ECE 60022: Wireless Communication Networks

An Introduction

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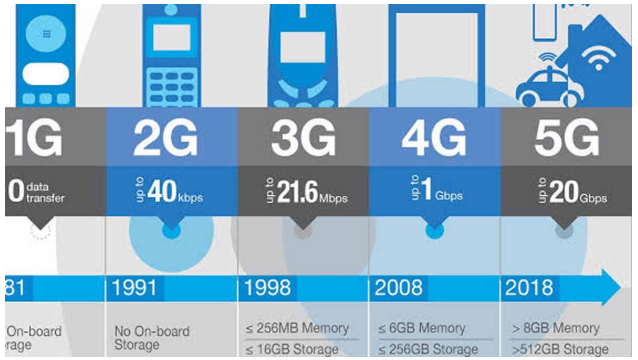
(adapted from materials developed by Xiaojun Lin and Ness Shroff)

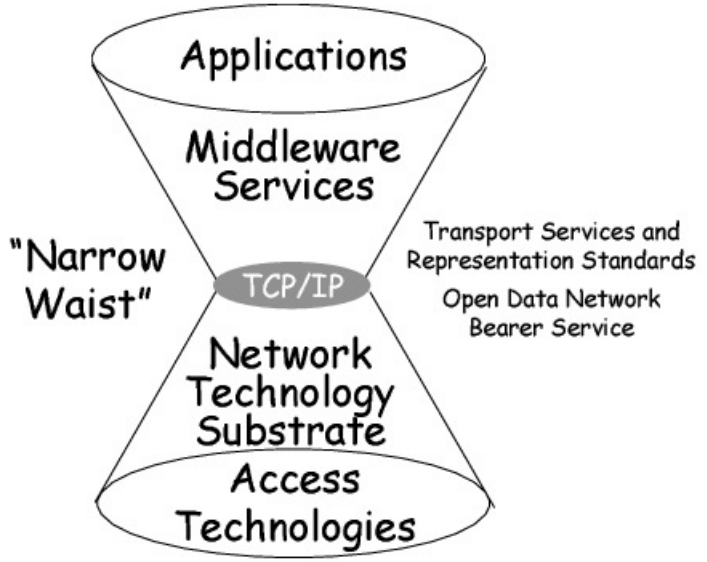
2G/3G/4G/5G/6G/…



- Over the past 20 years, wireless networks have seen dramatic changes over several generations of technology

- By contrast, the basic paradigm of the Internet (i.e., TCP/IP) has remained largely the same since the 1970s/80s

- What are the main drivers for these changes?
- What are the main technologies in each generation of wireless network technology?
- What lessons have we learned?



“Network” vs. Point-to-Point Communications

- Successful (non-network) systems have been built utilizing the capability of sending 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-multipoint

- “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 them?
- 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 progression of wireless networks, pay close attention to how each generation addresses these questions

- Importance of multiple access if prominent in the “cellular” concept

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 landline networks

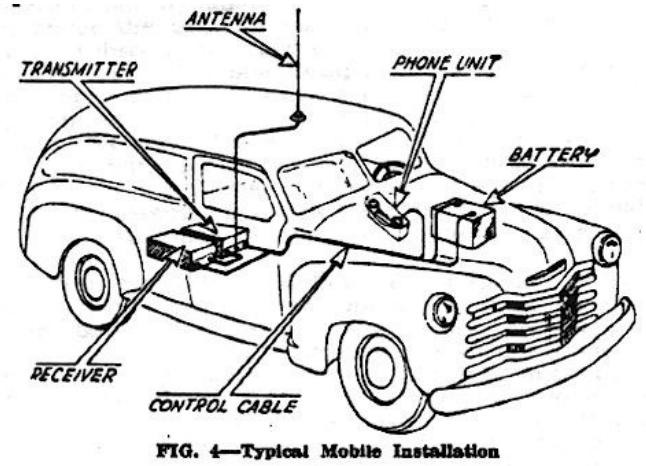


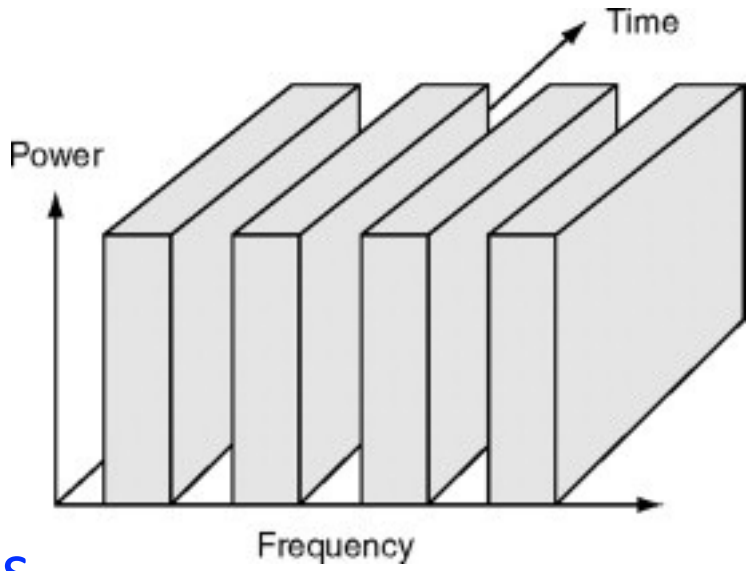
FIG. 4—Typical Mobile Installation

- Systems used a single powerful transmitter from the base station to cover up to approximately a 50-mile radius
- Systems were based on frequency modulation (FM) transmission
- Each frequency channel used 120 kHz of spectrum to transmit a voice connection with an effective bandwidth of only 3 kHz

First Mobile Telephone Service ("0G")

- 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



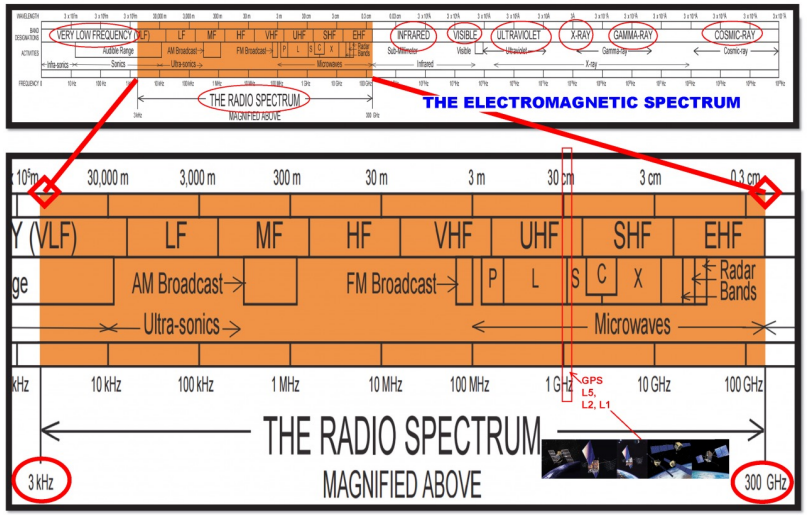
- Hence, service was terrible (blocking probabilities were as high as 65%, or even higher!)
  - Usefulness of mobile telephone decreased as users found that blocking often prevented them from getting a circuit during peak periods

First Mobile Telephone Service ("0G")

- Telephone companies soon realized that for true mobile services to develop …

1. 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!

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



Advent of Cellular Systems

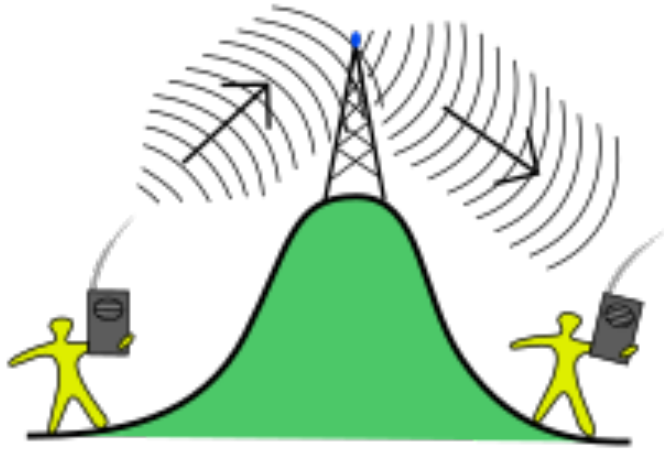
- In the mid-1960s, Bell Systems introduced the Improved Mobile Telephone Service (IMTS) with …
  - enhanced features such as: Direct Dialing, Automatic Trunking, Full-duplex service
  - a reduction in FM channel bandwidth requirements from 120 kHz to 25-30 kHz (4x improvement)
- However, the capacity problem was still not fundamentally solved as user demand increased
- In the late 1960s and early 1970s, work began on the first cellular telephone systems

Pre-Cellular Days

- The traditional approach to mobile radio involved setting up a high-power transmitter located on top of the highest point in the coverage area

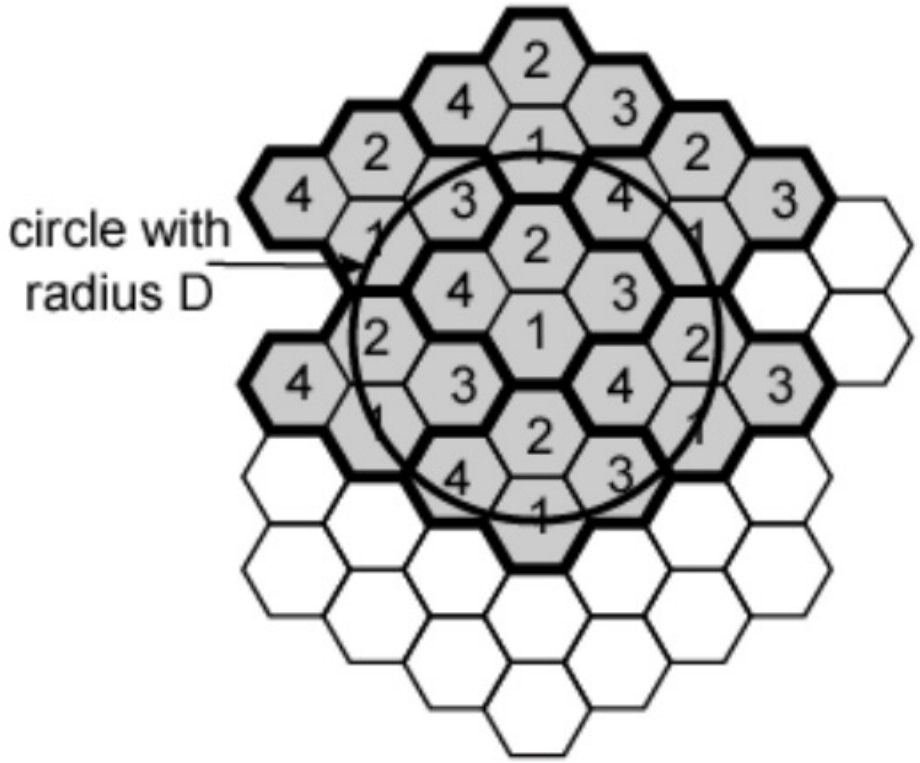
- This allows line-of-sight (LoS) transmission over the largest distance possible (as much as 40-50 miles away for a very high base station antenna)
  - Similar to satellite TV

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



Cellular Systems and Frequency Reuse

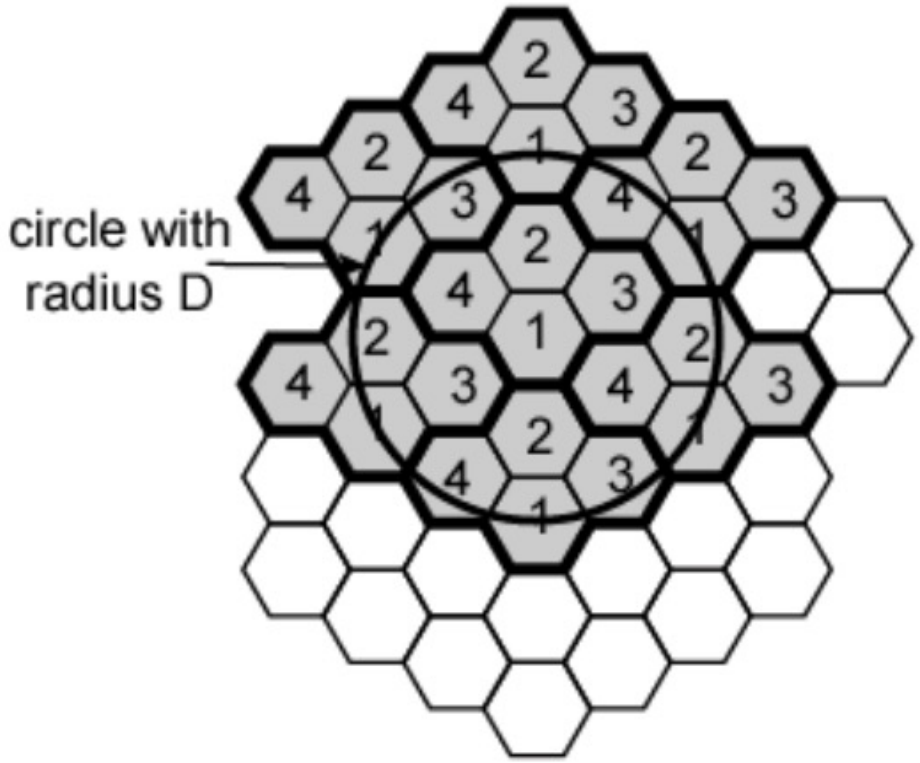
- The cellular concept handles the coverage problem differently
- Use a large number of low power transmitters, each designed to serve only a small area called a cell
- Frequencies not reused in adjacent cells to avoid interference
- However, the wireless spectrum is reused among those cells that are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



Frequency reuse pattern for $N = 4$

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



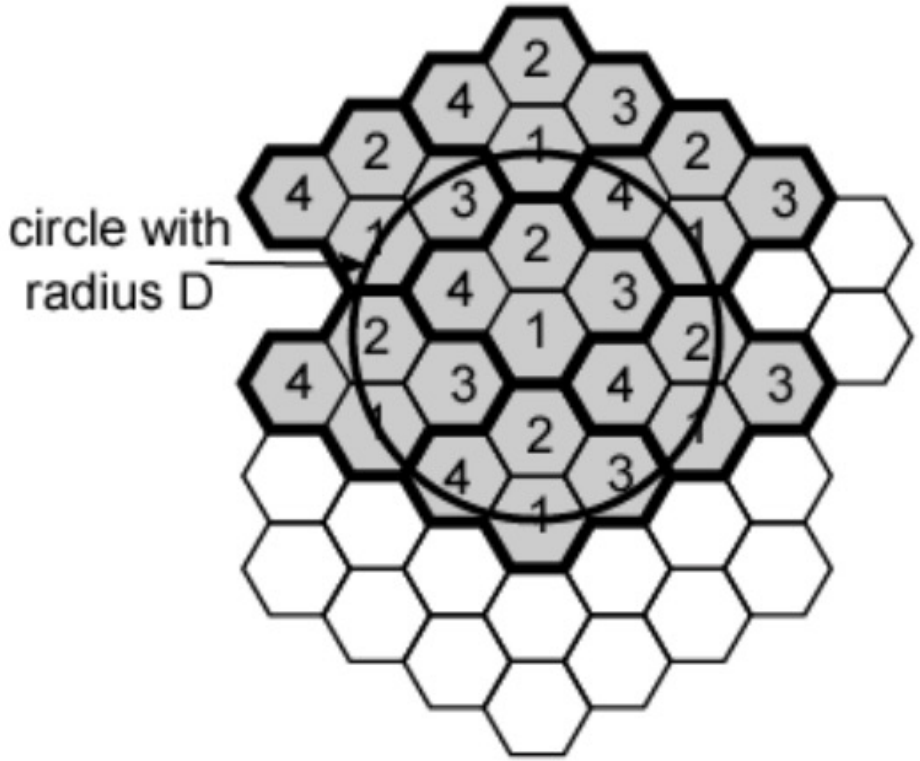
Frequency reuse pattern for $N = 4$

Example for AMPS (1G)

- Advanced Mobile Phone System (AMPS)
  - 1980s 1G cellular analog system in the US
  - FDMA

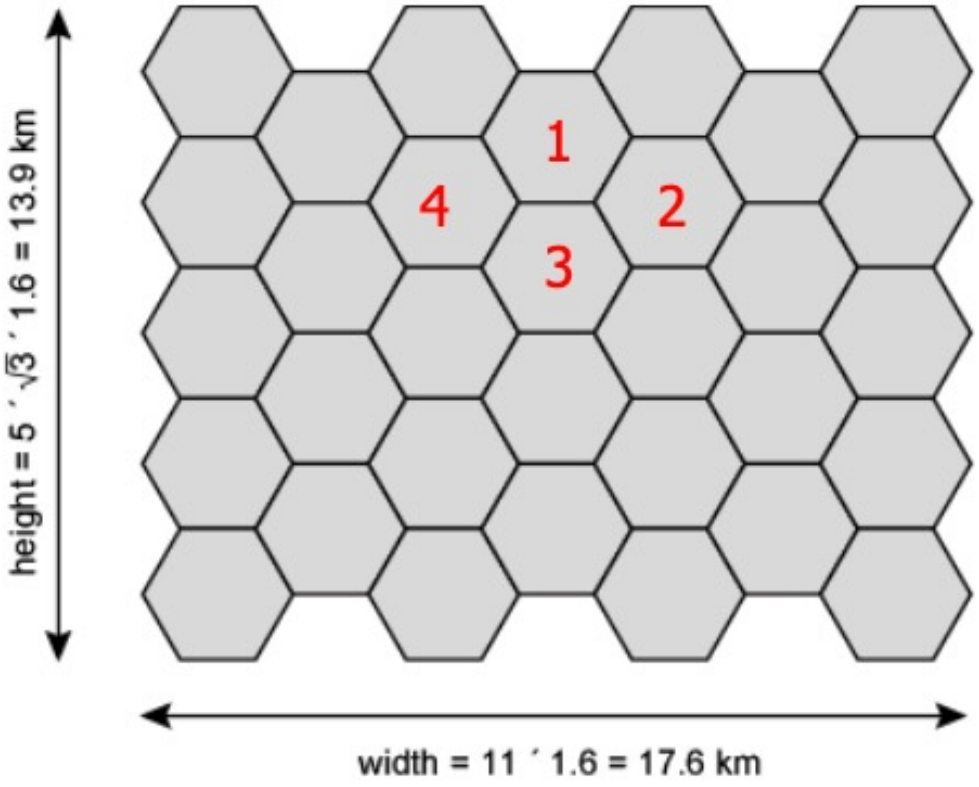
- Frequency bands
  - Uplink: 824 – 849 MHz
  - Downlink: 869 – 894 MHz
  - Each channel is 30 kHz

- So, we have 25M / 30K = 832 channels
  - Need to be allocated to cells/users so that neighboring cells do not interfere

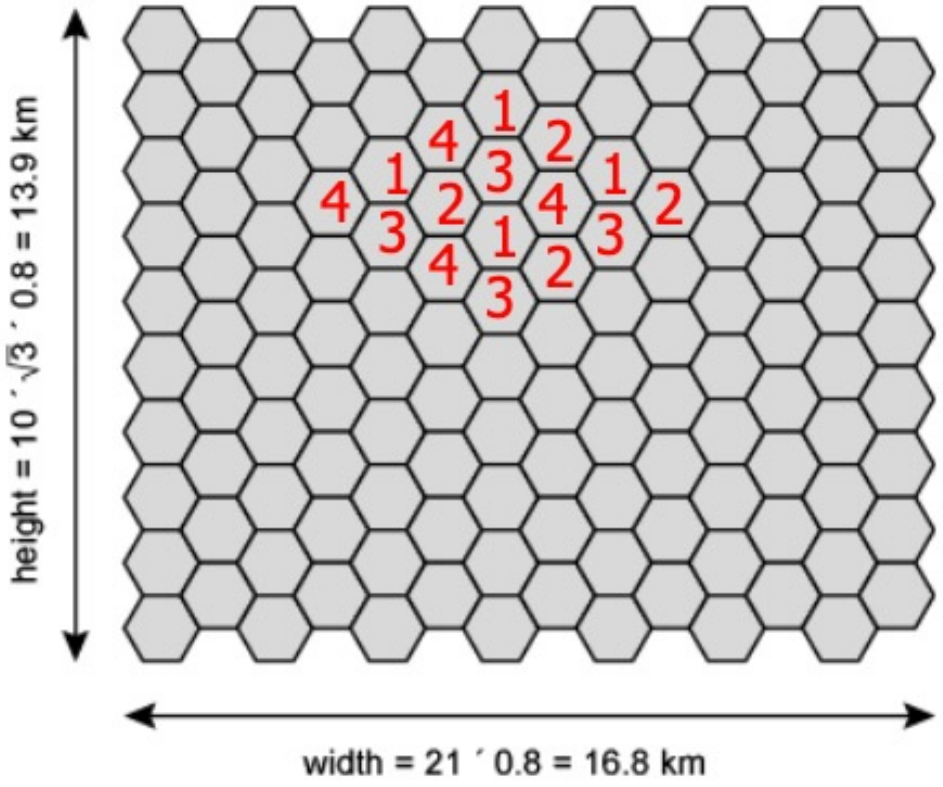


- For N=4, we have a reuse factor of 1/4, and we can serve 832 / 4 = 208 users per cell

Frequency Reuse Example



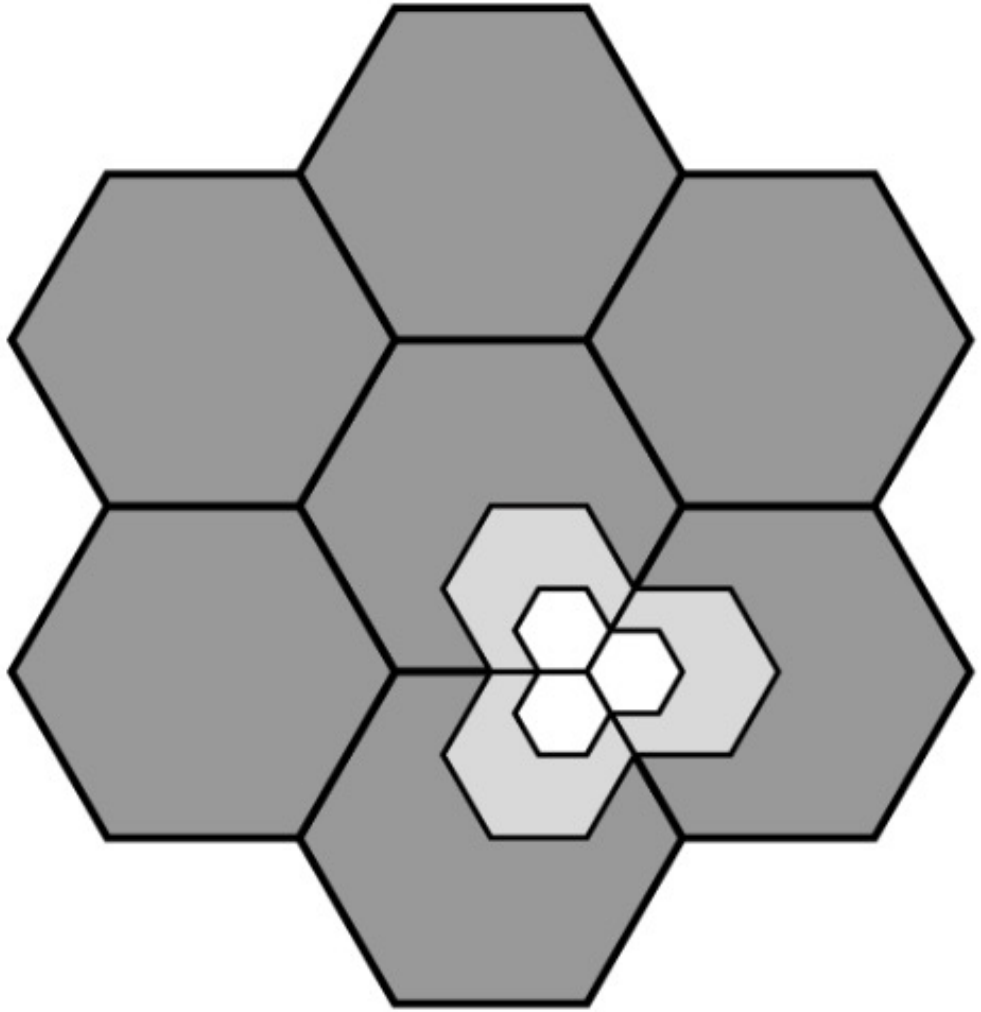
(a) Cell radius = 1.6 km



(b) Cell radius = 0.8 km

Cell Splitting

- Initially, very large radius cells were used (and still are in sparsely populated areas)
- As traffic continues to increase within a cell, the existing allocations have difficulty retaining high quality of service, motivating cell subdivision
- Thus, these macro-cells have evolved into smaller radius cells over time, using cell-splitting



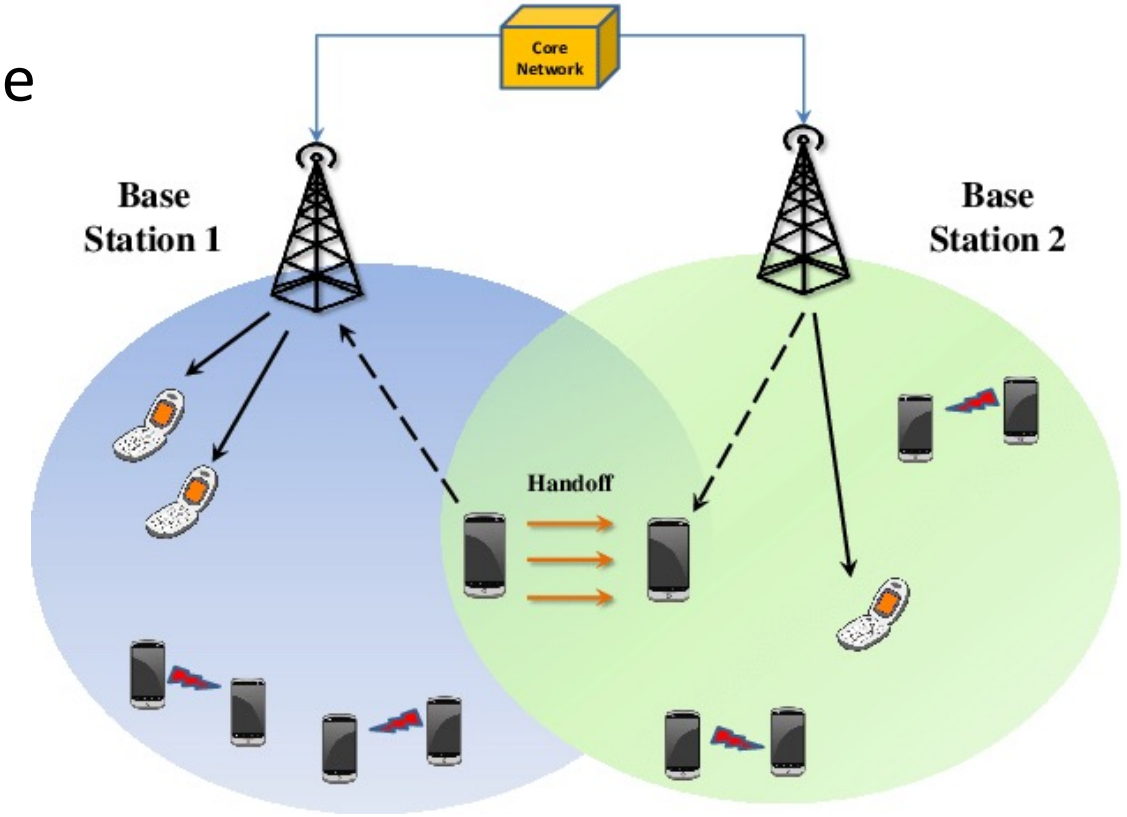
Can cells be split indefinitely?

- As cells become smaller, their shapes and locations become more irregular (moreso in 4G/5G systems), and interference conditions change

- More difficult to place the base stations and connect them to the wired backbone

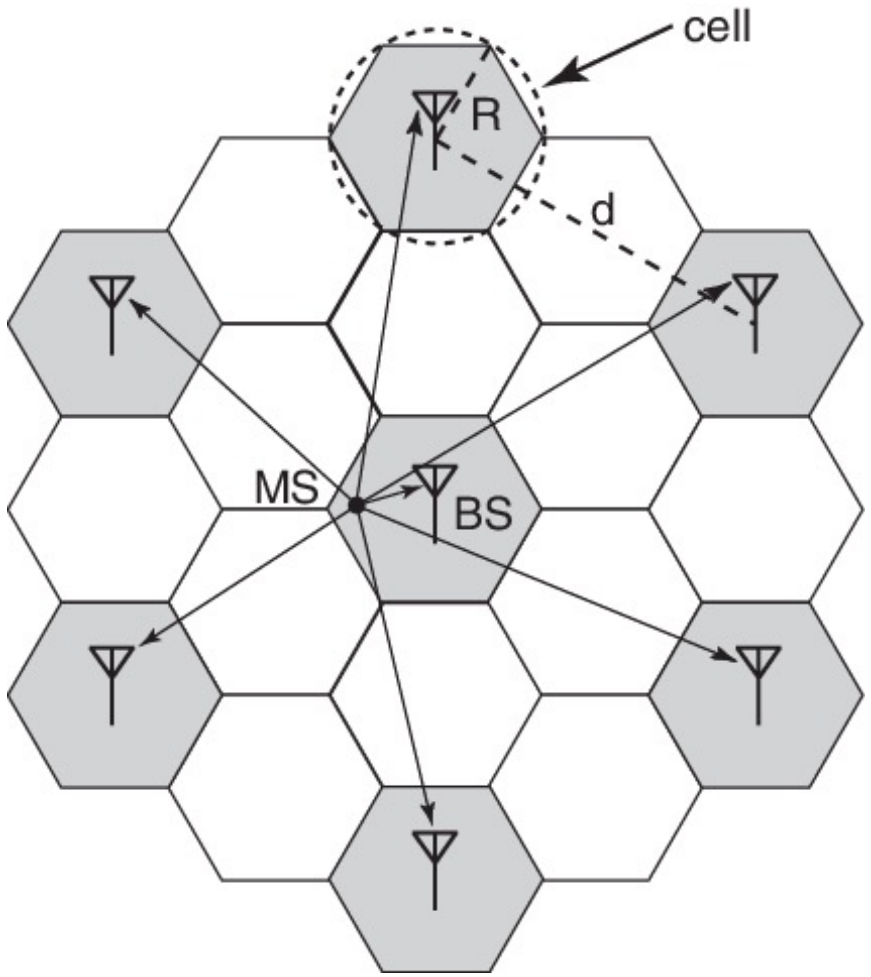
- Not all mobile calls completed within the same cell due to user mobility

- Handover procedures
  - When phone approaches boundary of its current cell
  - Some mechanism needed to allow the device to successfully end communication with the base station in its current cell, and begin with the new cell

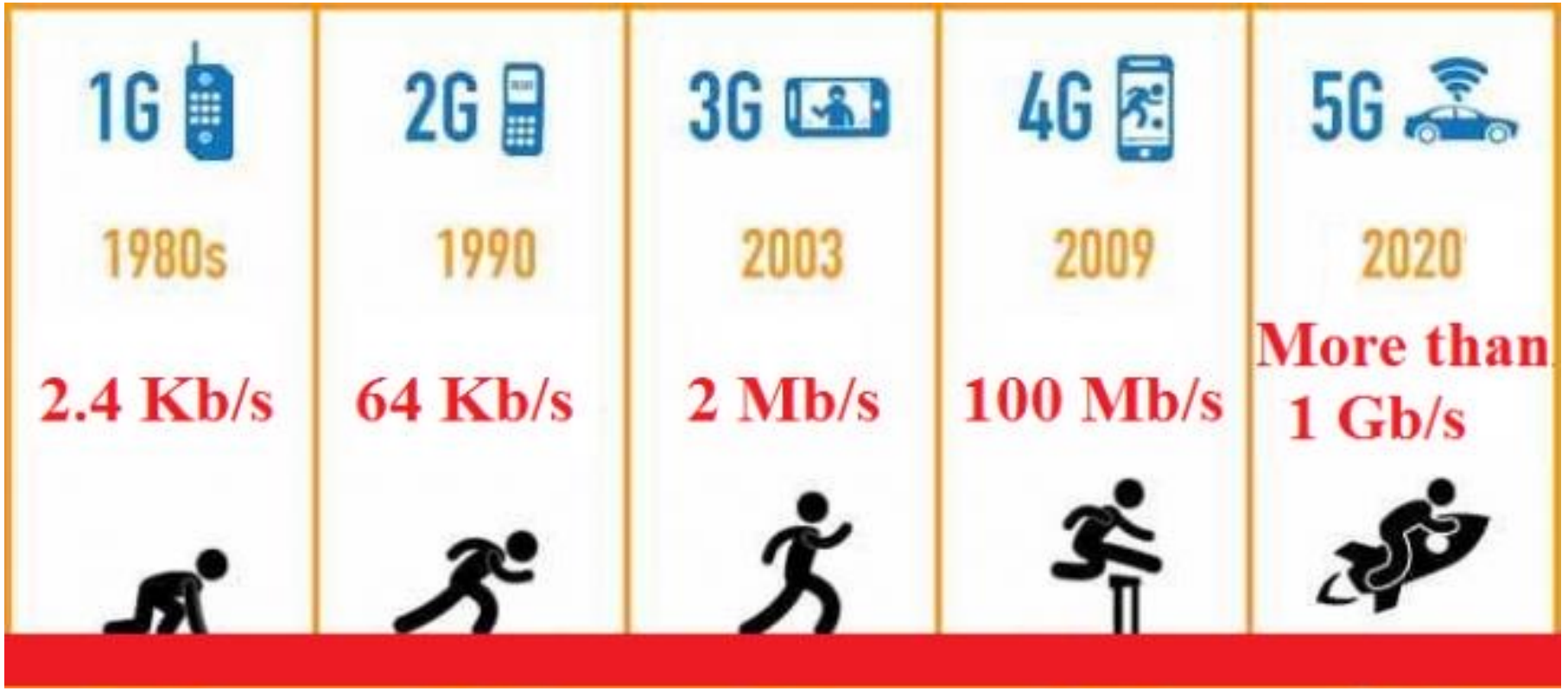


Cellular: Summary

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



Generations of Mobile Wireless Networks



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

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 analog voice and FDMA-based

Second Generation Cellular Systems

- The principal goals of second-generation wireless systems were:

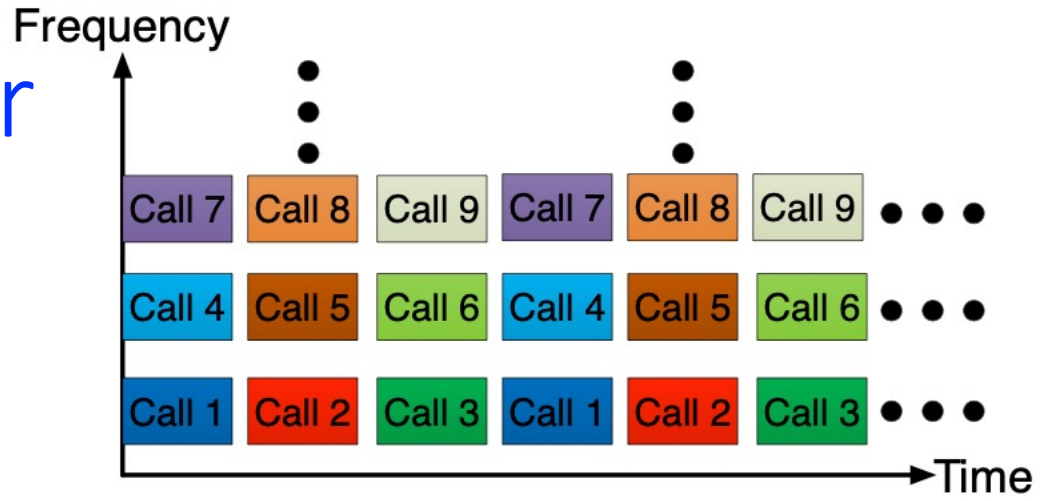
1. A digital system with higher capacity (hence lower cost) derived from digital techniques including …
   - efficient speech coding,
   - error-correcting channel codes
   - bandwidth-efficient modulation techniques

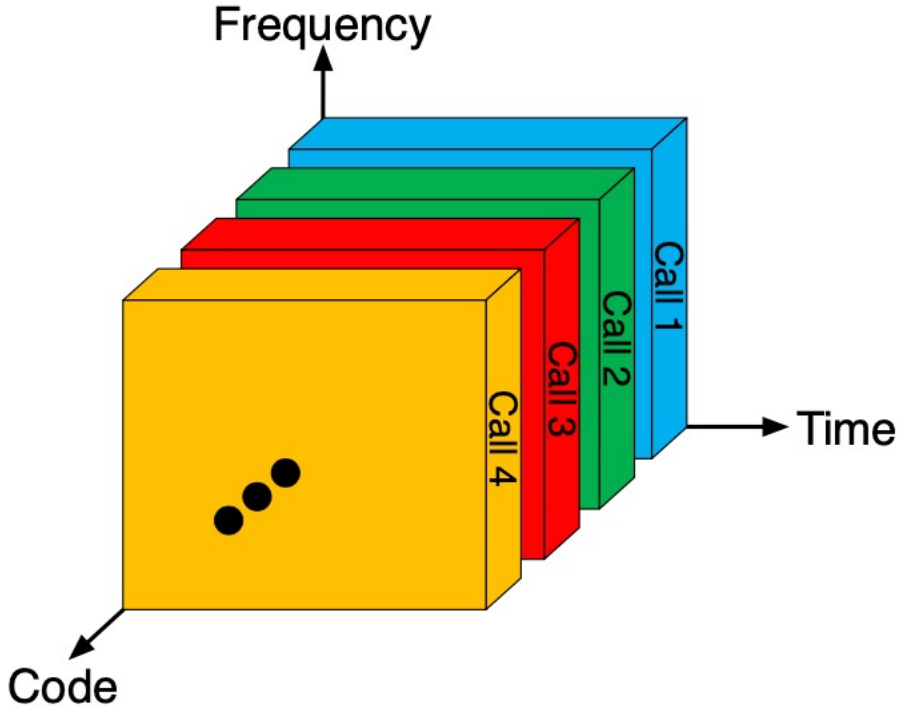
2. To offer, in addition to voice services, some rudimentary data services

Technologies for 2G Cellular

- Several standards and system designs proposed in 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

- For the most part, two standards prevailed:
  - GSM (a TDMA/FDMA standard)
  - IS-95 (a CDMA standard)





GSM (Example of a TDMA system)

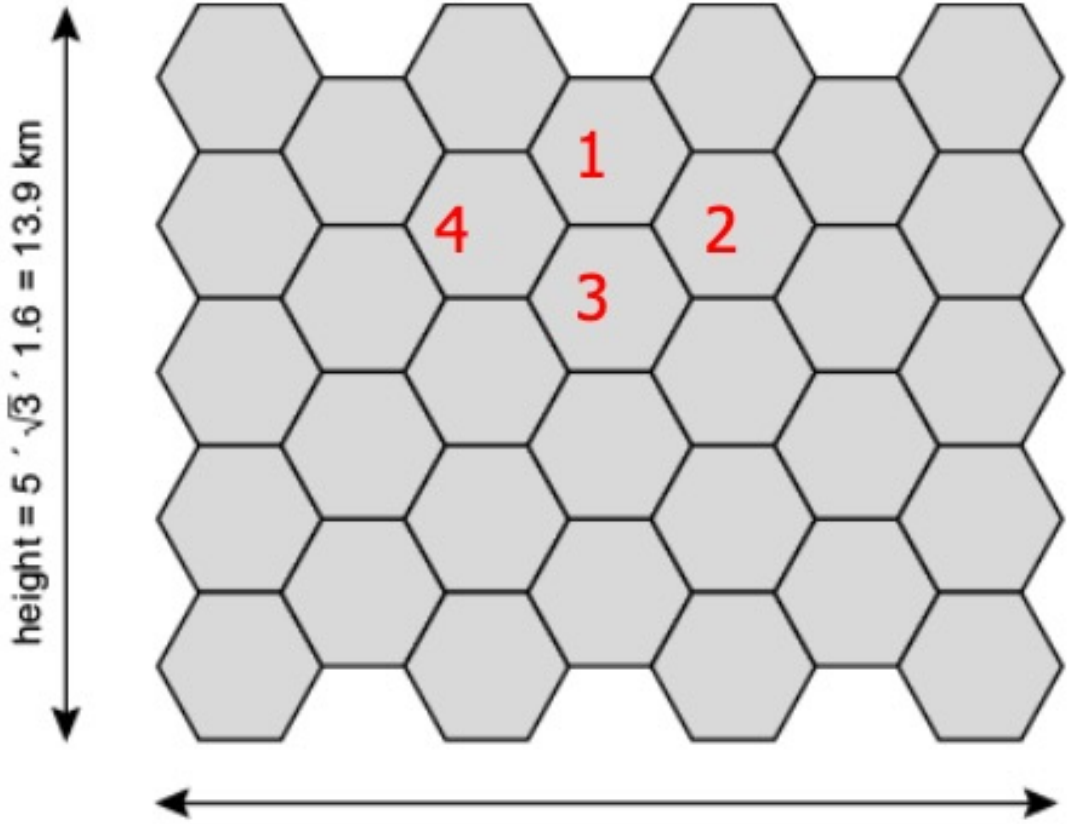
- GSM (Global System for Mobile Communications) was driven by …
  - need for a common mobile standard throughout Europe
  - desire for digital transmissions compatible with data and privacy

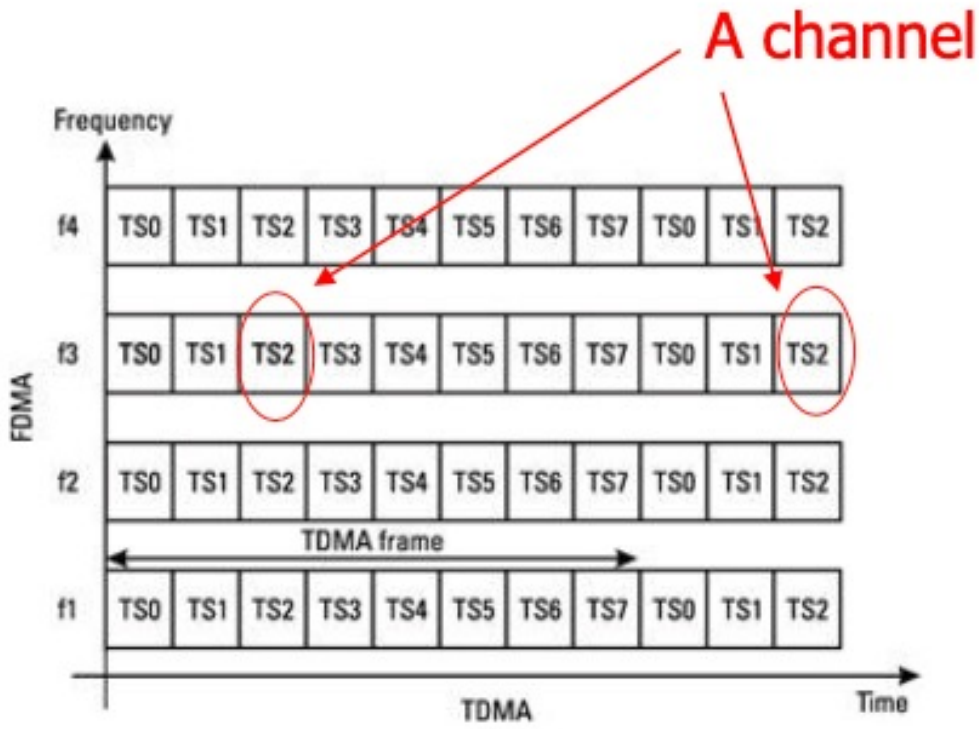
- Spectrum was reallocated for much of Europe near 900 MHz so that completely new technology could be developed around GSM

- The GSM effort in the mid-1980s considered several implementations including TDMA, CDMA, and FDMA. In the end, a TDMA/FDMA technology was chosen with a radio link-rate of 270 kbps

- Many third and fourth generation standards are extensions of GSM

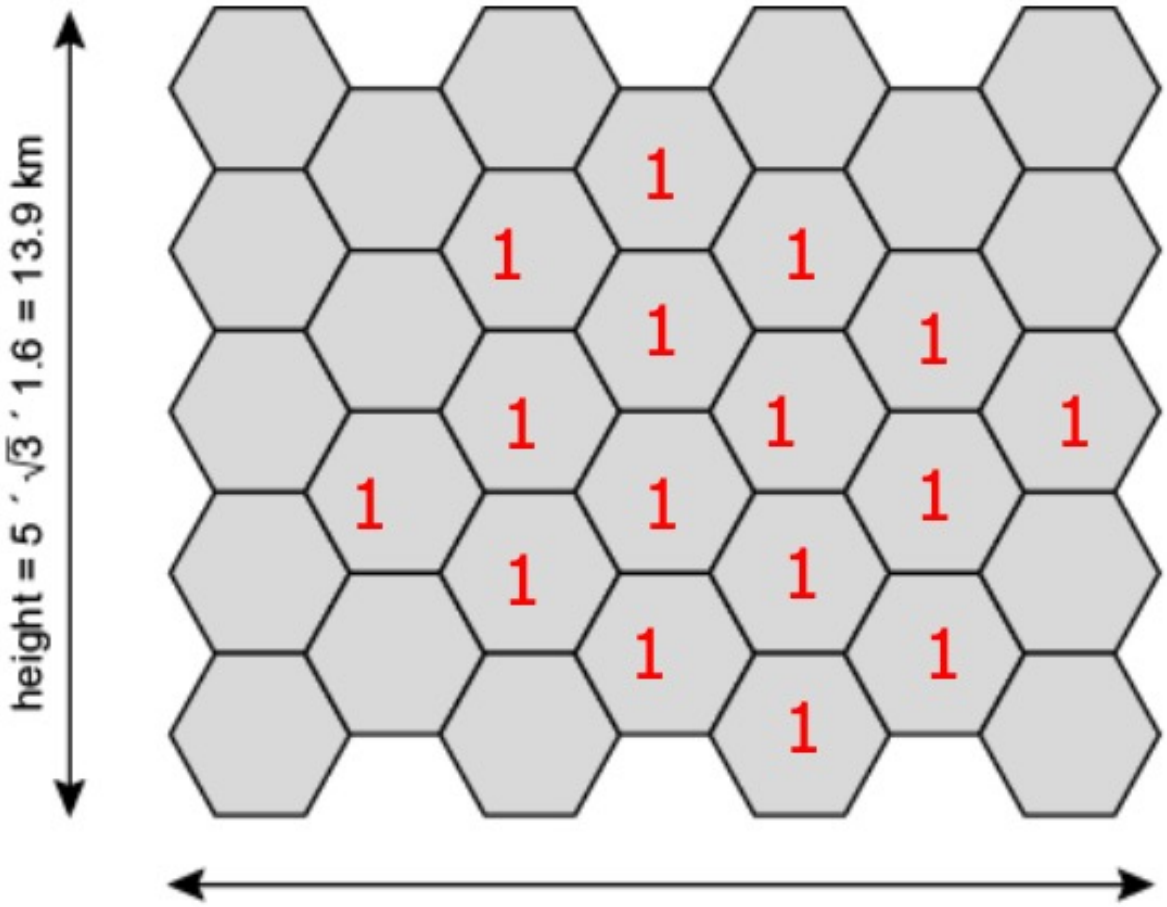
FDMA/TDMA in GSM





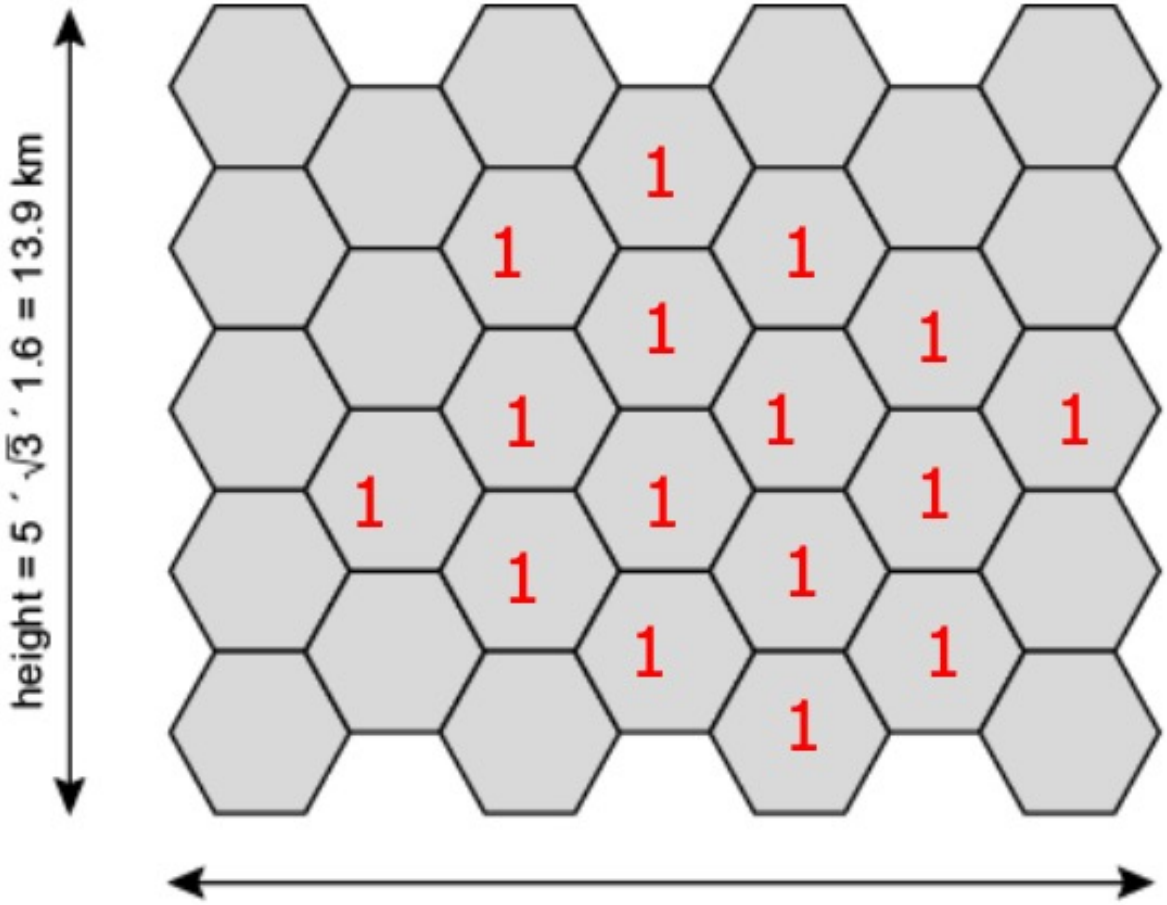
CDMA in IS-95

- All frequency channels are reused in all cells
- The frequency bands are also wider, 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



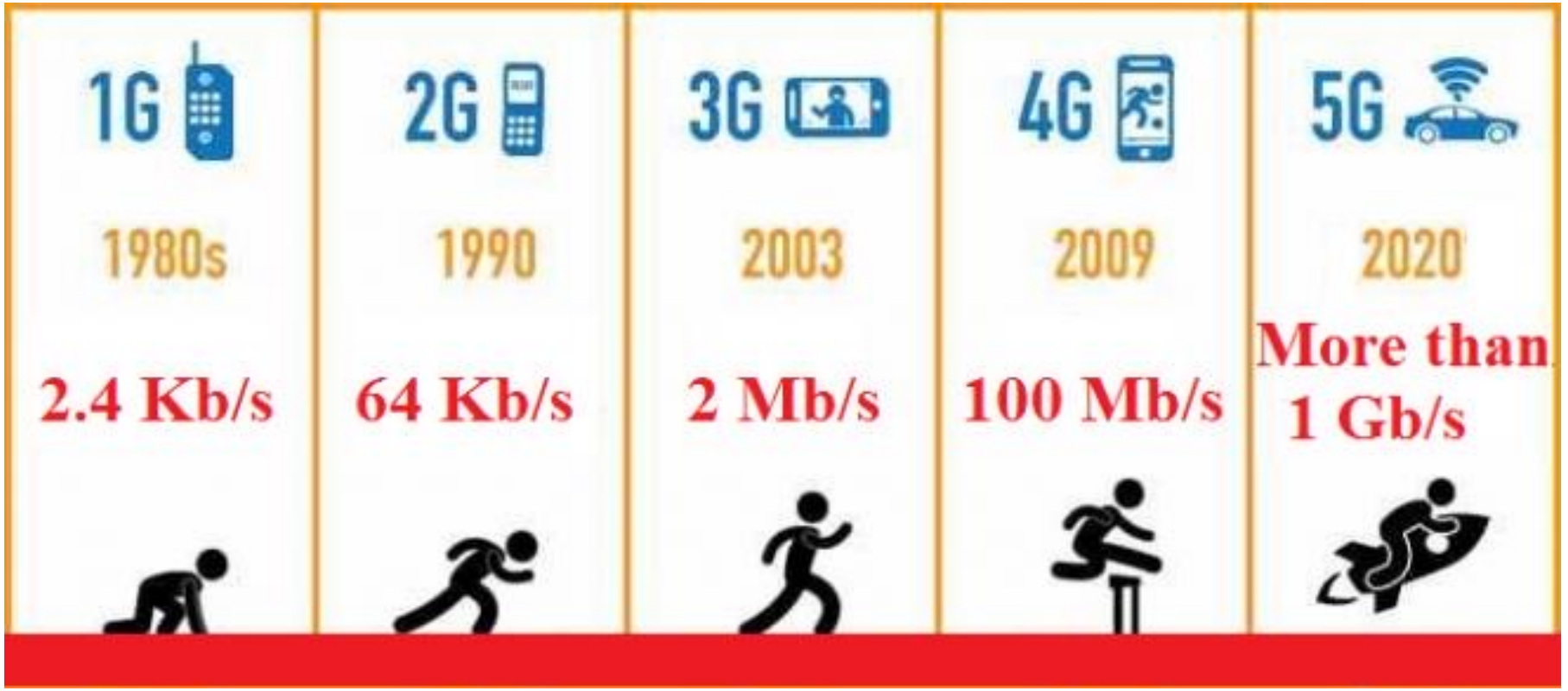
Code Division Multiple Access (CDMA)

- Claim by Andrew Viterbi (co-founder of Qualcomm): Because CDMA could use frequencies in all cells (universal reuse), capacity improvements are almost 30 times of TDMA/FDMA systems
  - We will examine the CDMA capacity later in the class
  - We will also examine distributed power control which manages interference

- CDMA also claims other benefits: Better multipath resistance, superior voice quality, increased call privacy, and soft handoff

- This frenzy about CDMA continues into 3G when all 3G systems are based on CDMA

Generations of Mobile Wireless Networks



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Third Generation Wireless Systems

- First-and second-generation digital systems were designed to support voice communication with limited data communication capability
- Third generation systems (and beyond) target offering high-data-rate communications and support for a wide range of applications
- Some key applications of 3G
  - Teleconferencing
  - Remote terminal access
  - Web browsing
  - Email

Extensions of GSM: GPRS/EDGE

- Generalized Packet Radio Service (GPRS)
  - Provides packet-switched data services at 5-100 kbps by reusing the existing narrow-band GSM channels/infrastructure for circuit-switched services
- Enhanced Data Rates for GSM Evolution (EDGE)
  - Uses adaptive modulation techniques and can produce 384 kbps maximum transmission
- Both GPRS and EDGE aim not to replace the current GSM infrastructure, but to co-exist with it
  - Achieving Mbps bit rates requires 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:

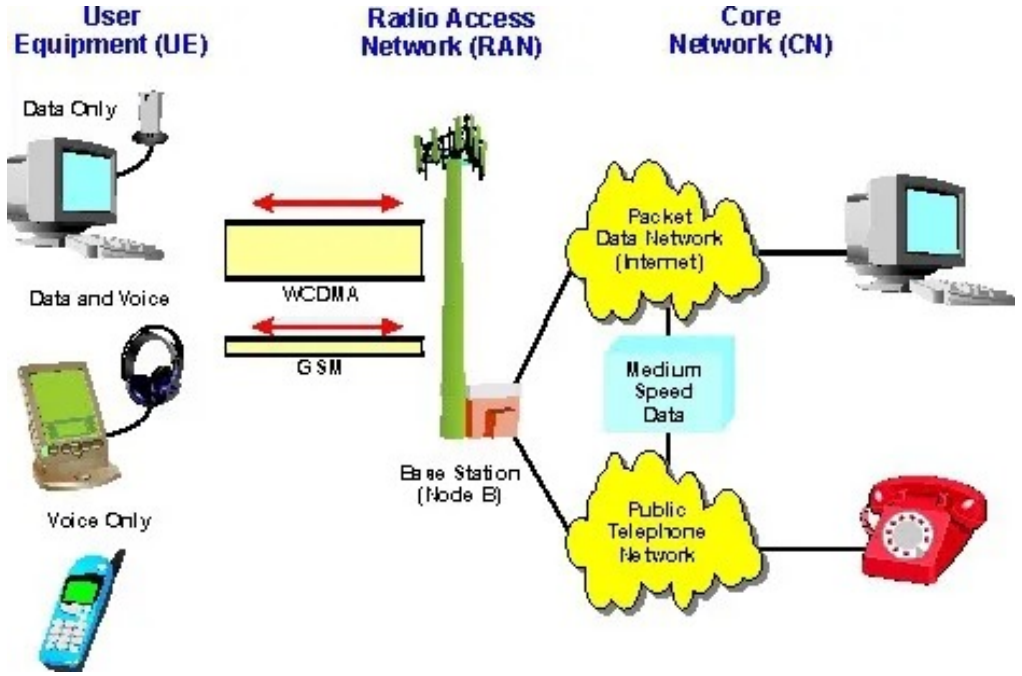
1. W-CDMA (or UMTS): CDMA Direct Spread, 5 MHz channel, Frequency Division Duplex (FDD)
   - Based on Europe (ETSI) and Japan (ARIB)'s FDD proposal

2. CDMA-2000: CDMA multi-carrier, multiple 1.25 MHz channels
   - Based on US (TIA)'s proposal

3. TD-SCDMA: CDMA TDD (time division duplex), multiple time slots
   - Based on China's proposal

Wideband CDMA

- W-CDMA was meant to serve as an evolution path for GSM
  - GSM → GPRS/EDGE → W-CDMA
  - Uses much of same core network as GSM
- CDMA 2000 was meant to serve as evolution path for IS-95
  - Including 1xRTT, EV-DO
- Envisioned bitrate support up to 2 Mbps
  - Sufficient for reasonably sophisticated multimedia applications
  - Over time, downlink speeds were able to reach 10+ Mbps



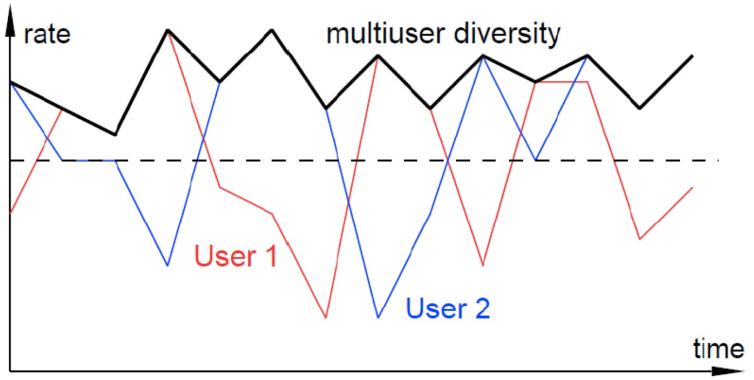
Key Technology in 3G Systems

- However, in 3G, what we refer to as “CDMA” is actually a very different way of resource/radio management and spatial reuse under the hood

- In each cell and channel, at most one user is active at a time
- CDMA is only to manage interference from other cells

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

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



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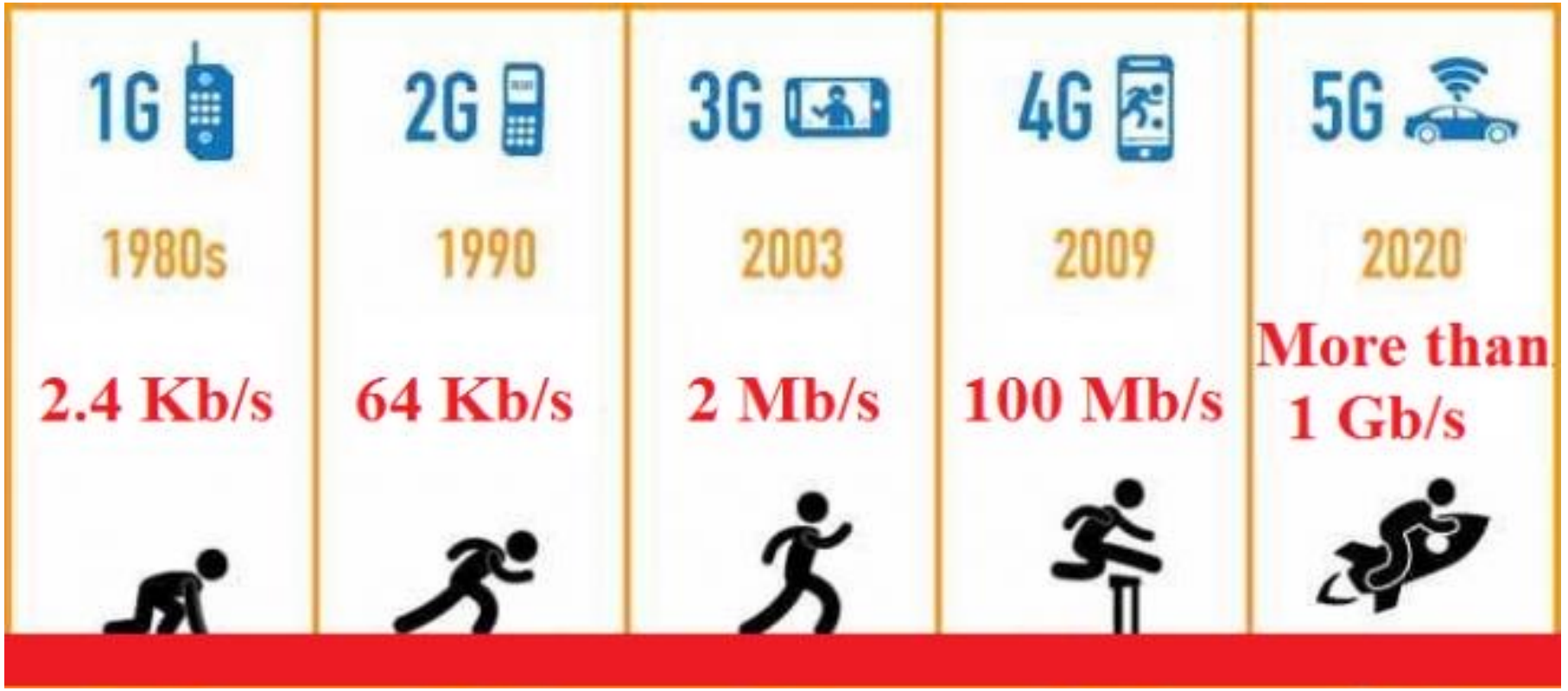

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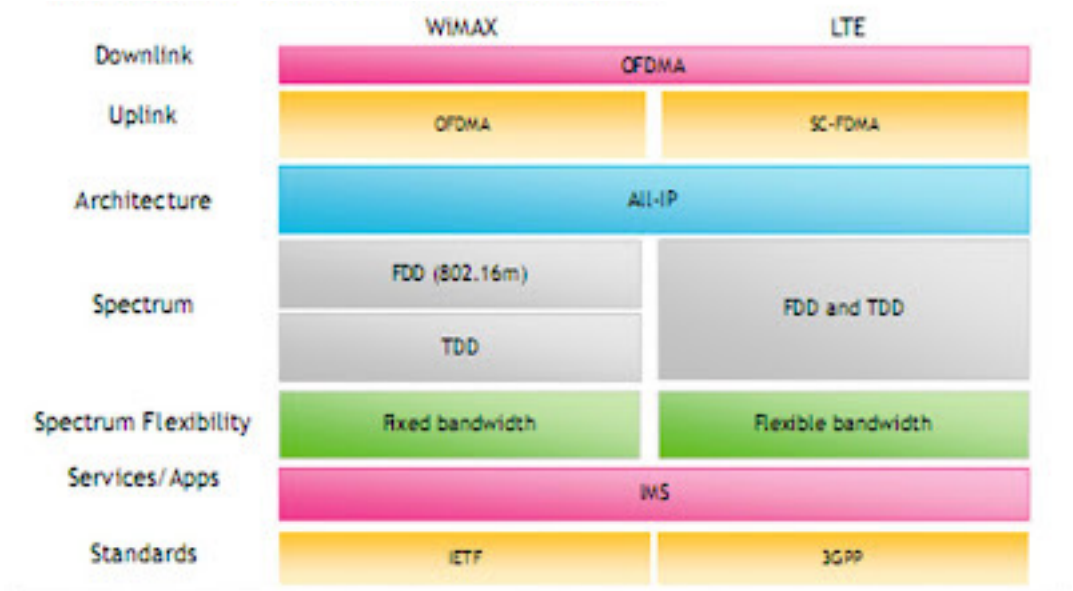
4G Wireless Systems

- Need to push the achievable data rate higher
  - Envisioned to attain 100 Mbps for high mobility, 1 Gbps for low mobility
- CDMA is abandoned, and OFDM is used instead
  - We will study the reason why
- High spectral-efficiency
  - Spectrum is scarce and expensive!
- Envisioned to be all IP, packet switched
  - Integrated service, like VoIP (voice over IP)

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

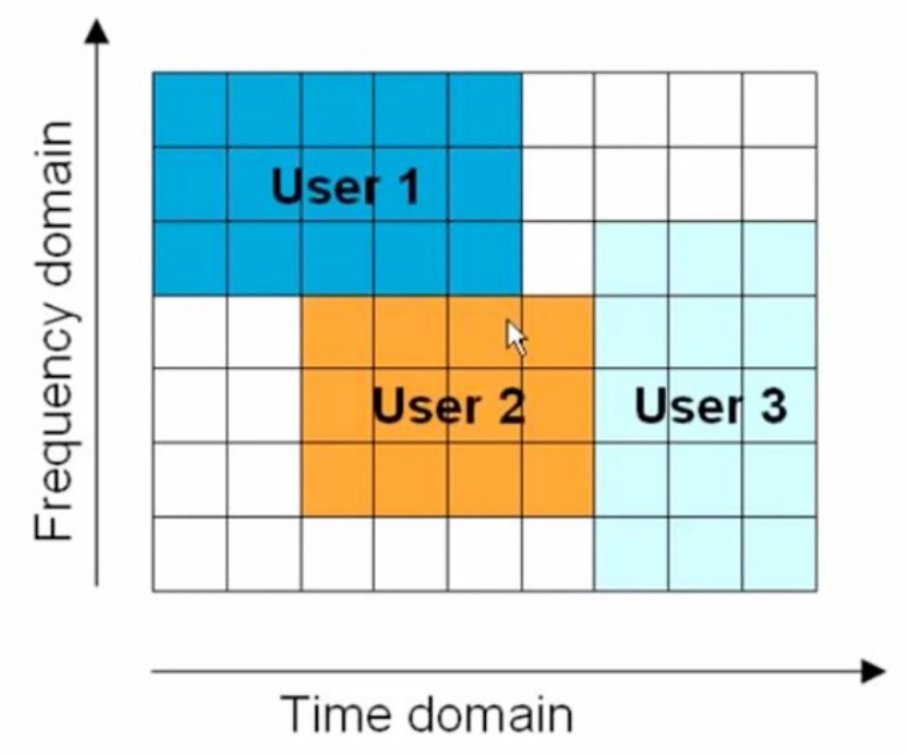
- With 100 MHz aggregated bandwidth, LTE-Advanced provides almost 3.3 Gbit peak download rates per sector of the base station
  - Under ideal conditions
  - Rate observed in practice may be lower, using 20MHz band

- Voice over LTE was to eventually get rid of legacy circuit-switched systems altogether

Key Technology for 4G LTE

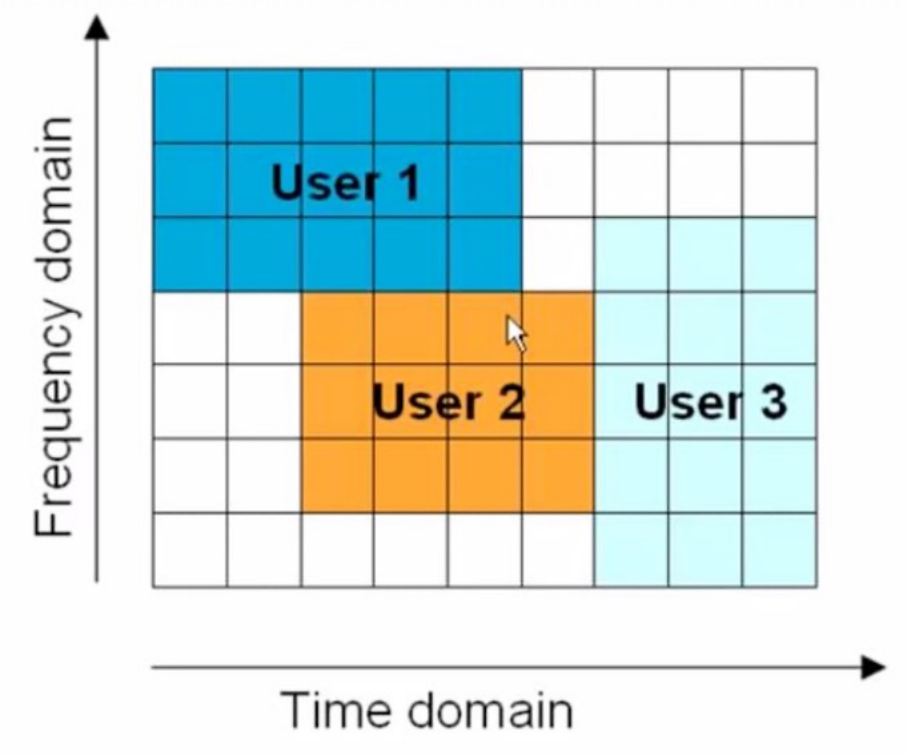
- OFDM: Orthogonal Frequency Division Multiplexing
  - More efficient frequency-time modulation
- MIMO: Multiple Input Multiple Output
  - Advances in physical layer technology
- HetNets: Heterogeneous networks of many small cells

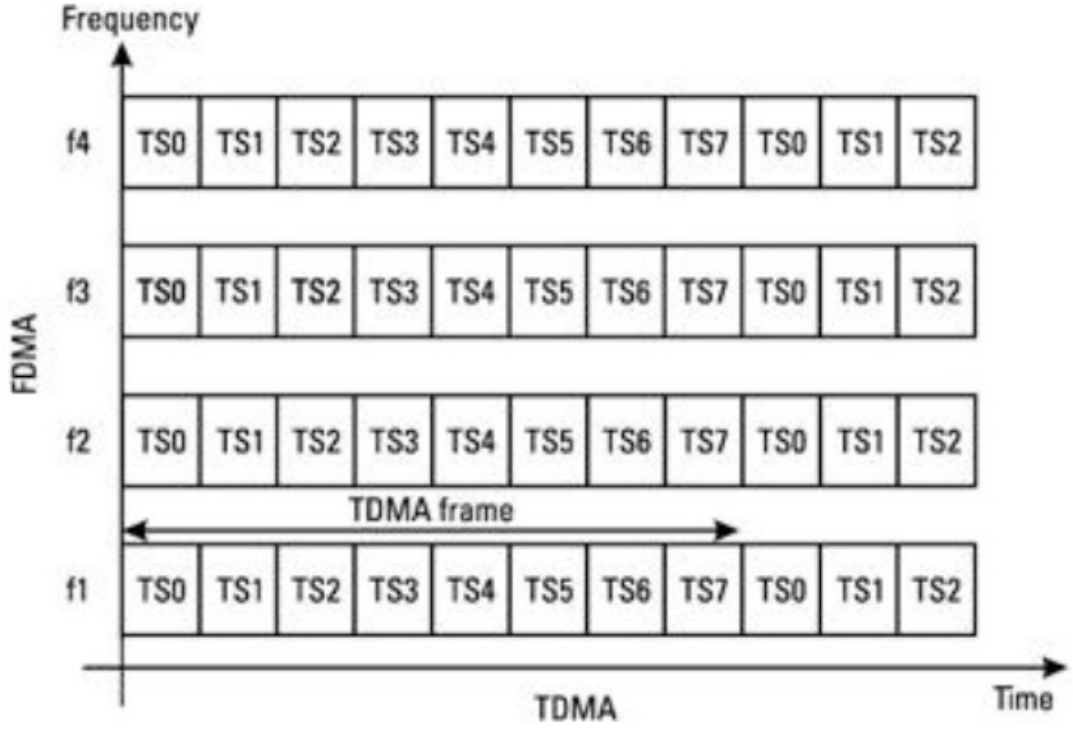
OFDM in 4G LTE



- OFDM divides a wide band into several 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

OFDMA in 4G LTE

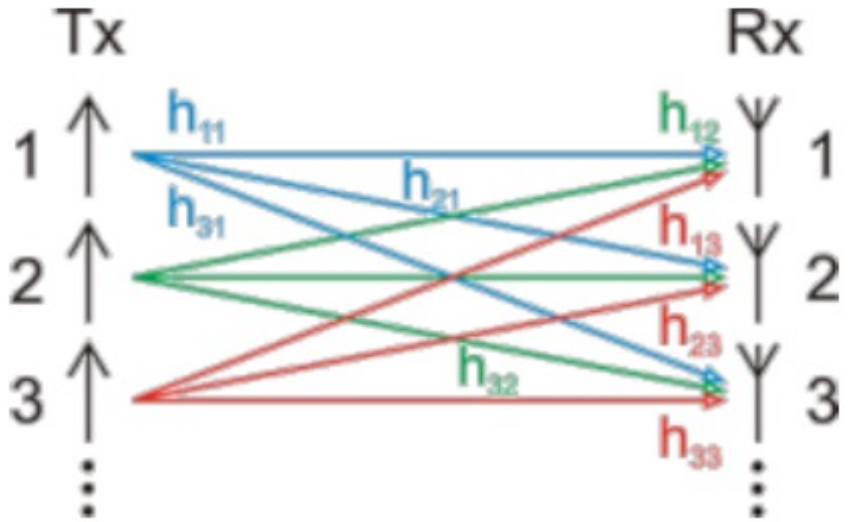




- OFDMA in 4G LTE
  - higher peak rate
  - better handling of freq. selectivity
  - higher spectrum efficiency

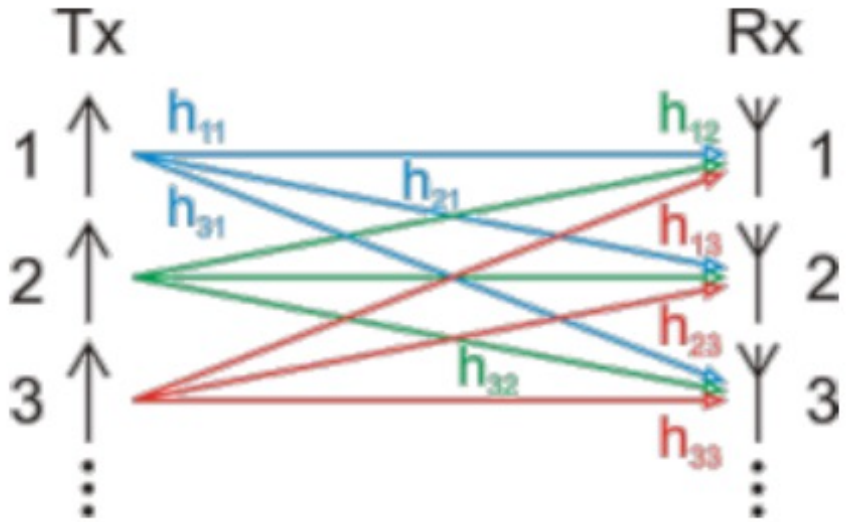
- TDMA/FDMA in 2G GSM

MIMO Transmissions



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

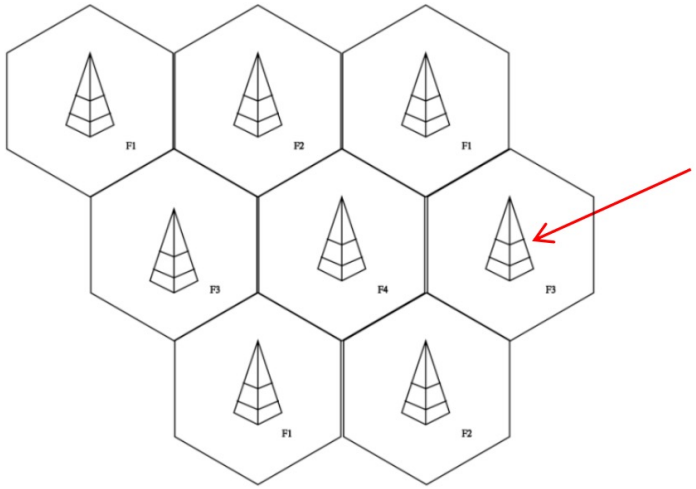
MIMO Transmissions



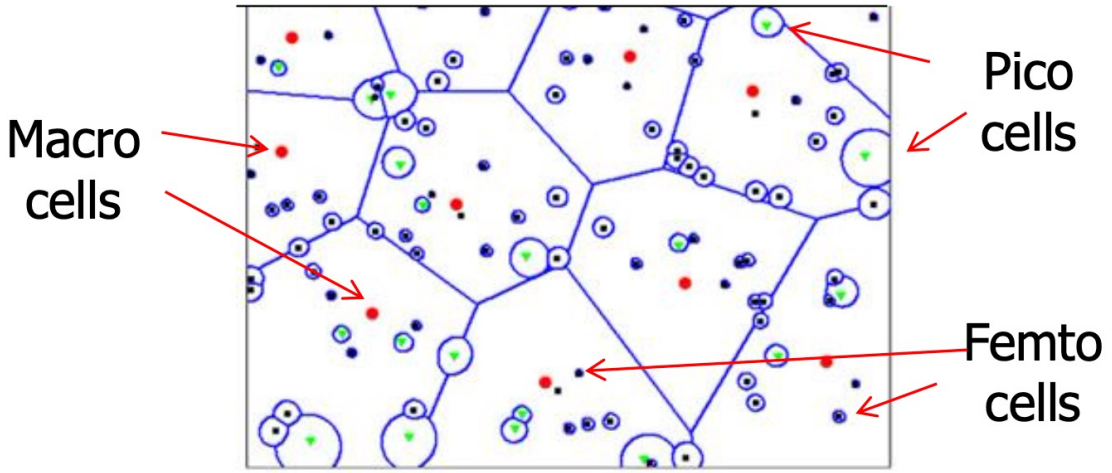
- MIMO is said to exploit spatial diversity
  - In contrast, opportunistic scheduling exploits frequency- and time- diversity
- Multi-User MIMO (MU-MIMO) can benefit even if the receiver only has a single antenna

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!



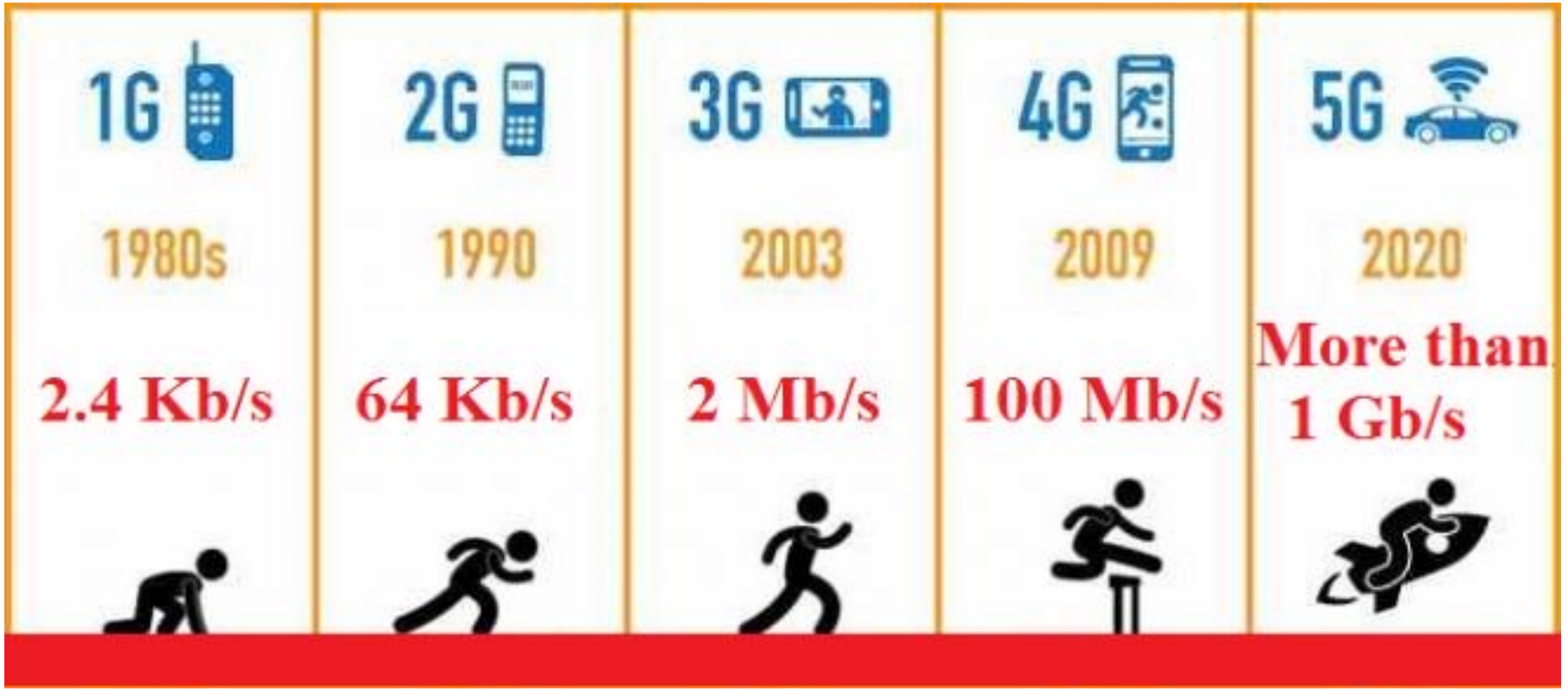
Traditional Cellular Networks



(Source: Prof. Jeffery Andrews, UT Austin)

Heterogeneous Cellular Networks

Generations of Mobile Wireless Networks



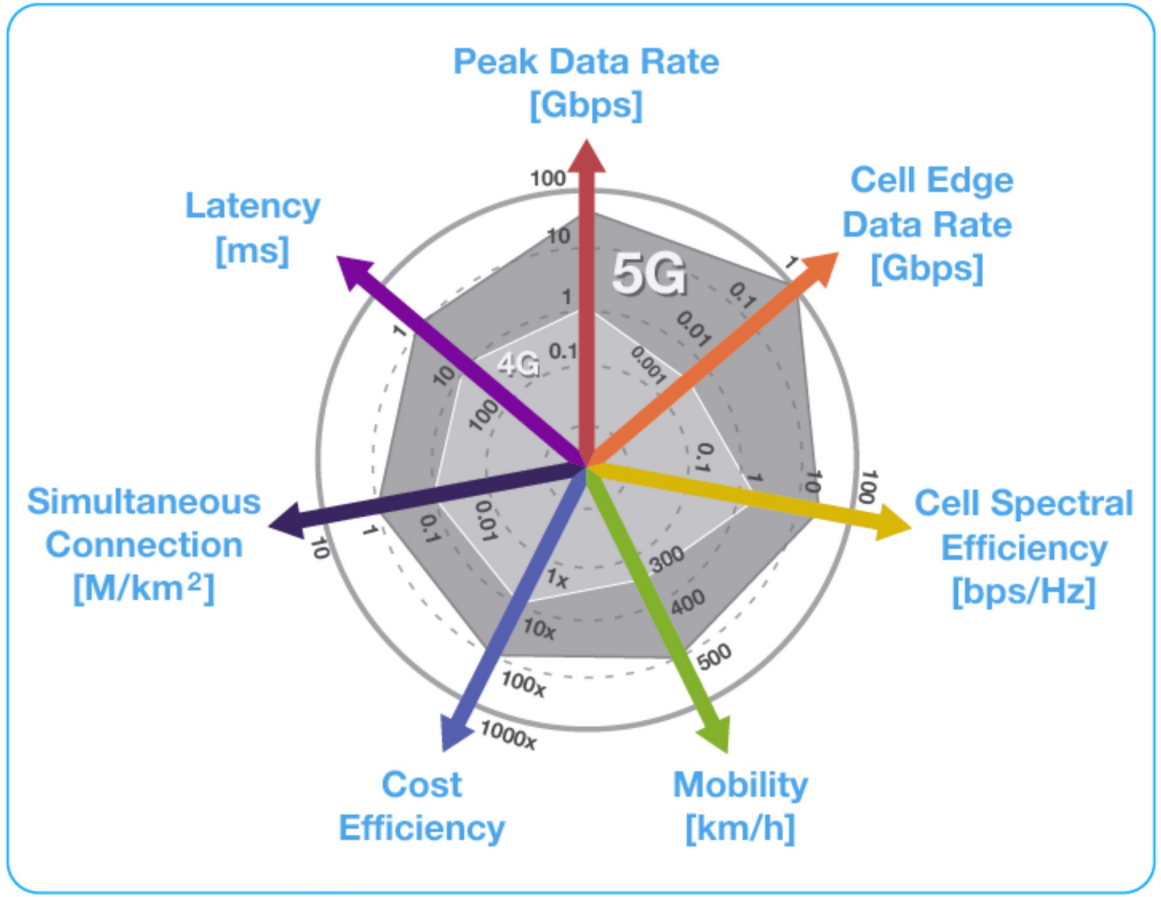
1981	1992	2001	2011	2020
Analog voice	Digital voice	Data service	OFDM	mmWave
Cellular	TDMA	Opportunistic	MIMO	Massive MIMO
FDMA	CDMA	scheduling	HetNets	NOMA

How about 5G?

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

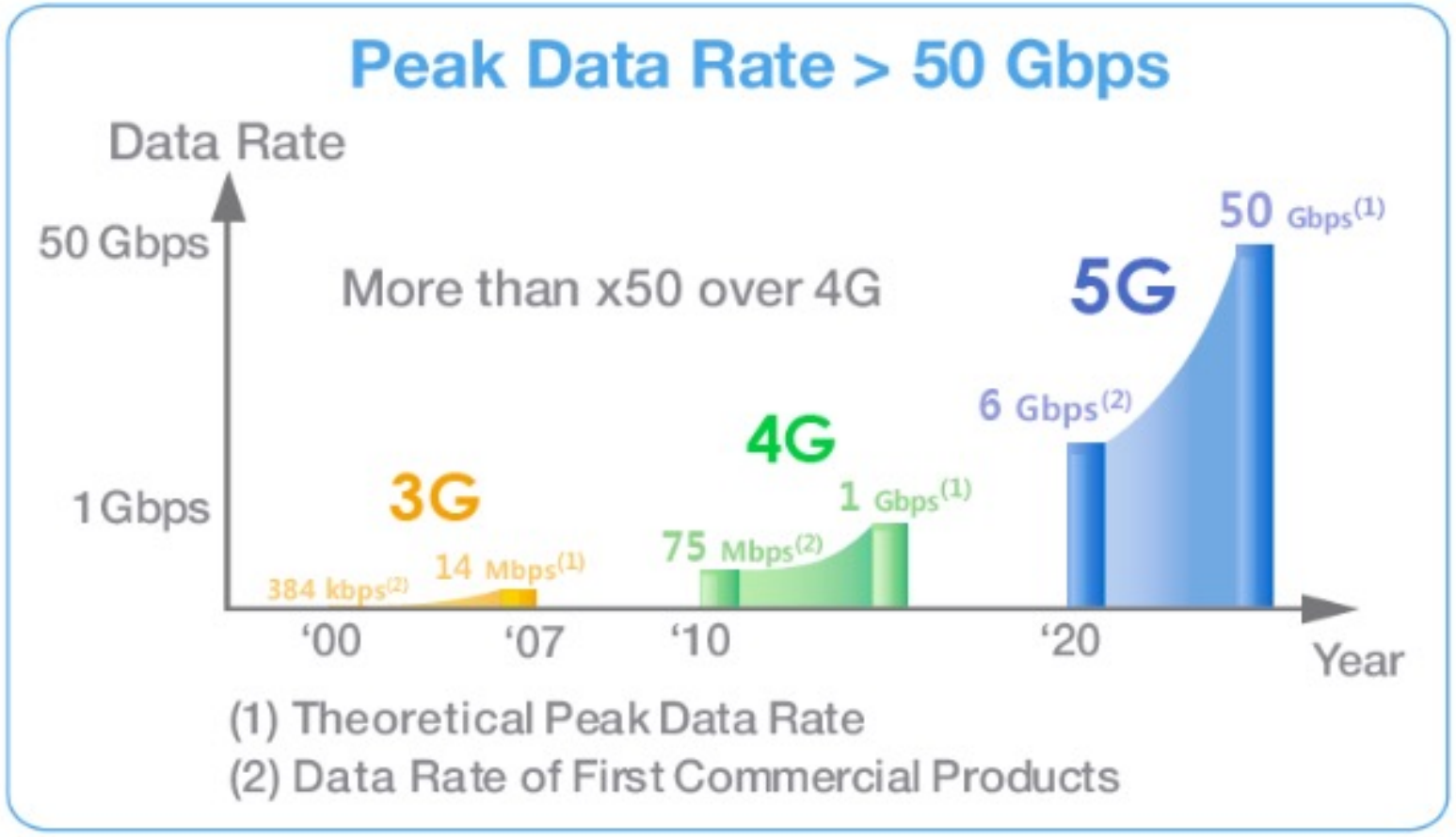
Wish Lists (3 Use Cases) for 5G

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



Source: Samsung

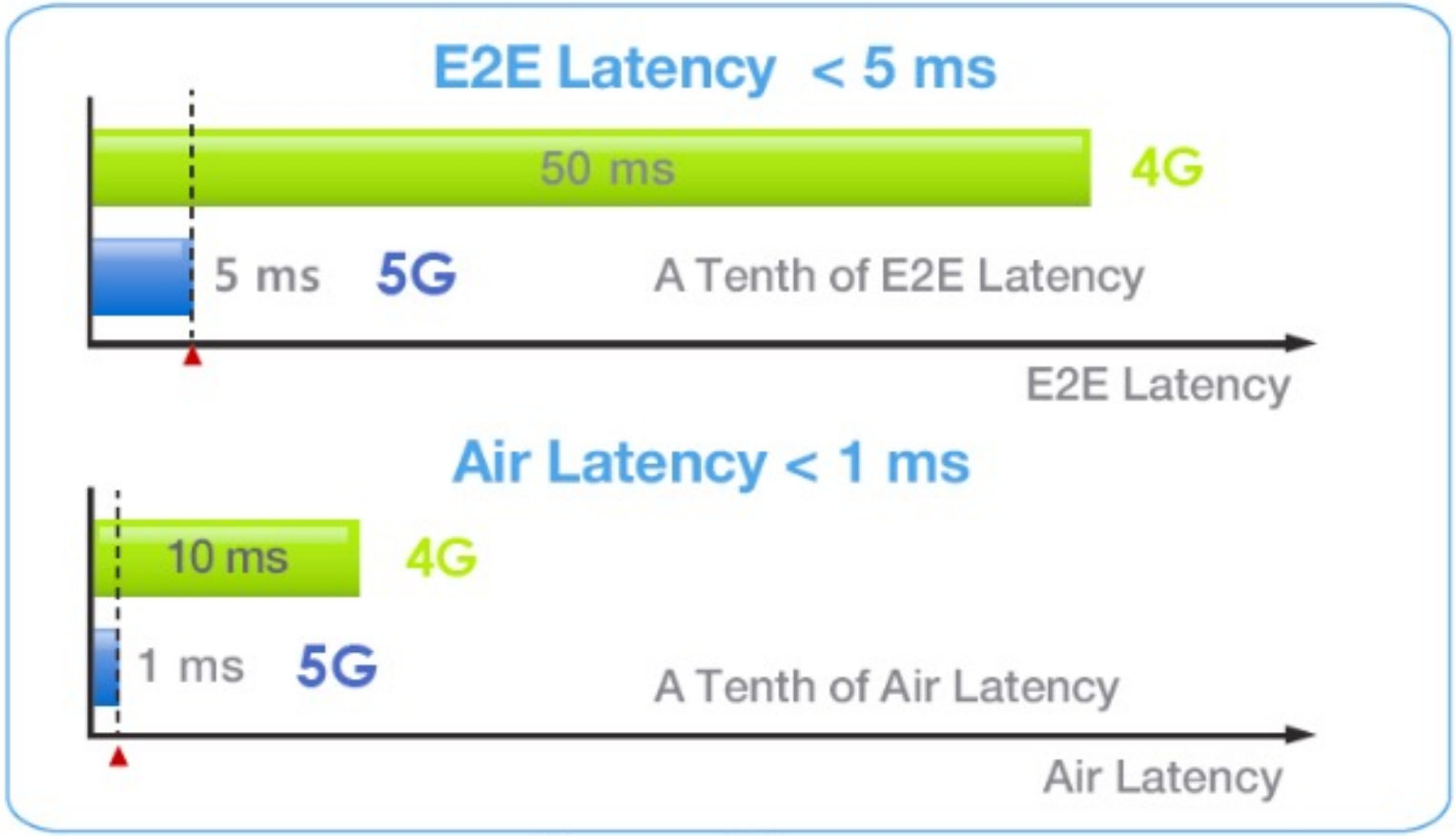
High Data Rate



Source: Samsung

- What driving applications?

Ultra Low Latency



Source: Samsung

- What driving applications?

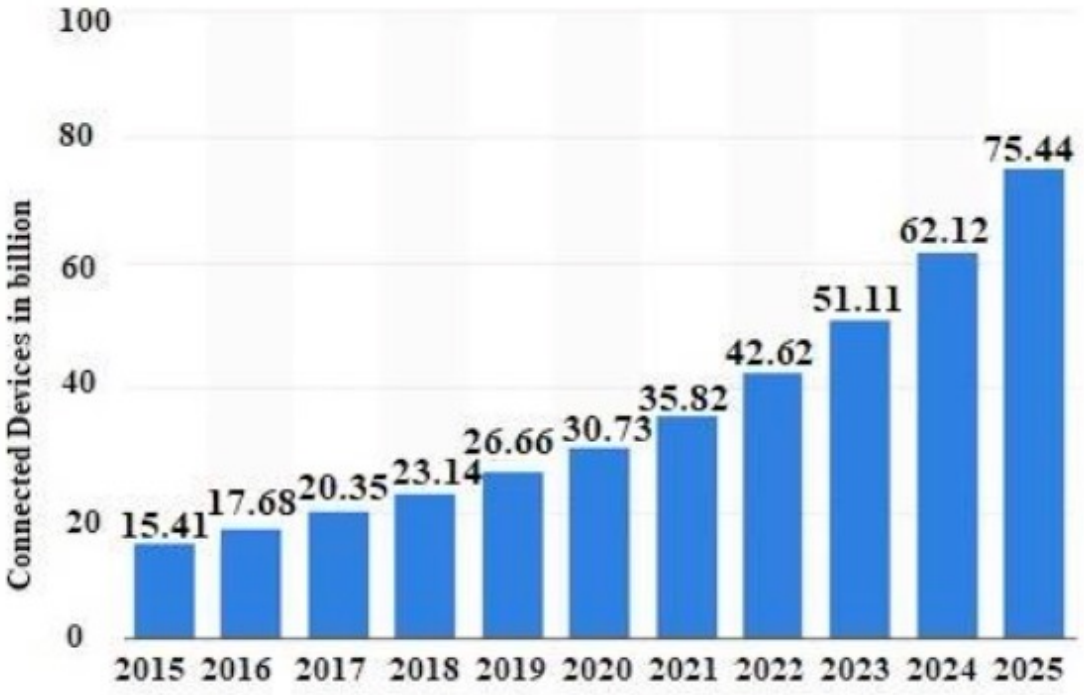
Ultra Low Latency

- Virtual Reality, Augmented Reality

- Automation, robotics, remote-control

Massive Connectivity

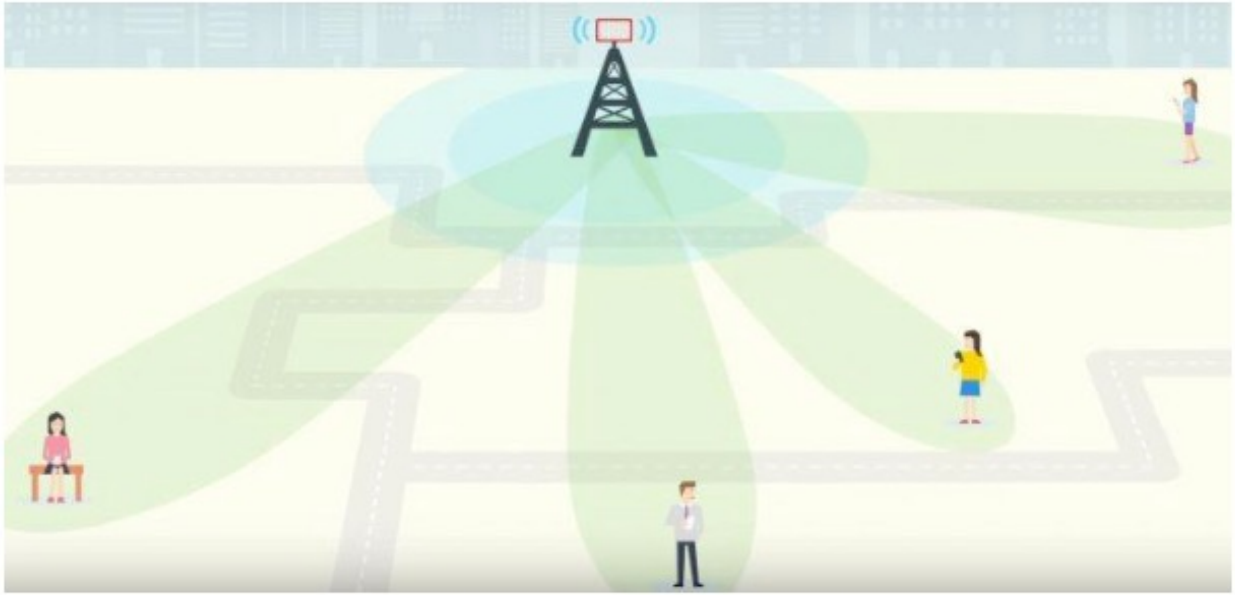
- Internet of Things (IoT)
- But each device may be heterogeneous and of low rate
- Low overhead is critical
  - Low latency
  - Low power



Some Technology used in 5G

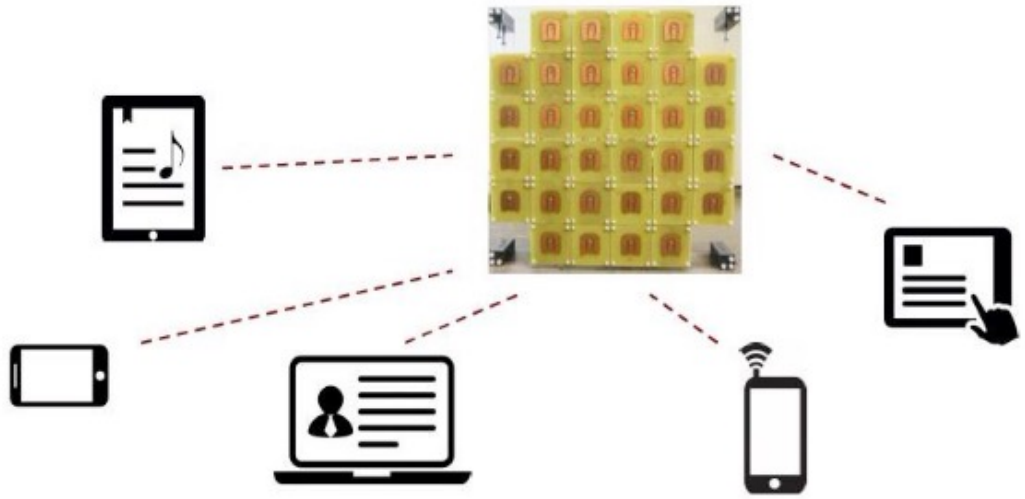
- mmWave
  - 30-300 GHz, sometimes including 24 GHz (about 10mm and below)
  - Much higher free-space loss
  - Absorption by atmosphere, rain, etc.
  - Line-of-sight propagation: Low diffraction, does not penetrate walls/objects

Some Technology used in 5G



- 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 Technology used in 5G



- 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)

Technology that may be used in 5G

- Non-orthogonal multiple 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.?

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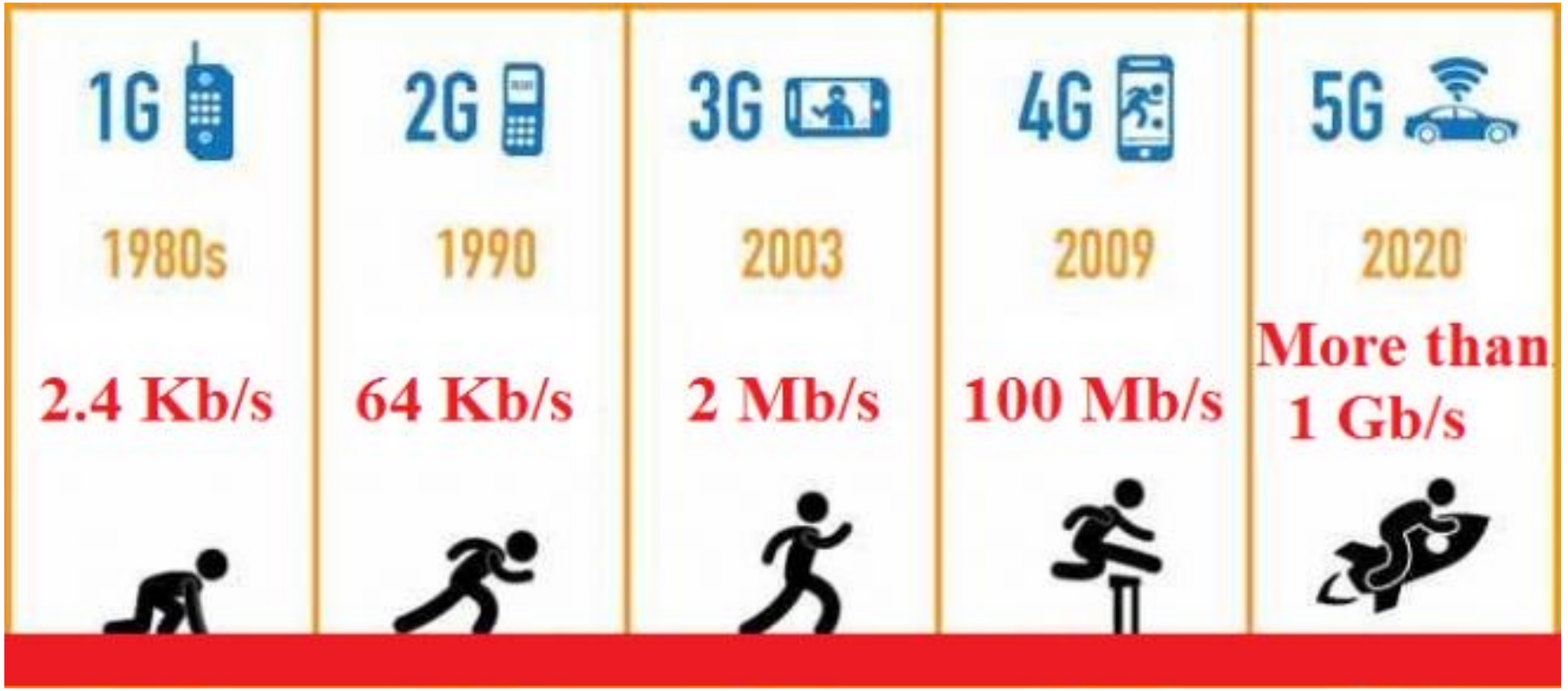

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Technology Competing with Cellular Systems

- Wireless LAN
- Bluetooth
- Ad Hoc Networks

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

In Summary

- Demand for service keeps increasing
- Although the cellular concept prevails, there has been 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

Many Detailed Questions

- How to deal with variations in channel quality?
- How to maximize the network-layer benefits 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?