ECE-60022
Wireless Communications Networks

An Introduction

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2G/3G/4G/5G?

- Overall the past 20 years, wireless networks have seen dramatic changes over several generations of technology
- In comparison, the basic paradigm of the Internet (i.e., TCP/IP) remains the same since 70s/80s
- What are the main drivers for these changes? What are the main technologies in each generation of wireless networks? What lessons have we learned?

"Network" vs. Point-to-Point Communications

- Prior to wireless networks, successful systems have been built that utilize the capability of send information over wireless signals
  - Radio, Television, etc.
  - AM (amplitude modulation), FM (frequency modulation), phase modulation, etc.
  - Utilize PHY layer that is point-to-point or point to multi-point
- "Network" is inherently different
  - It must be able to support multiple point-to-point connections simultaneously

Multiple Access

- How many users should be allowed to transmit simultaneously on a single unit of resource?
- How to handle the interference between then?
- How to allocate resources across users to meet their possibly diverse application requirements?
- What is the “capacity” of the network as a whole?

As we review the advance of wireless networks, let us pay close attention to how each generation of wireless networks address these questions

There is perhaps one concept that represent the importance of multiple access most prominently, i.e., **cellular**

First Mobile Telephone Service (0G?)

- Introduced in the U.S. by AT&T (1946)
- Used to interconnect Mobile Users (usually in automobiles) to the public telephone land-line networks.
- Systems used a single powerful transmitter from the base-station to cover up to approx. 50 miles radius.
- Systems were based on Frequency Modulation (FM) transmission.
- Each frequency channel used 120KHz of spectrum to transmit a voice connection with an effective bandwidth of only 3KHz

First Mobile Telephone Service (cont'd)

- Advanced systems for their time but clearly very inefficient.
  - The first system can accommodate only 40 users at any time.
- In the meantime, demand for mobile telephone service grew very quickly and stayed ahead of available capacity in many large cities.
- Offered traffic load >> available capacity
- Hence, service was terrible (blocking probabilities were as high as 65%, or even higher!)

  ⇒ Usefulness of mobile telephone decreased as users found that blocking often prevented them from getting a circuit during peak periods.

First Mobile Telephone Service (cont’d)

Telephone companies soon realized that for true mobile services to develop:

- Large blocks of spectrum would be needed to satisfy the demand of users, especially in urban areas.
  - But the amount of usable spectrum is limited!

- Significant improvements need to be made in the usage of the available spectrum.

Advent of Cellular Systems

- In the mid-1960s, Bell Systems introduced the Improved Mobile Telephone Service (IMTS) with
  - enhanced features such as: Direct Dialing, Automatic Trunking, Full-duplex service
  - a reduction in FM channel BW from 120Khz to 25-30KHz.
- However, the capacity problem is not fundamental solved.
- In the late 1960s and early 1970s, work began on the first cellular telephone systems.

Pre-Cellular Days

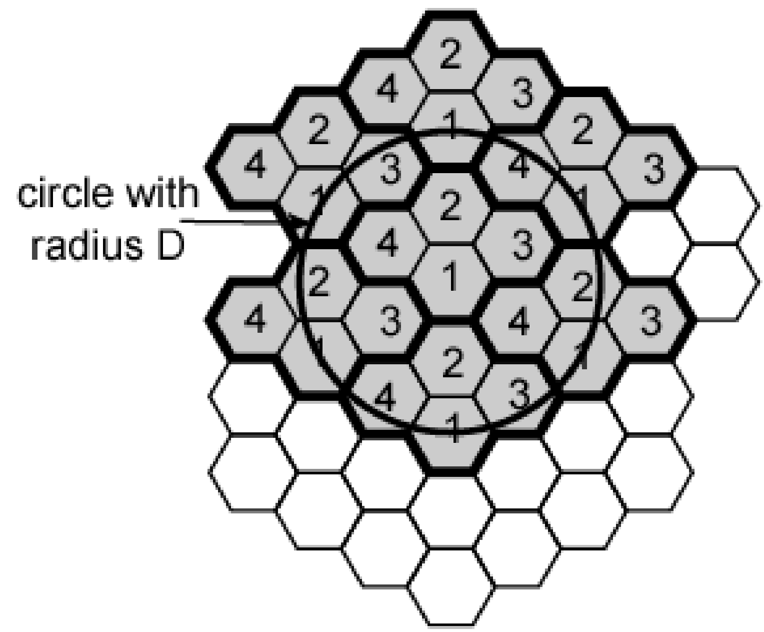
- As discussed earlier, the traditional approach to mobile radio involved setting up a high-power transmitter located on top of the highest point in the coverage area.

- This allows line-of-sight transmission to a large distance (as much as 40-50 miles away for a very high base-station antenna).
  - Similar to TV

- However, the result was that few available radio channels were locked up over a large area

Cellular Systems and Frequency Reuse

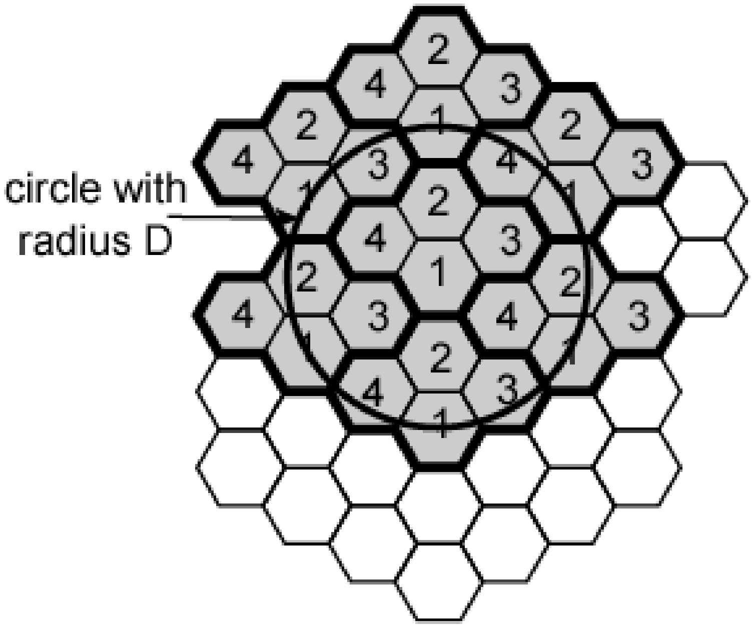
- The cellular concept handles the coverage problem differently
- Use a large number of low power transmitters, each designed to serve only a small area called a cell.
- Frequencies were not reused in adjacent cells to avoid interference
- However, the wireless spectrum is reused among those cells that are further away.



(a) Frequency reuse pattern for N = 4
(Source: Prof. Vladimir V. Riabov)

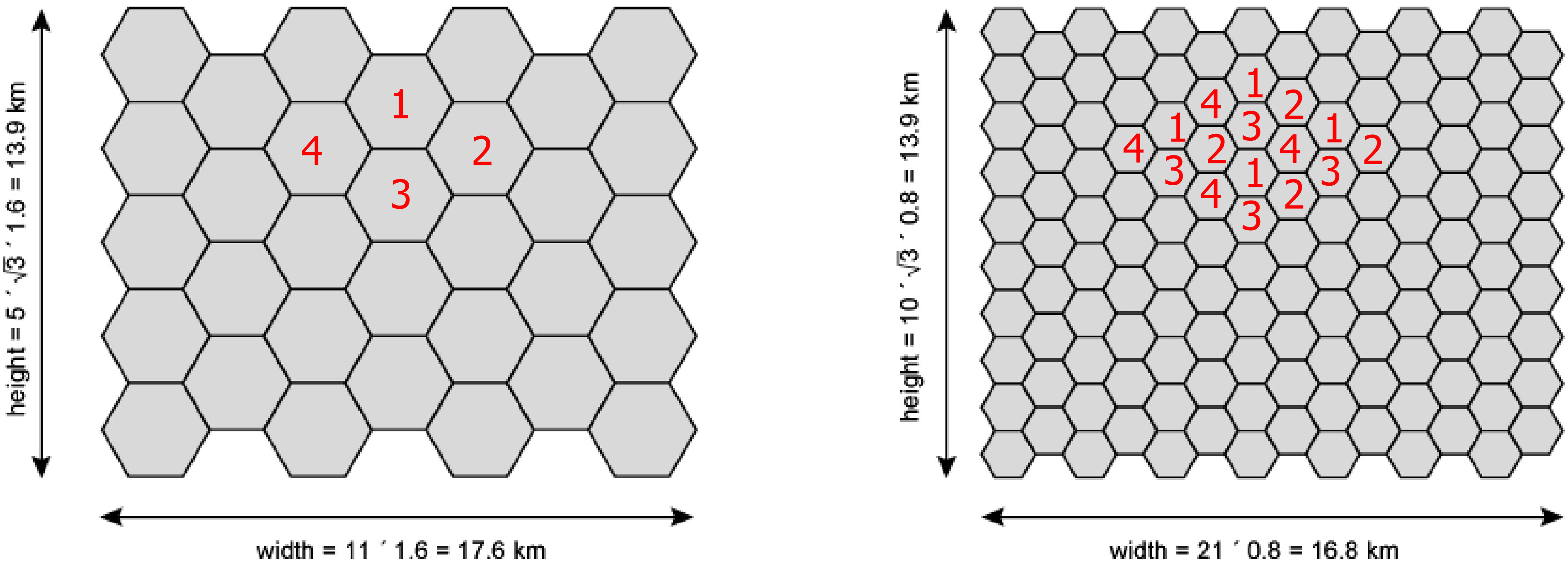
Cellular Systems and Frequency Reuse

- We will call a unit of wireless spectrum a channel.
- Depending on the specific system, a channel could be a frequency (FDMA), time-slot (TDMA), or a code (CDMA). The concept of a channel allows us to understand these systems through a unifying framework.



(a) Frequency reuse pattern for N = 4

Frequency Reuse Example

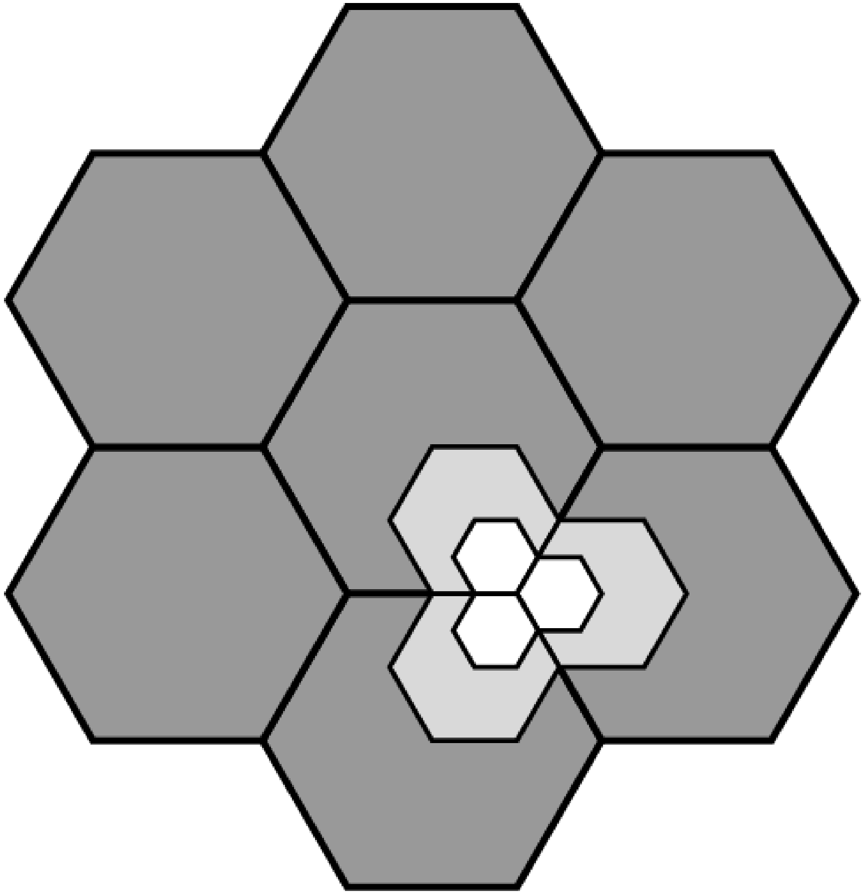


(a) Cell radius = 1.6 km

(b) Cell radius = 0.8 km

(Source: Prof. Vladimir V. Riabov)

Cell Splitting



(Source: Prof. Vladimir V. Riabov)

Can cells be split indefinitely?

- As cells become smaller, their shapes and locations become more irregular (even more true for 4G/5G systems).
- It is also more difficult to place the base-stations and connect them to the wired backbone
- Further, for voice calls, the problem now was that not all mobile calls would be completed within a cell.
- When a mobile approached the boundary of its current cell, heading to a new cell, some mechanism was needed in place to allow the mobile to successfully end its communication with the base-station in its current cell, and begin its communication with the base-station of its new cell. This procedure is called **handoff**.

Cellular: Summary

So, in summary, cellular is way to organize **multiple access** so that channels can reused among cells to improve network capacity.

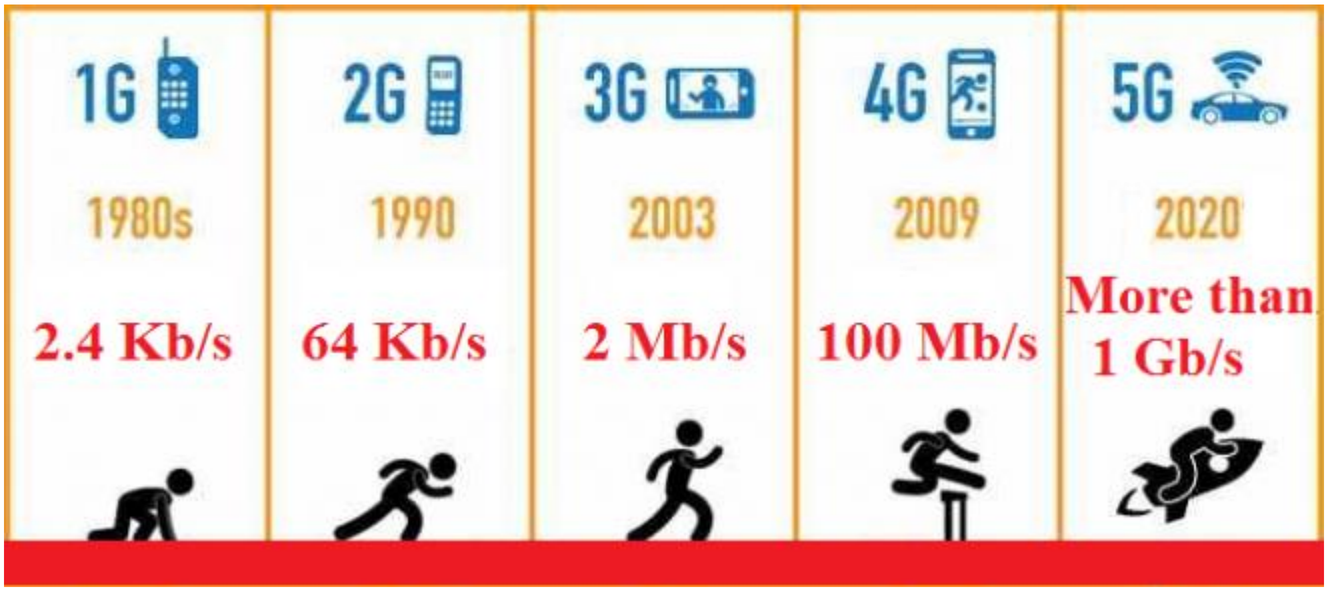
However, cell splitting will lead to increased complexity (handoff), and will eventually face practical limits.

In addition to adding spectrum and splitting cells, other innovations in managing multiple access are needed to meet the continuing demand for more network capacity.

Question

- So, what are the key distinguishing features of a wireless system versus a wireline system (e.g., those studied in ECE 547)?

Generations of Mobile Wireless Networks



1981	1992	2001	2011	2020
Analog voice	Digital voice	Data service	OFDM	mmWave
Cellular	TDMA, CDMA	Opportunistic scheduling	MIMO	Massive MIMO
FDMA			HetNets	MTC
				NOMA

(Source: itinfozone.com)

First Generation Cellular Systems

- First generation cellular systems started appearing in the 1970s
- Simultaneously in developed countries:
  - Advanced Mobile Phone System(AMPS) in North America
  - Total Access Communications Systems (TACS) in U.K.
  - Nordic Mobile Telephone (NMT) in Scandanavian countries
  - C450 in West Germany
  - Nippon Telephone and Telegraph(NTT) in Japan
- All use analog voice and FDMA

Second Generation Cellular Systems

The principal goals of second-generation wireless systems were:

- A digital system with higher capacity (hence lower cost) derived from digital techniques including efficient speech coding, error-correcting channel codes, and bandwidth-efficient modulation techniques.
- To offer, in addition to voice services, some rudimentary data services.

Technologies for Second-Generation Cellular Systems

Several standards and system design were proposed for competing technologies for second-generation cellular systems.

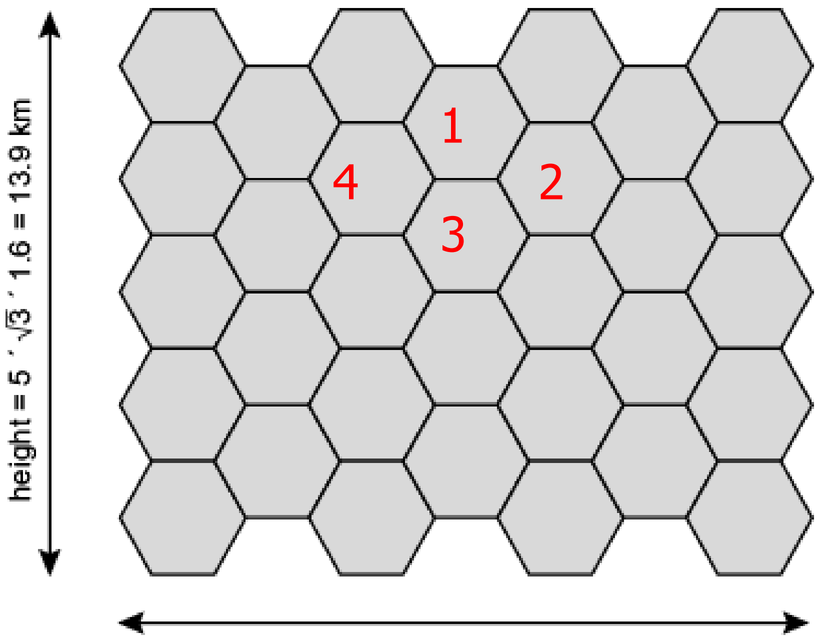
- FDMA (N-AMPS): North America
- TDMA/FDMA (GSM): Europe (where the need for a common standard is higher)
- CDMA spread spectrum (IS-95): North America

Mostly two standards prevailed: GSM (a TDMA/FDMA) standard and IS-95 (a CDMA standard)

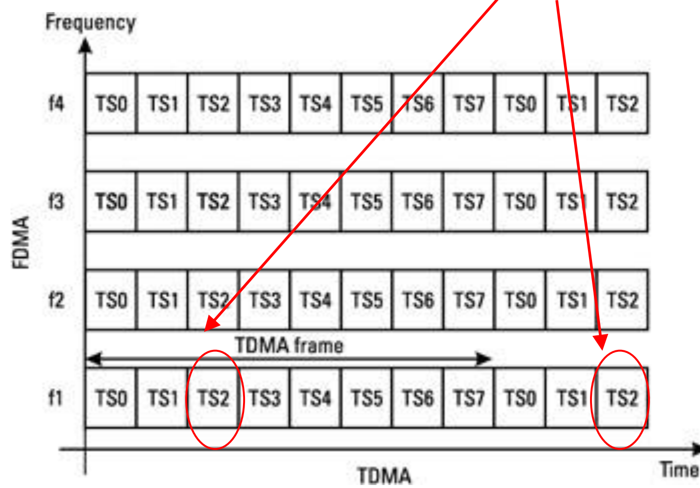
GSM (Example of a TDMA/FDMA system)

- GSM (Global System for Mobile Communications) was driven by the need for a common mobile standard throughout Europe and the desire for digital transmission compatible with data and privacy.
- Spectrum was reallocated for much of Europe near 900MHz so that completely new technology could be developed around GSM.
- The GSM effort in the mid-1980s considered several system implementations including TDMA, CDMA, and FDMA technologies. In the end, a TDMA/FDMA technology was chosen with a radio link-rate of 270kbs.
- The GSM standard is important and many third and fourth generation standards will be extensions of it.

FDMA/TDMA in GSM



A channel

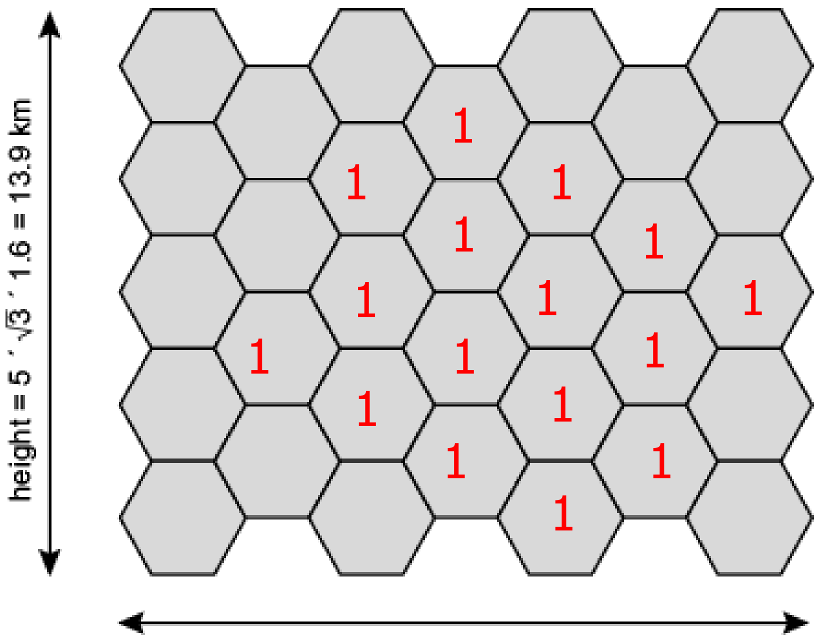


200Khz
per band

25M/200k -> 125 FDMA bands
8 TDMA channels per FDMA band

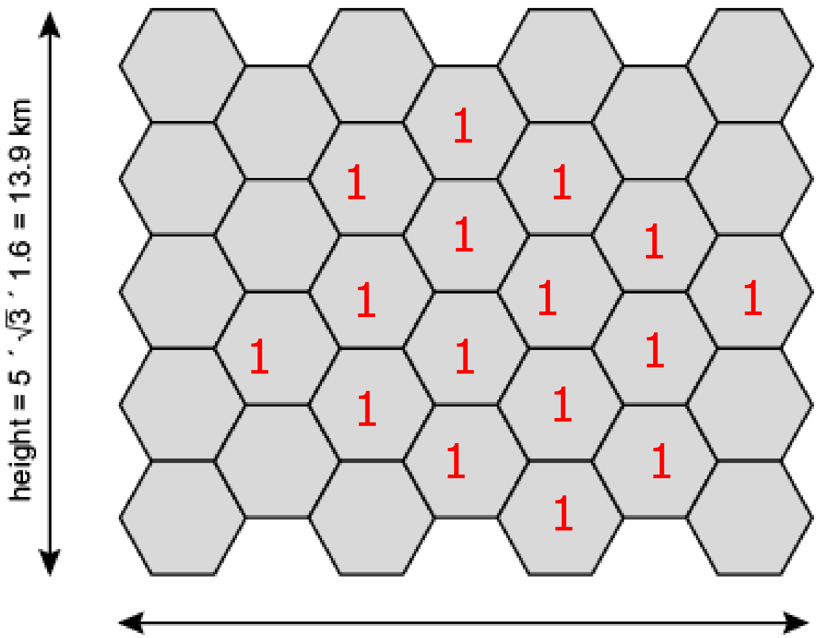
(Source: Prof. Vladimir V. Riabov
and etutorials.org)

CDMA in IS-95



- All frequency channels are reused in all cells
- The frequency bands are also wider (1.25Mhz), so multiple users transmit in the same band simultaneously
- Interference between users is suppressed by a technique called direct-sequence spread-spectrum (DSSS)

CDMA in IS-95

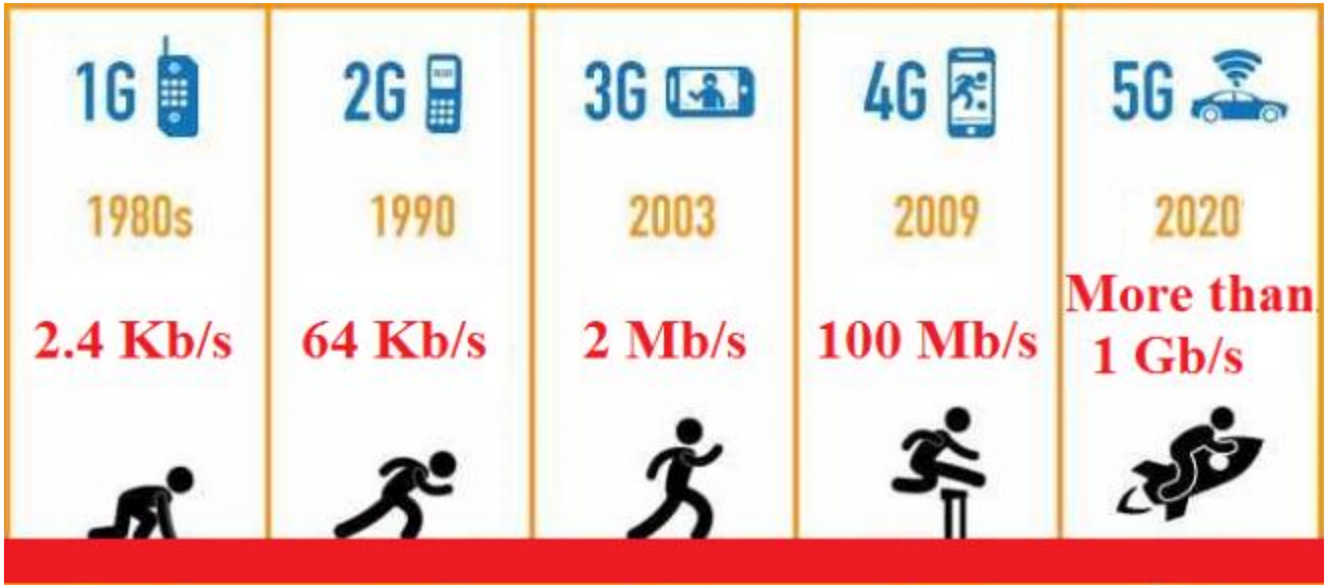


- The number of users that can simultaneously transmit now depends on how much interference is suppressed by DSSS

Code Division Multiple Access (CDMA)

- The claim by Vitterbi (CEO of QUALCOMM) was that, because CDMA could use frequencies in all cells (**universal reuse**), the capacity improvements in CDMA were almost 30 times of TDMA/FDMA systems.
  - We will examine the CDMA capacity later in the class
- CDMA also claims better multipath resistance, superior voice quality, increased call privacy, and soft handoff.
- This frenzy about CDMA continues into 3G when all 3G standards are based on CDMA, but …

Generations of Mobile Wireless Networks



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Third Generation Wireless Systems

- First-and second-generation digital systems are designed to support voice communication with limited data communication capability.
- Third generation systems (and beyond) are targeted to offer high-data-rate communications and expect to support a wide variety of applications
- What was the killer app for 3G?

Third Generation Wireless Technologies

The development of 3G is carried out by the standardization procedure called IMT-2000 (International Mobile Communications 2000) initiative.

The standardization procedure was done in parallel in different parts of the world and the eventual standards are mainly:

- Extensions of GSM -2.5 G
- Wideband CDMA systems -3 G.

Extensions of GSM (2.5G): GPRS/EDGE

- Generalized Packet Radio Service (GPRS) is an enhancement of GSM
- GPRS provides packet-switched data services at 5K-100Kbps by reusing the existing **narrow-band** GSM channels/infrastructure for circuit-switched services such as voice telephony.

- Enhanced Data Rates for GSM Evolution (EDGE) uses adaptive modulation techniques and can produce 384Kbps maximum transmission.
- Both GPRS and EDGE aim not to replace the current infrastructure, but to co-exist with it.

- To achieve Mbps bit rates will require using more sophisticated physical layer as well as resource & radio management.

Wideband CDMA

In March 1999, the final decision was made to select wideband CDMA as the access scheme for 3G, with three optional modes:

- W-CDMA (or UMTS): CDMA Direct Spread. 5MHz channel. Frequency Division Duplex(FDD).Based on Europe (ETSI) and Japan (ARIB)'s FDD proposal.
- CDMA-2000: CDMA Multi-carrier. Can use multiple 1.25Mhz channels. Based on US (TIA)'s proposal.
- TD-SCDMA:CDMA TDD (time division duplex). Can use multiple time slots. Based on China's proposal.

Wideband CDMA

- W-CDMA is meant to serve as an evolution path for GSM (GSM ->GPRS/EDGE->W-CDMA). It uses much of same core network as GSM.
- CDMA 2000 is meant to serve as an evolution path for IS-95 (including 1xRTT, EV-DO).
- Downlink speed can reach 10+Mbps.

Key Technology in 3G Systems

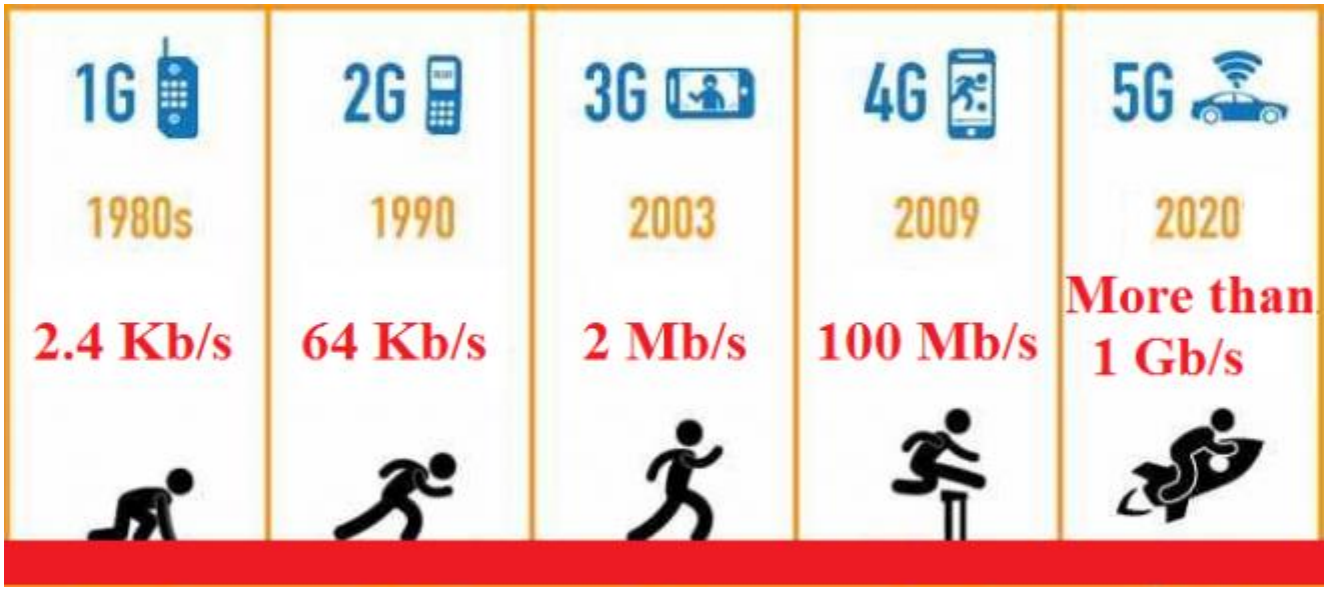
- However, under the disguise of CDMA is a very different way of resource/radio management and spatial reuse

- In each cell and channel, at most one user is active at a time
- CDMA is only to suppress interference from other cells
- (We will study the reasons behind this change of direction)

- The single user will transmit at a higher rate if its channel condition is good (e.g., closer to the base-station) and will get higher data rate
  - **Adaptive modulation and coding (AMC)**

- Among many users, the one with best channel condition will be scheduled to transmit
  - **Opportunistic scheduling** to exploit **diversity** in time

Generations of Mobile Wireless Networks



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4G Wireless Systems

- Even higher data-rate: envisioned to attain 100Mbps for high mobility, 1Gbps for low mobility
- CDMA is abandoned. OFDM is used instead. (Will study the reason why.)
- High spectral-efficiency (via OFDM, MIMO)
- All IP, packet switched

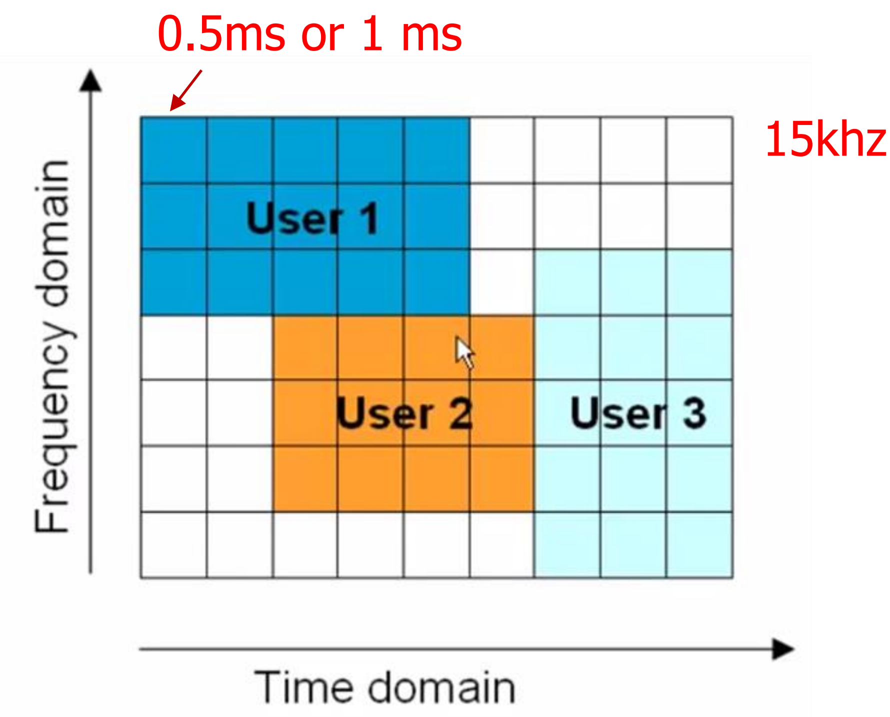
4G Wireless Systems

- Two competing standards:
  - LTE (Long Term Evolution) by 3GPP: driven by telecom industry.
  - WiMax (802.16): driven by computer vendors.
  - Both based on OFDM
- LTE prevails and becomes the first universal standard across the globe
- With 100 MHz aggregated bandwidth, LTE-Advanced provides almost 3.3 Gbit peak download rates per sector of the base station under ideal conditions. (Typically rate may be lower, using 20Mhz band.)
- Voice over LTE will eventually get rid of legacy circuit-switched systems altogether.

Key Technology for 4G LTE

- OFDM: more efficient frequent-time modulation
- MIMO: Multi-Input Multi-Output communications
- HetNets: Heterogeneous networks of many small cells

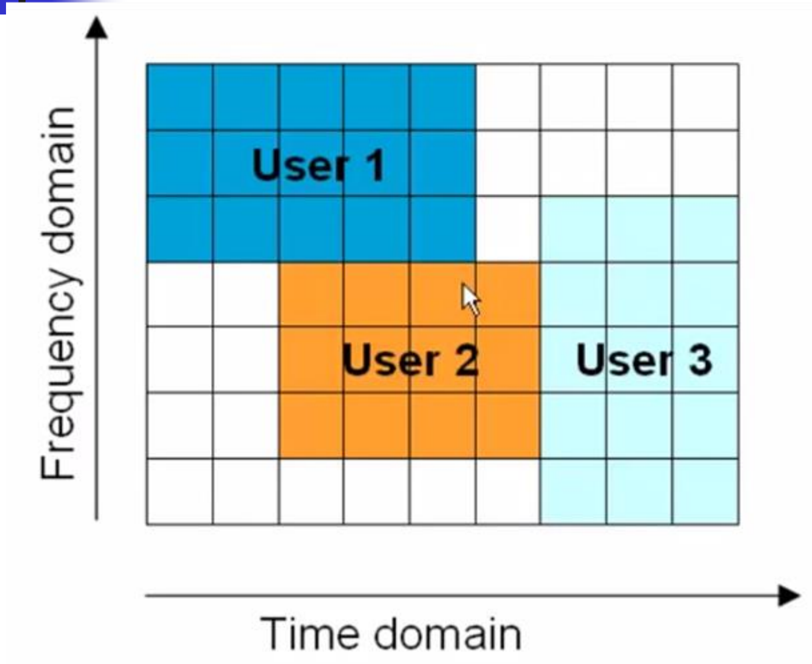
Orthogonal Frequency Division Multiplexing (OFDM) in 4G LTE

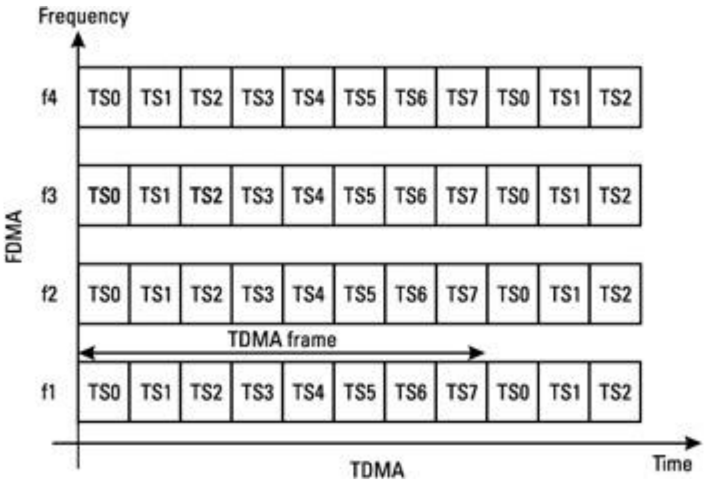


- OFDM divides a wide band into a number of narrow-band sub-carriers, each of which carries information
- OFDMA allow each user to be scheduled on a subset of frequency-time slots.
- **Opportunistic scheduling** can now exploit **diversity in both frequency and time**

Source: eventhelix.com

OFDMA in 4G LTE

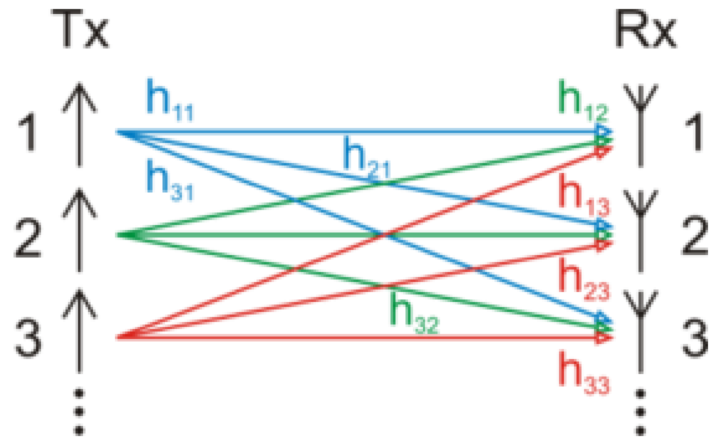




OFDMA in 4G LTE:
- higher peak rate
- better handling of freq. selectivity
- higher spectrum efficiency

TDMA/FDMA in 2G GSM

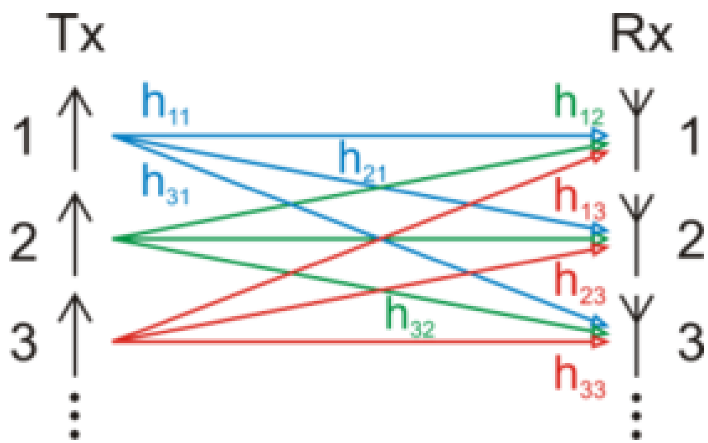
Multi-Input Multi-Output (MIMO) Transmissions



Source: wikipedia

- N_t antennas at the transmitter, N_r antennas at the receiver
- If the channel matrix is of full rank, $\min\{N_t, N_r\}$ data streams can be sent in parallel (known as **spatial multiplexing**)
- Potential data rate increases linear with the antenna size $\min\{N_t, N_r\}$

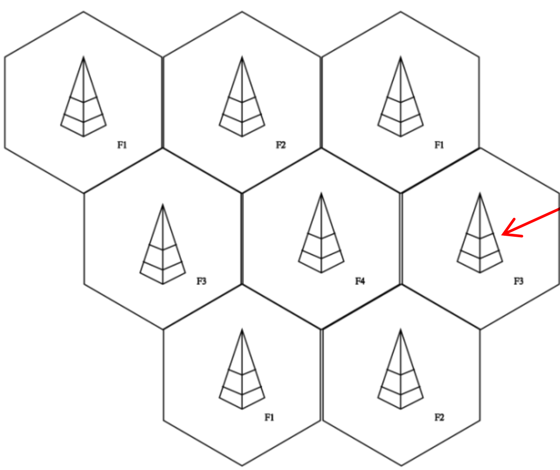
Multi-Input Multi-Output (MIMO) Transmissions



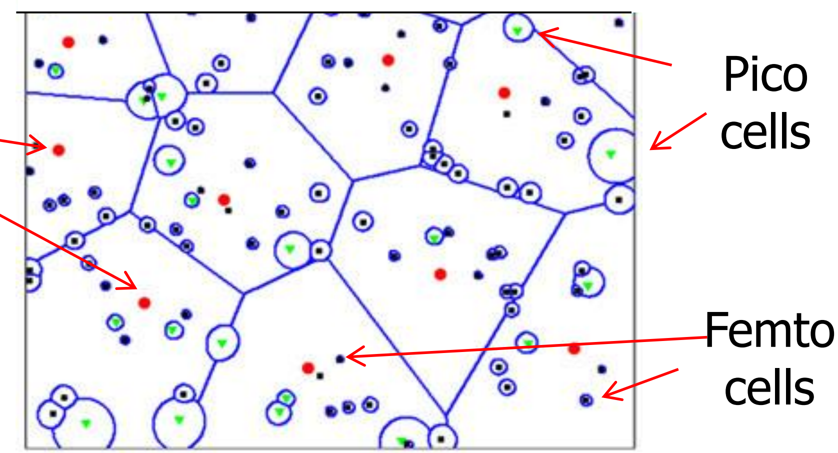
- MIMO is said to exploit **spatial diversity.** (In contrast, opportunistic scheduling exploits **frequency- and time-diversity**)
- Need to know the channel gain between every pair of transmit-/receive-antennas (CSI): Significant overhead in 4G
- Multi-User (MU-) MIMO can benefit even if the receiver only has a single antenna

Heterogeneous Networks (HetNet)

- Smaller cells are needed to accommodate increasing traffic demand: micro/pico/femto cells.
- The result is highly ***irregular topology and load***
- Challenge: more like an ad hoc network. Traditional network planning and control based on cellular no longer work! (See "Seven ways that HetNets are a Cellular Paradigm Shift")



Macro cells

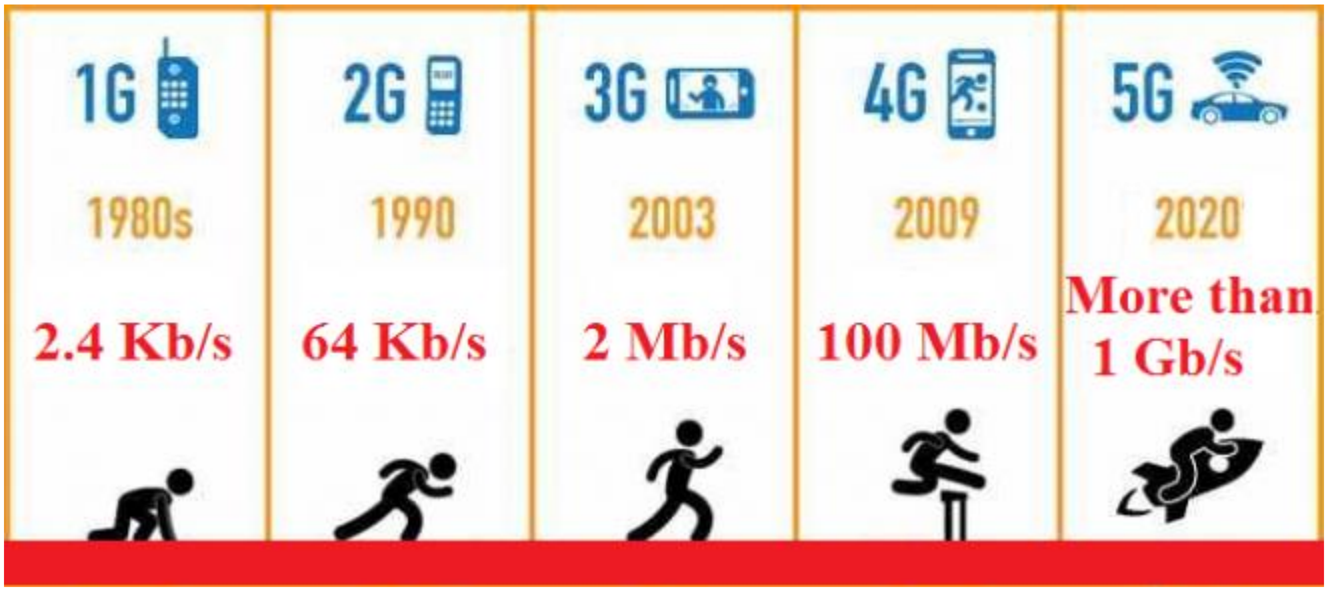


(Source: Prof. Jeffery Andrews, UT Austin)

Traditional Cellular Networks

Heterogeneous Cellular Networks

Generations of Mobile Wireless Networks



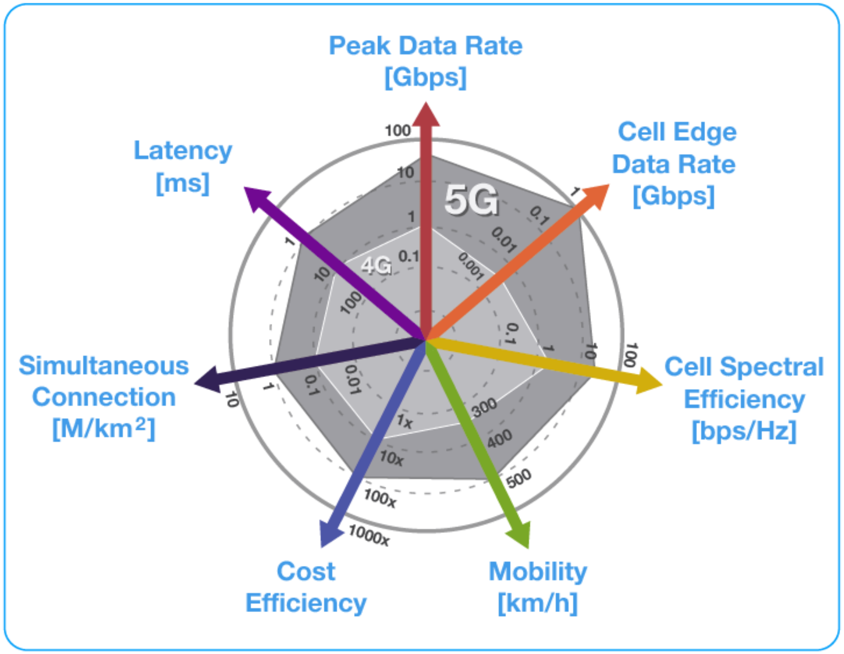
1G	2G	3G	4G	5G
1981 Anolog voice Celluar FDMA	1992 Digital voice TDMA, CDMA	2001 Data service Opportunistic scheduling	2011 OFDM MIMO HetNets	2020 mmWave Massive MIMO MTC NOMA

How about 5G?

- First specification (Phase 1) agreed on Dec. 2017

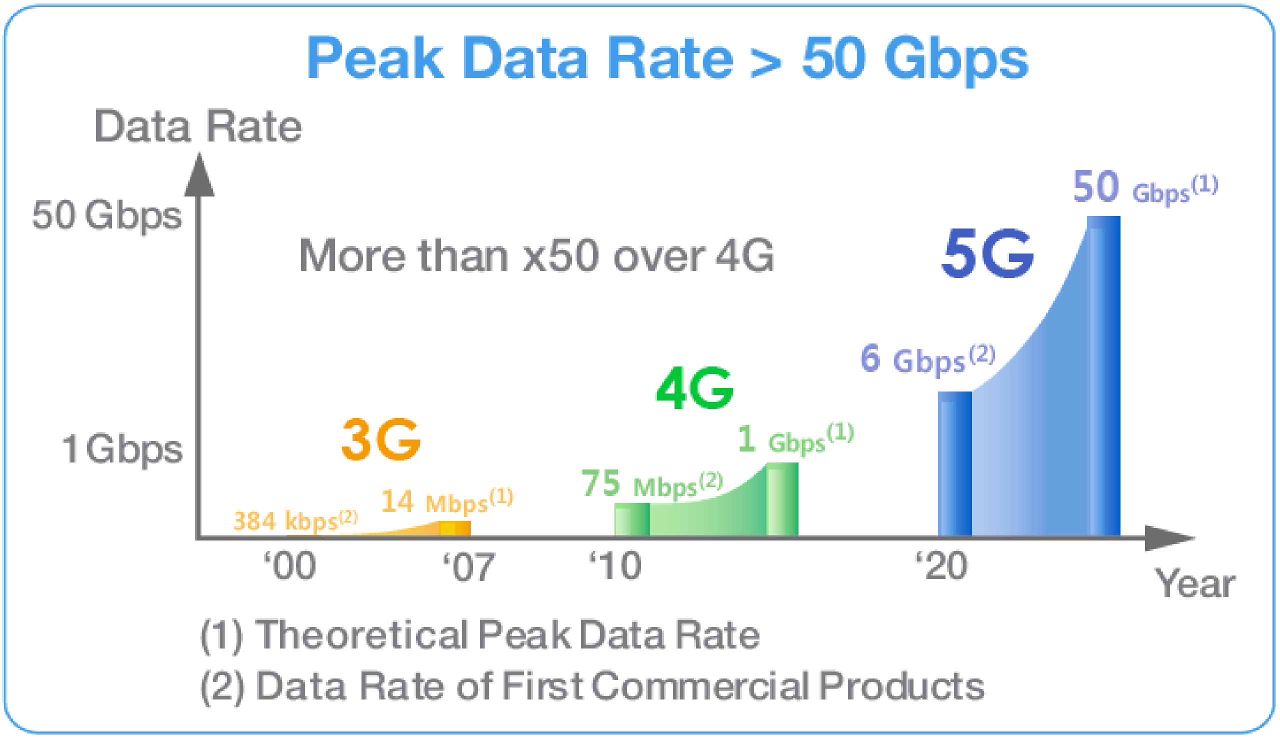
Wish Lists (3 Use Cases) for 5G

- High Data Rate: Enhanced mobile broadband (eMBB)
- Low Delay: Ultra-reliable low latency communications (URLLC)
- Massive # of devices: machine-type communications (mMTC)
- Possibly along different “slices” of the same core network (network virtualization)



Source: Samsung

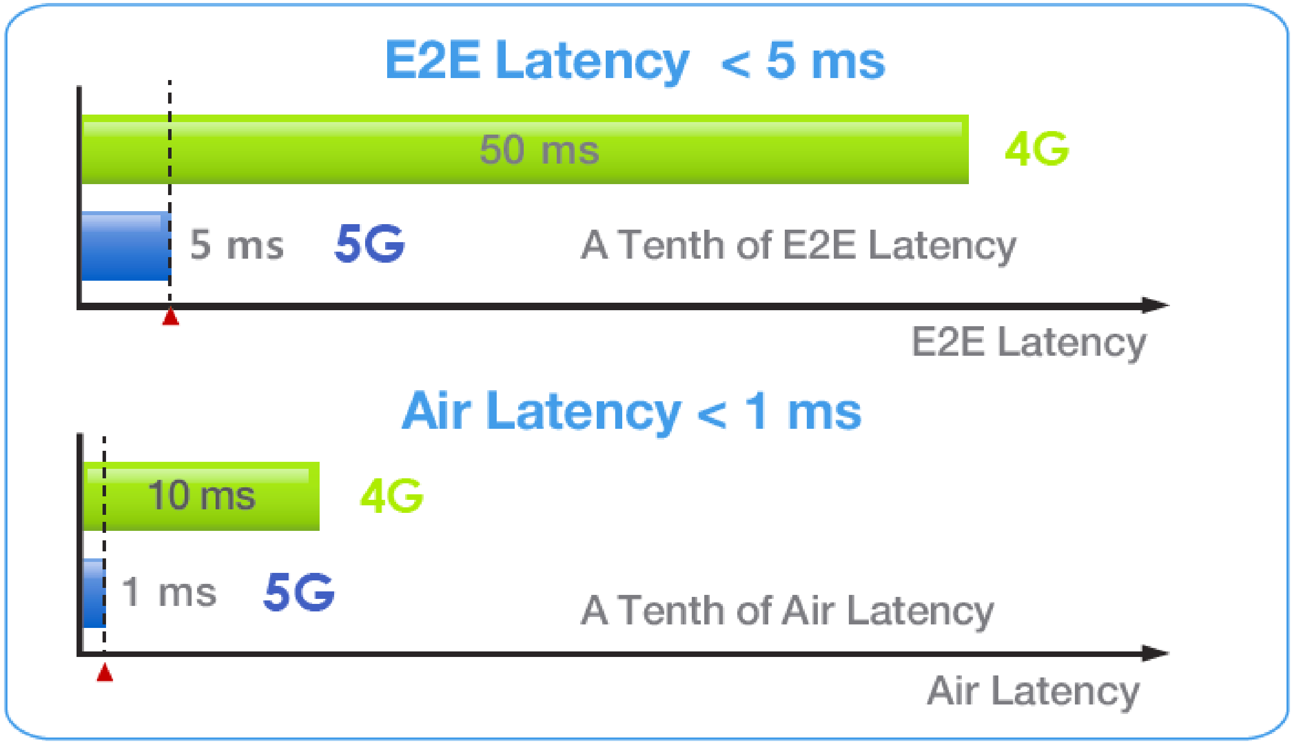
High Data Rate



Source: Samsung

What driving applications?

Ultra Low Latency



Source: Samsung

What driving applications?

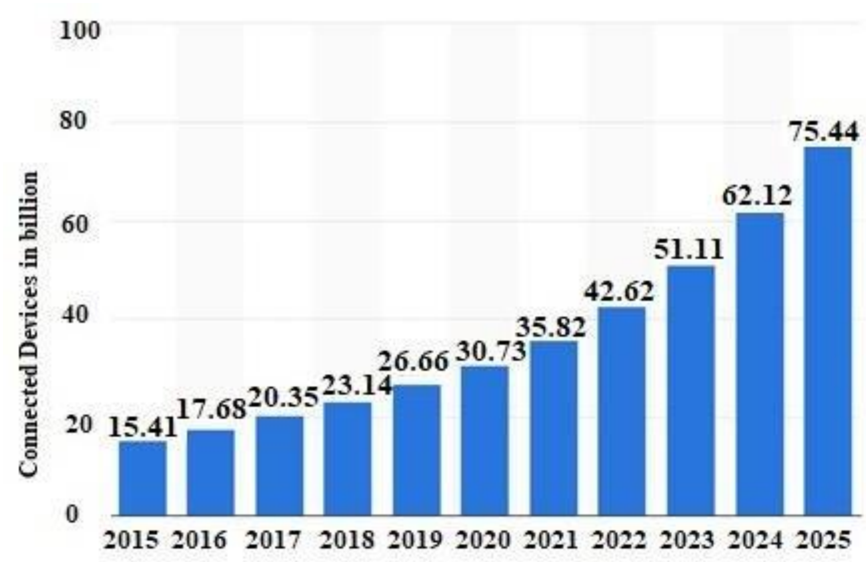
Ultra Low Latency

- Virtual Reality, Augmented Reality
- Automation, robotics, remote-control

Massive Connectivity

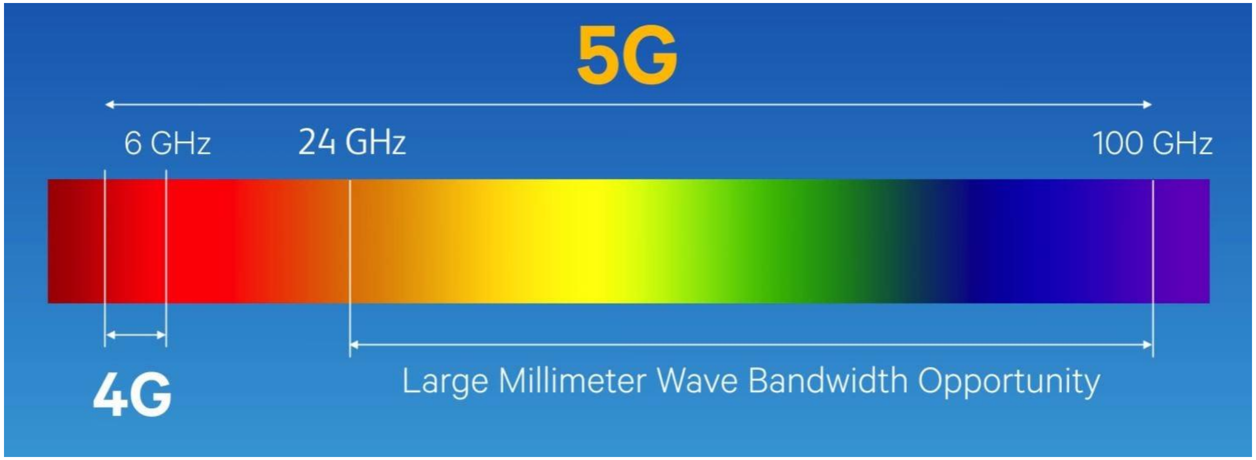
- Internet-of-Things
- But each device may be of low rate

- **Low overhead** is critical
- Low latency
- Low power



Source: statista.com

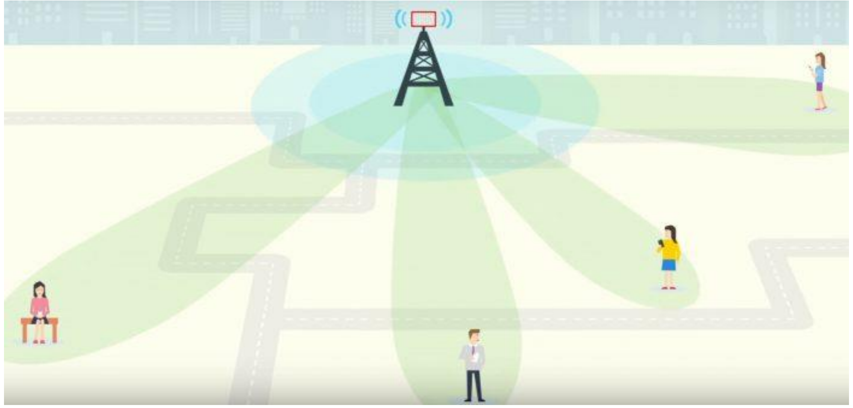
Some Likely Technology for 5G



Source: rcrwireless.com

- mmWave
  - 30-300Ghz, sometimes including 24Ghz (about 10mm and below)
  - Much higher free-space loss
  - Absorption by atmosphere, rain, etc.
  - Line-of-sight propagation: low diffraction, does not penetrate walls/objects

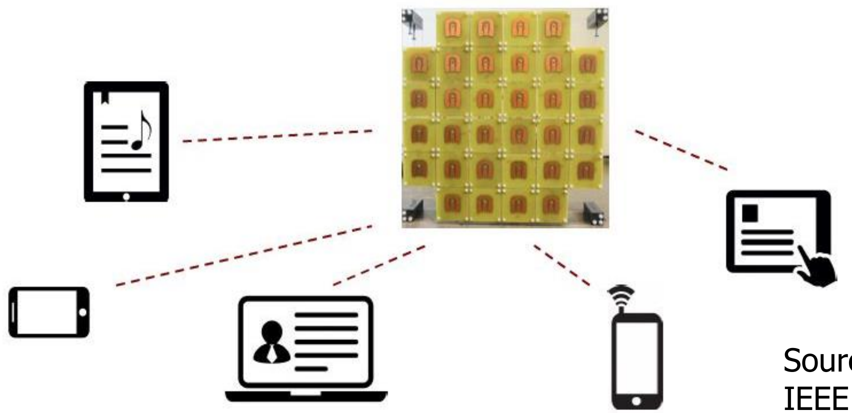
Some Likely Technology for 5G



Source: rcrwireless.com

- mmWave
  - Smaller coverage (100-200m), higher frequency reuse
  - Highly-directional beams may be needed to improve coverage
  - Beam alignment and beam tracking becomes a problem

Some Likely Technology for 5G



Source: Massive MIMO for 5G, IEEE 5G Tech Focus: Volume 1, Number 1, March 2017

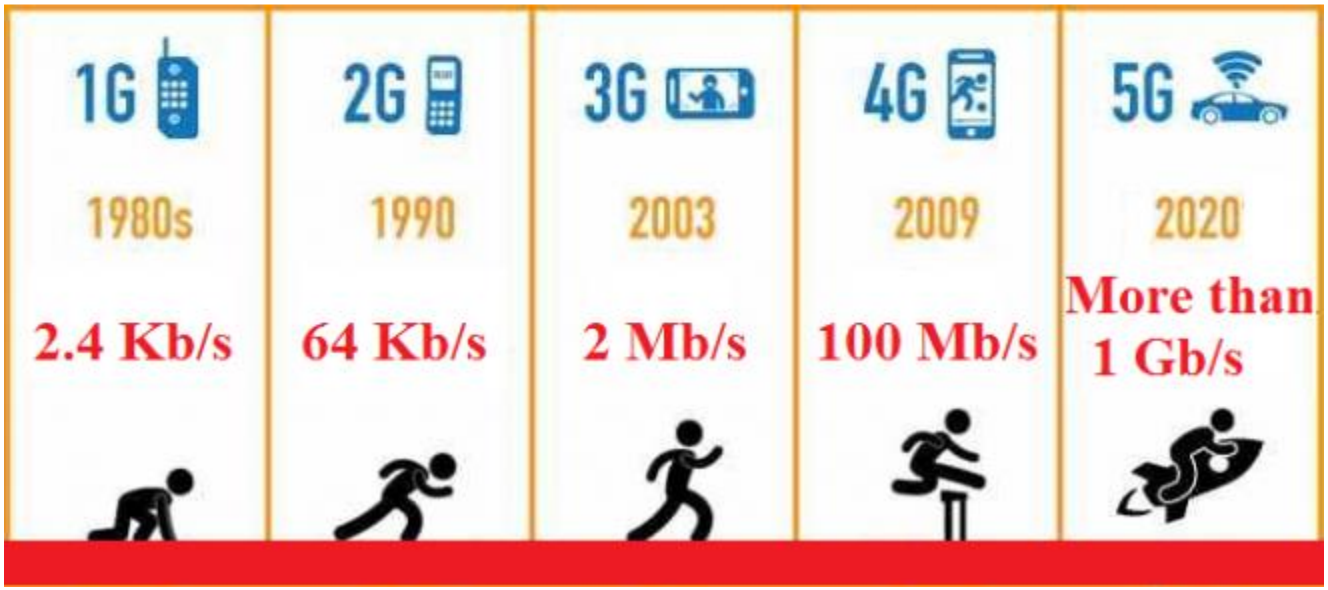
- Massive MIMO
  - Smaller wavelength of mmWave allows large antenna arrays to be packed at the transmitter/receiver
  - Potentially huge spectrum efficiency gain
  - High directionality
  - More resources needed for channel estimation/feedback. Pilot contamination

Some Likely Technology for 5G

- Non-orthogonal access (NOMA)
  - In 3G/4G each user is assigned orthogonal resource (time/frequency) when transmitting
  - Signaling is needed for scheduling resources
  - For low-rate IoT applications, such signaling incurs high overhead
  - Potentially more advantageous to have multiple transmissions over the same set of the orthogonal resources

  - Sounds like CDMA?
  - How about spectrum efficiency, diversity gain, etc?

Generations of Mobile Wireless Networks



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Technologies Competing with Cellular Systems

- Wireless LAN
- Bluetooth
- Ad Hoc Networks

- Unlicensed band
- Very different multi-access technology: e.g., CSMA
- Often ad-hoc deployed (somewhat like HetNet now)
- Will discuss later in random access

In Summary

- Demand for mobile network service keeps increasing
- Although the **cellular** concept prevails, a lot of change in the underlying technology for **multiple access** and resource management
- Why are particular changes are made in a new standard?
- We need to understand the implication to **multiple access** and how it impacts the system capacity

Two High-Level Considerations

- Whether to design for the **worst-case** or for the **average-case**?

- How to deal with variations in the channel quality (i.e., **diversity**)?

Many Detailed Questions

- How to maximize the network-layer benefits (e.g., capacity, delay) of various new PHY-layer technologies?
- How to manage highly irregular/ad-hoc topology and load?
- How to achieve various types of Quality-of-Service for different applications (e.g., high throughput versus low delay)?
- How to accomplish all these with low complexity and overhead?

Overview of the Rest of the Class

- Understanding the wireless channel
- Cellular capacity and cellular channel allocation (Voice systems)
- Optimal capacity and scheduling in broadband wireless networks (Data systems)
- Stochastic geometry and scaling laws
- Case studies of 2G/3G/4G systems (with student participation)
- Random access (for both wireless LAN and low-overhead IoT access)
- Wireless control algorithms for low-delay
- Project presentation

Questions?

Learning Objectives

- Identify the key technology advances in each generation of wireless networks
- Identify key considerations for multiple access and resource management in wireless networks
- Identify the challenges ahead for 5G and Internet-of-Things