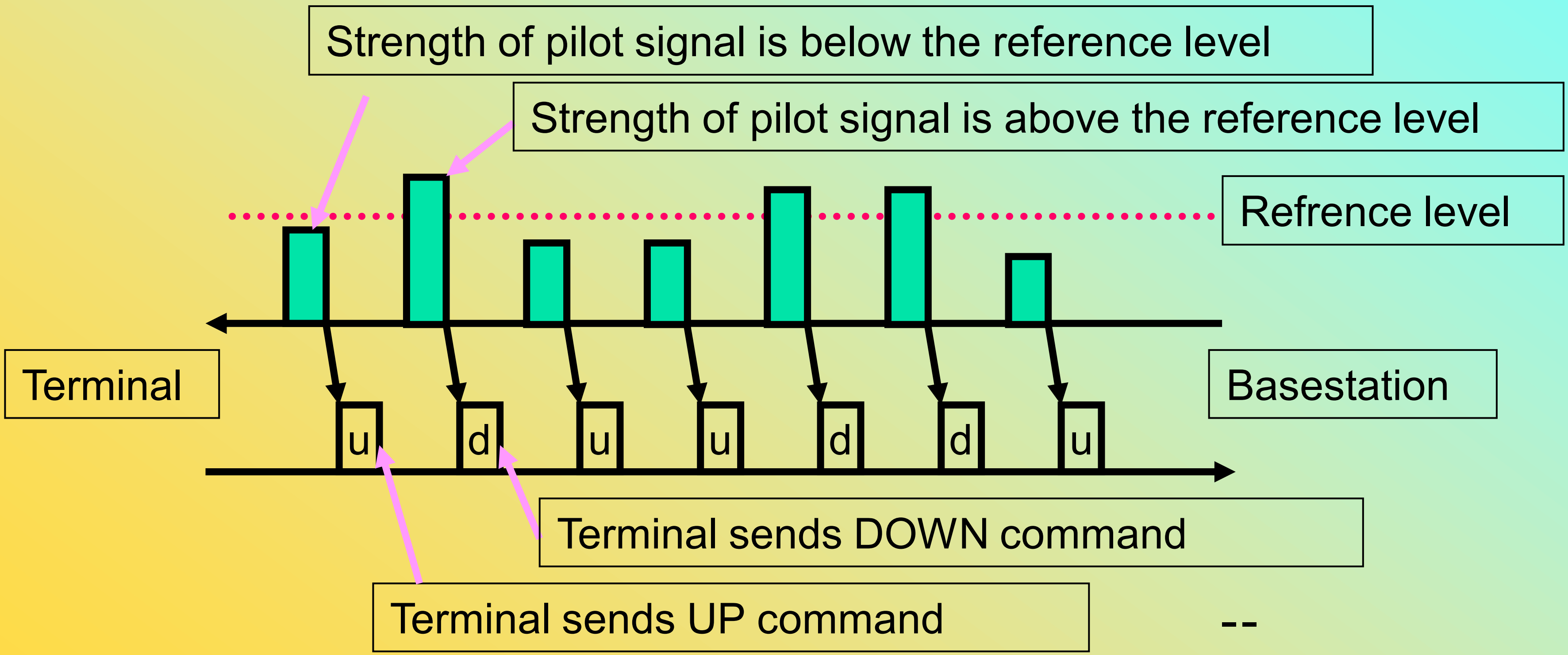
Power Control

- Power at the Base Station MUST have the same Spectral Density
- Base Station adjusts your phone transmit power

: Pilot Signal

u : Power Control Command

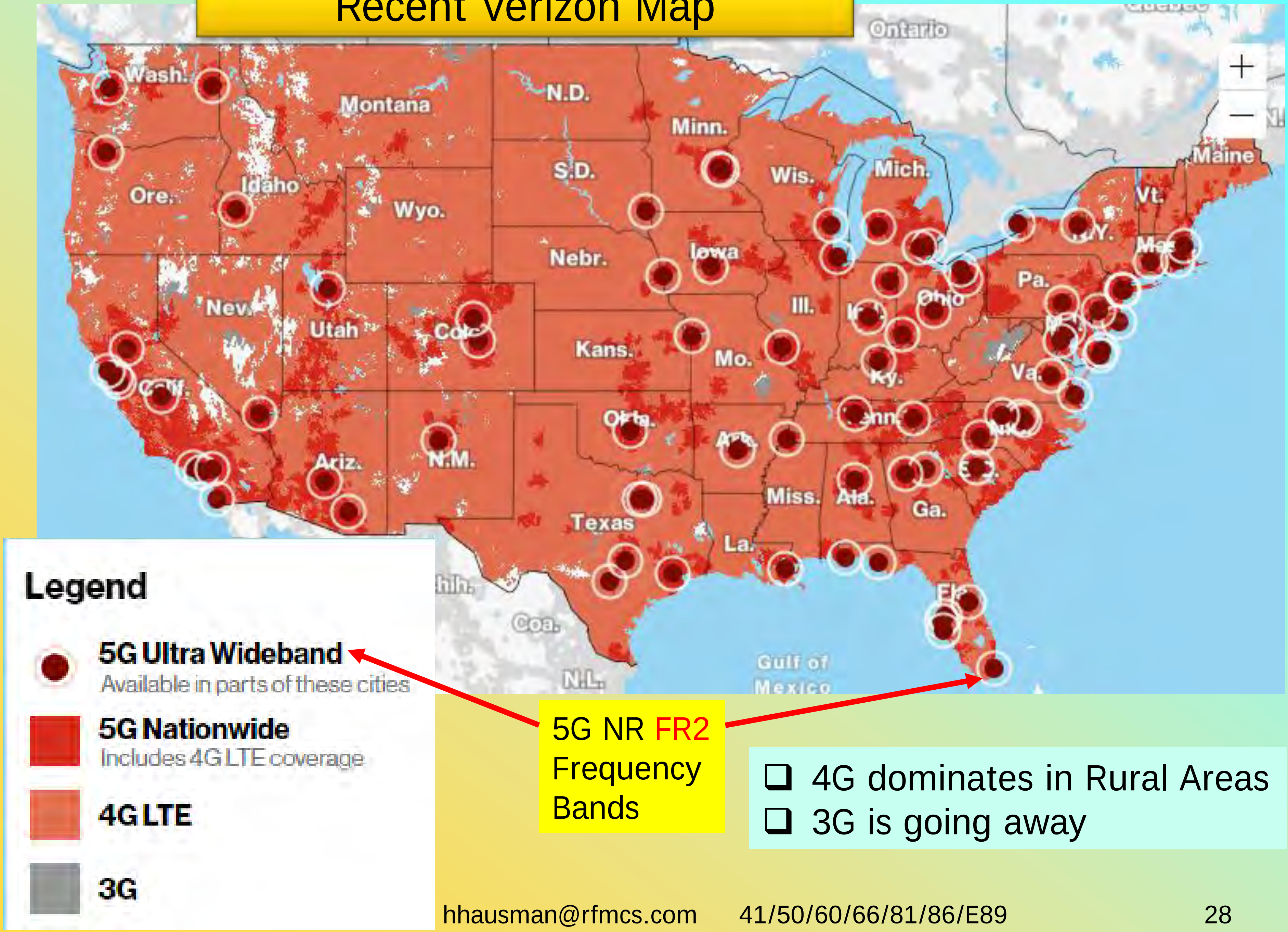
- Receiver controls the transmission power of transmitter in order to minimize the interference to other users.
- Required computation is negligible



Cell types		Deployment environment	Max. number of users	Output power (mW)	Max. distance from base station
5G NR FR2 Frequency Bands	Femtocell (10^{-15})	Homes, businesses	Home: 4–8 Businesses: 16–32	indoors: 10–100 outdoors: 200–1000	tens of meters
	Pico cell (10^{-12})	Public areas like shopping malls, airports, train stations, skyscrapers	64 to 128	indoors: 100–250 outdoors: 1000–5000	tens of meters
	Micro cell (10^{-6})	Urban areas to fill coverage gaps	128 to 256	outdoors: 5000–10000	few hundreds of meters
	Metro cell	Urban areas to provide additional capacity	more than 250	outdoors: 10000–20000	hundreds of meters
Wi-Fi (for comparison)		Homes, businesses	fewer than 50	indoors: 20–100 outdoors: 200–1000	few tens of meters

WiFi: 2.4 GHz and 5 GHz (some homes have repeaters)

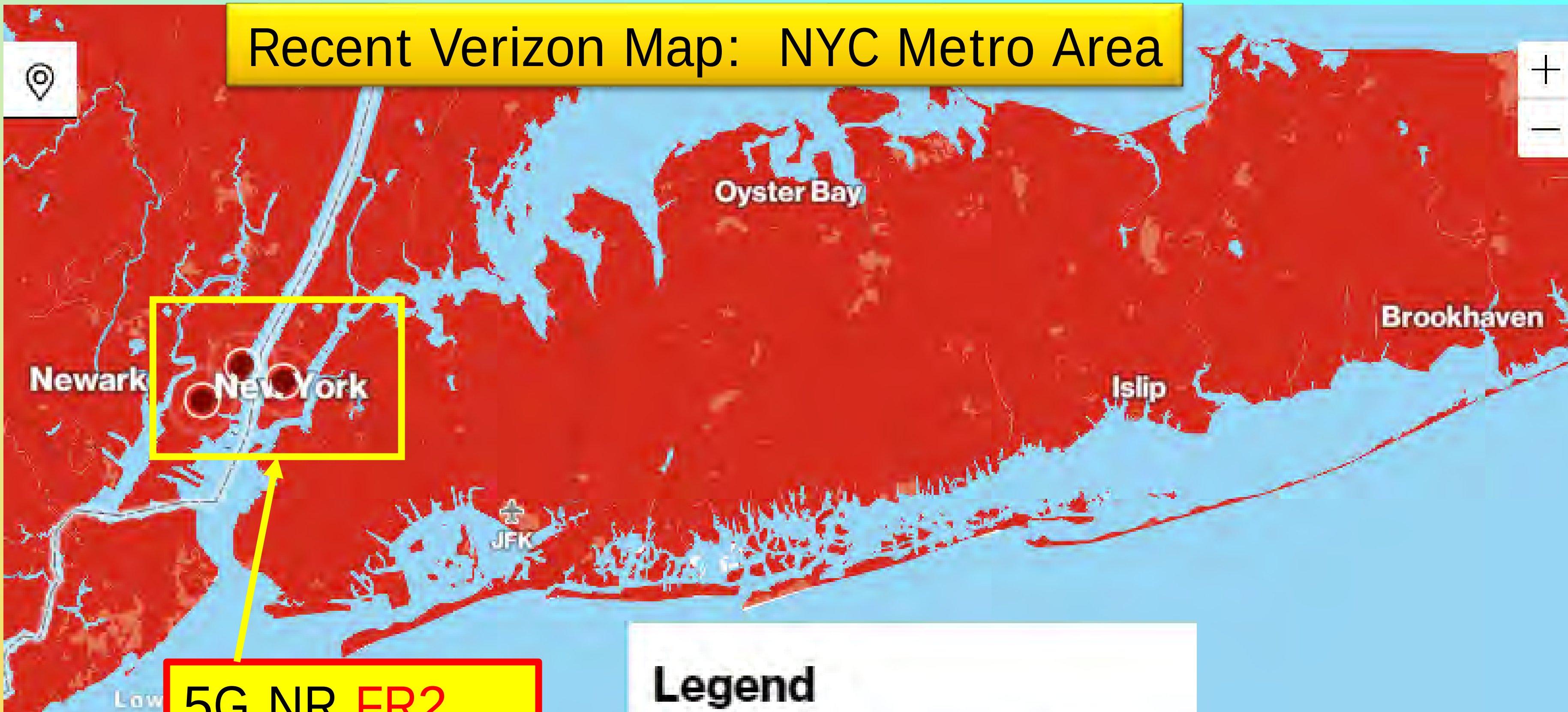
Recent Verizon Map



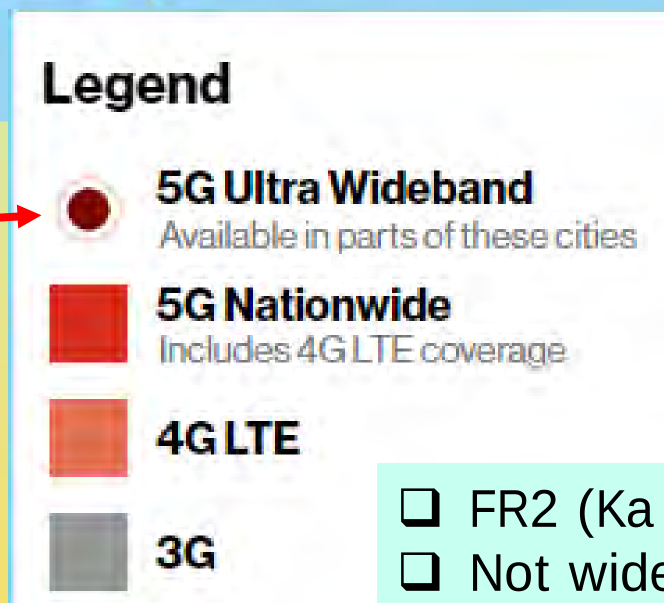
5G NR FR2 Frequency Bands

- 4G dominates in Rural Areas
- 3G is going away

Recent Verizon Map: NYC Metro Area



5G NR FR2 Frequency Bands



- ❑ FR2 (Ka Band, ≈ 30GHz)
- ❑ Not widely employed

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Topic 03: Signal Routing 3G to 4G/5G

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Network Architecture Evolution

- Two different switching technologies
  - Circuit switching
  - Packet switching

Telecomm Infrastructure (Circuit switching) → **IP-based Internet (Packet switching)**

2G → 3G → 4G & 5G

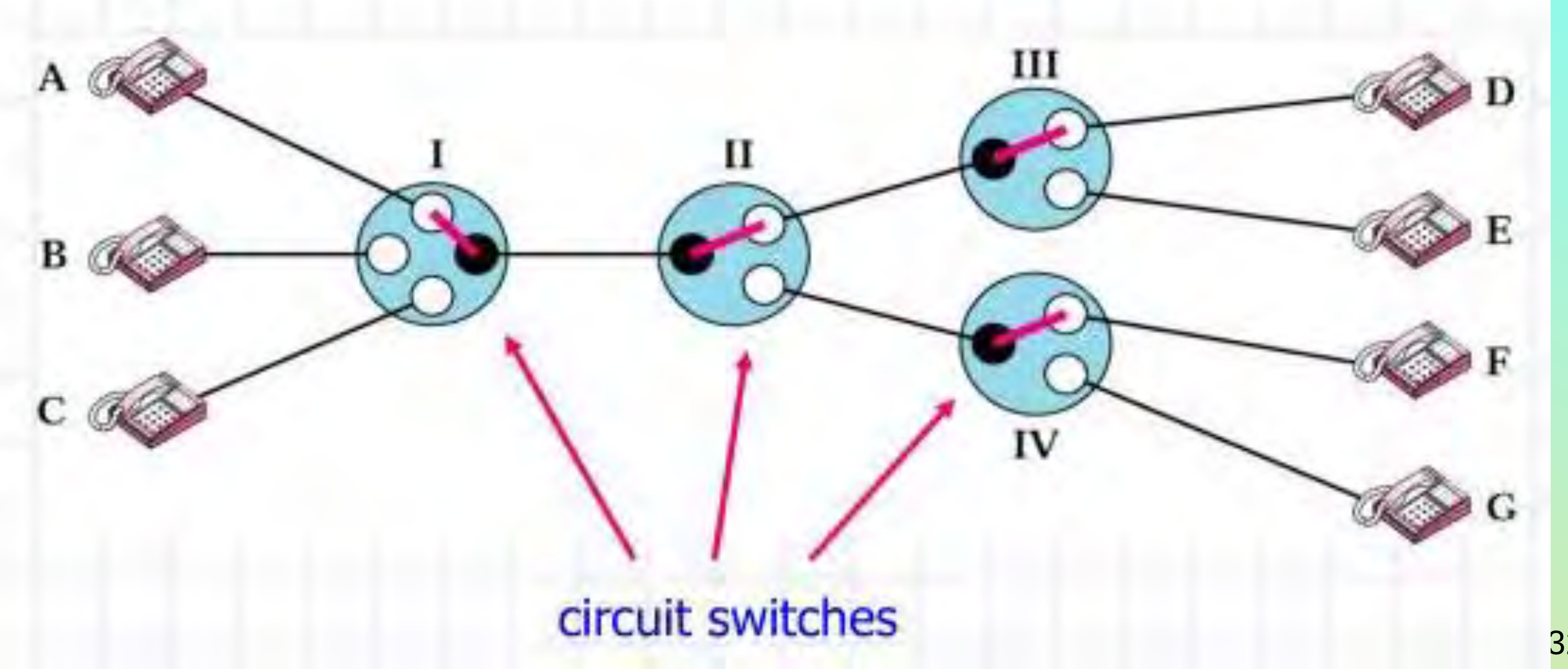
2G
- Circuit-switching for voice

3G
- Circuit-switching for voice
- Packet-switching for data

4G & 5G
- Packet-switching for everything
- IP-based --

Pre-4G Circuit Switching

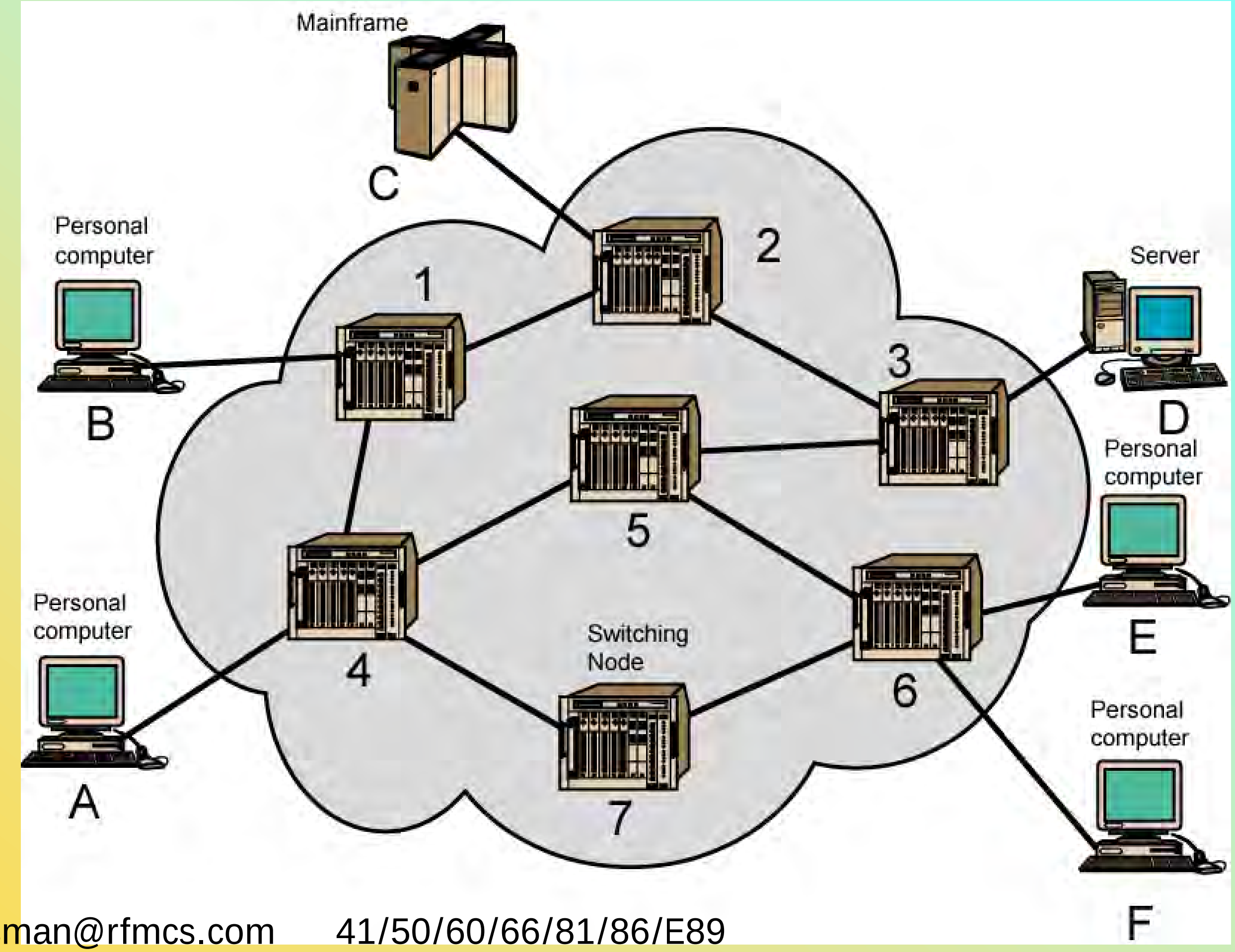
- Circuit switching was designed in 1878
- Direct Physical Connection
- Send telephone calls down a dedicated channel
- Channel remains open throughout the call
- Connection cannot be shared --



Circuit Switching

- Telephone message is not broken up.
- Message arrives in the same order as sent
- Excellent for data that needs a constant link from end-to-end

- Data routed by being switched from node to node --



Circuit Switching: Advantages/Disadvantages

Advantages

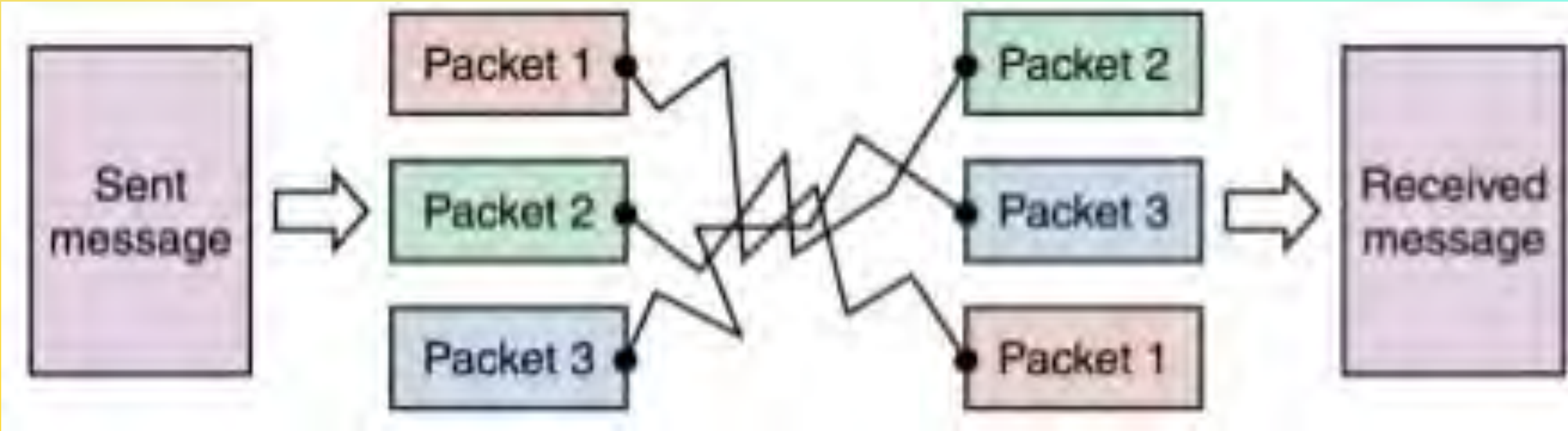
- Circuit is dedicated
  - No interference, no sharing
- Guaranteed the full bandwidth
- Guaranteed quality of service

Disadvantages

- Inefficient
  - If no data is being sent, line remains open.
- Takes a relatively long time to set up the circuit.
- During a disaster
  - Network may become unstable or unavailable.
- Developed for voice traffic rather than data

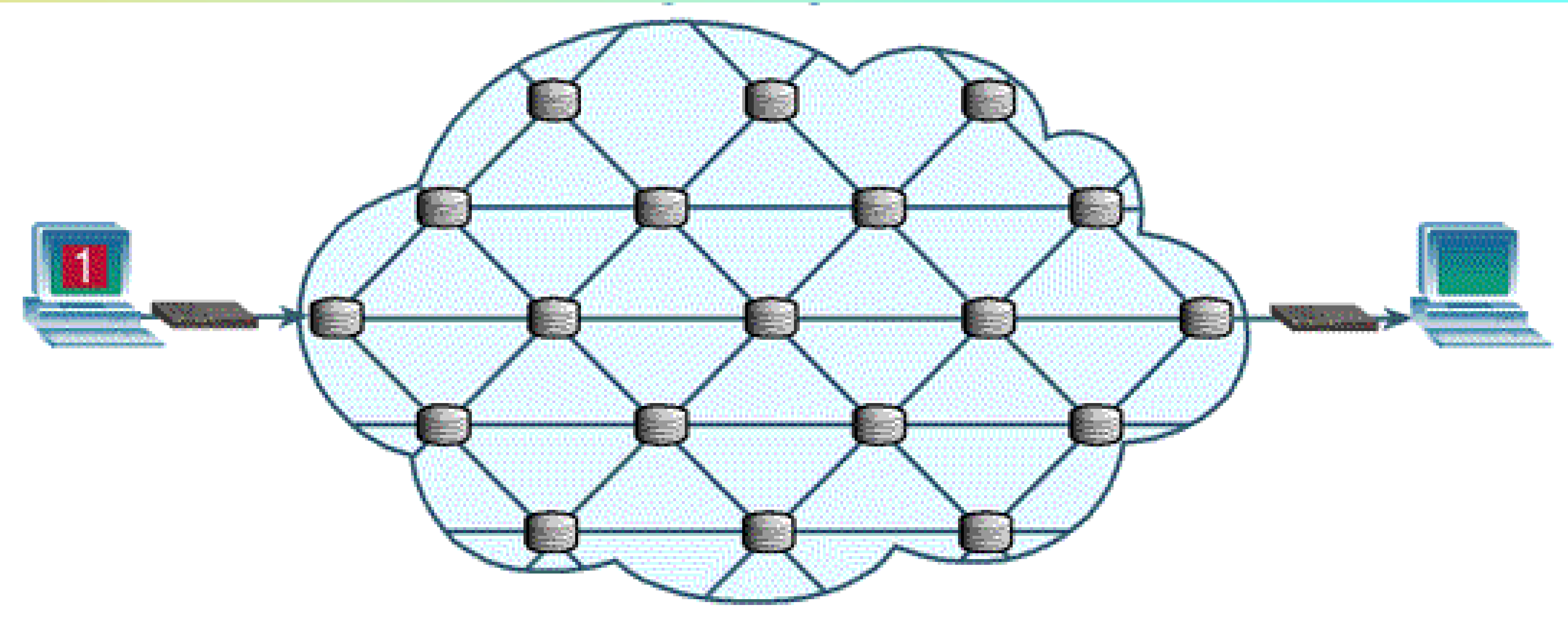
Packet Switching: 4G/5G

- Message gets broken into small data packets
- 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)



- ❑ Packets are received out of order
- ❑ 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
- One packet also contains details
  - How many packets should be arriving

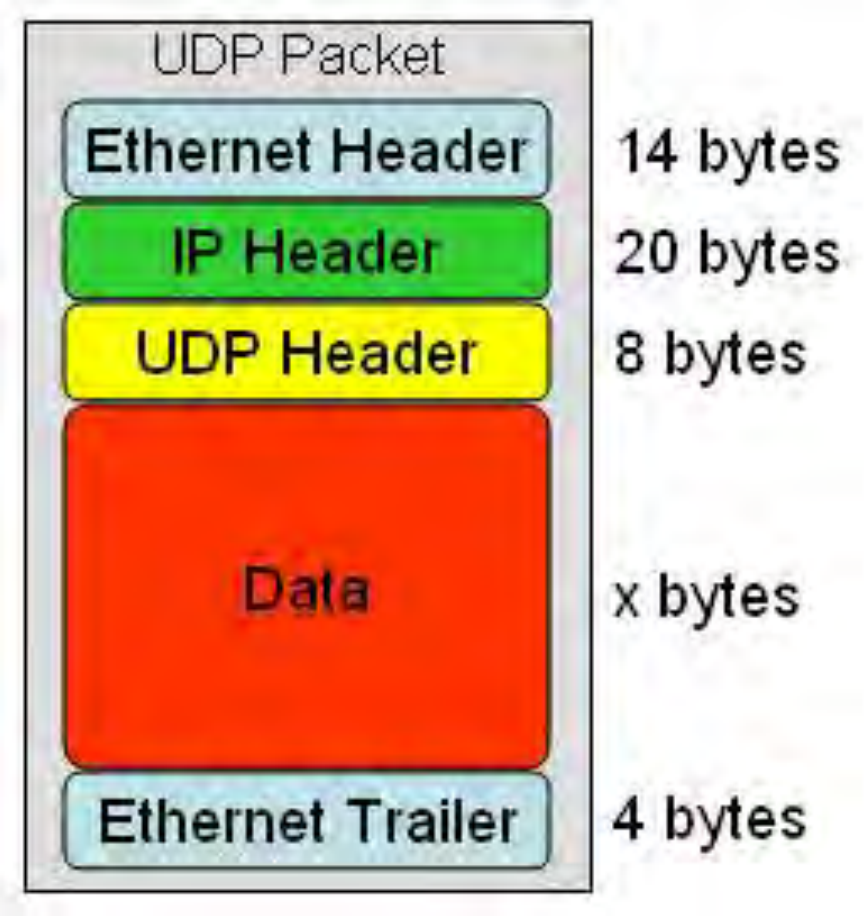
Packets are Stored and Forward

- 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 --

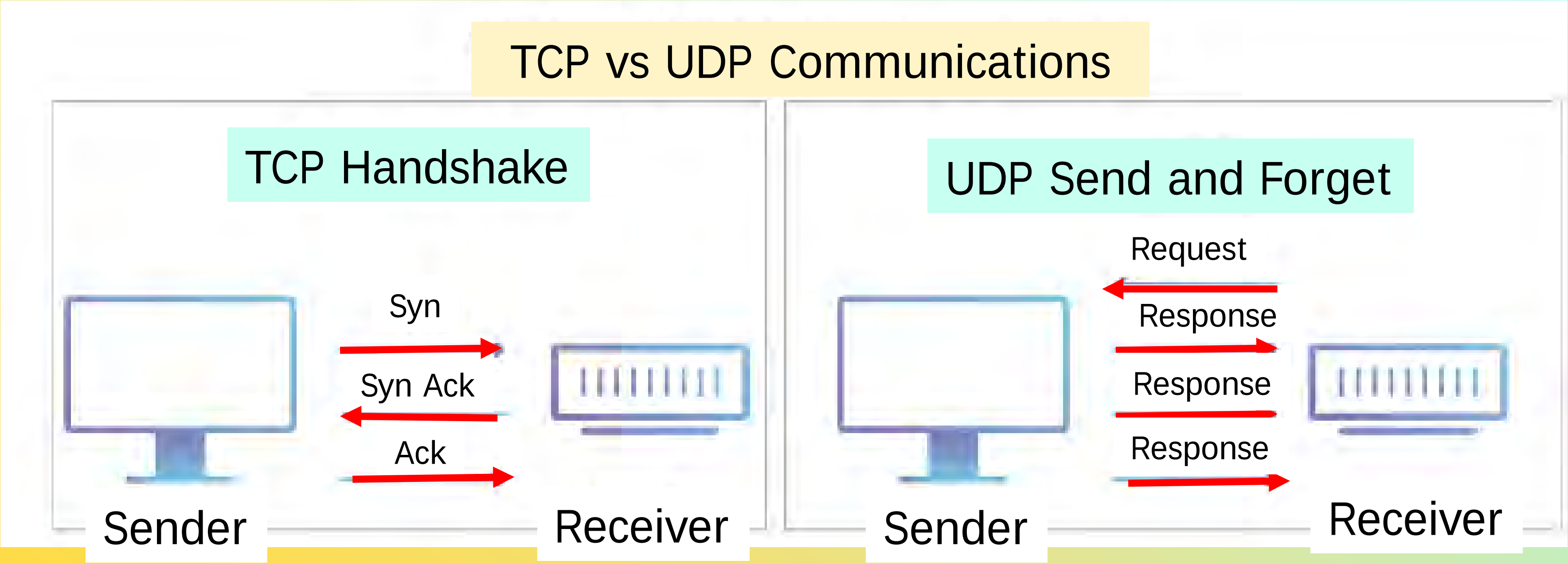
UDP: User Datagram Protocol
IP: Internet Protocol



Two principal 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: 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
  - Data Rates are a function of the number of users
- Data packets can get lost or become corrupted
- Protocols are imbedded for a reliable transfer
- Can lose frames due to the way packets arrive out of sequence --

End of Lecture Part 1