Cellular Networks

Overview

1. Cell Structure/Geometry
2. Cellular Frequency Reuse
3. Cellular Handoff
4. Cellular System Capacity
5. Overview of Cellular Generations: 1G→2G→3G→LTE/4G→5G

Wide Area Networking

- Bluetooth is good to exchange short messages between two devices located close to each other (~10m)
- WiFi is good mainly within a home/building (~20-50m)
- How about wide area networking (many kilometers)?
- Cellular networking addresses wide area; much more complex and expensive

Bluetooth

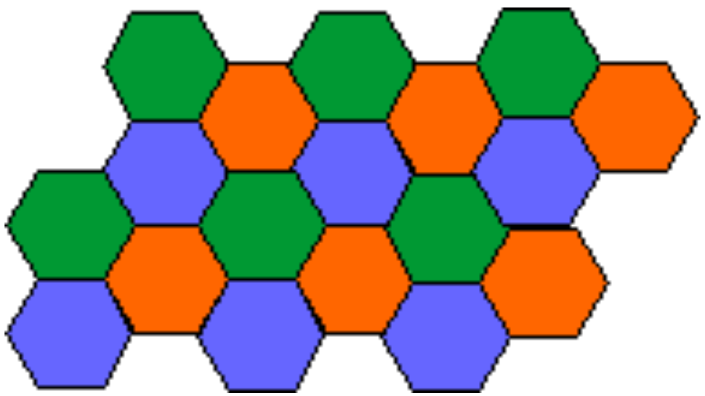
WiFi

Cellular

Cellular Concept

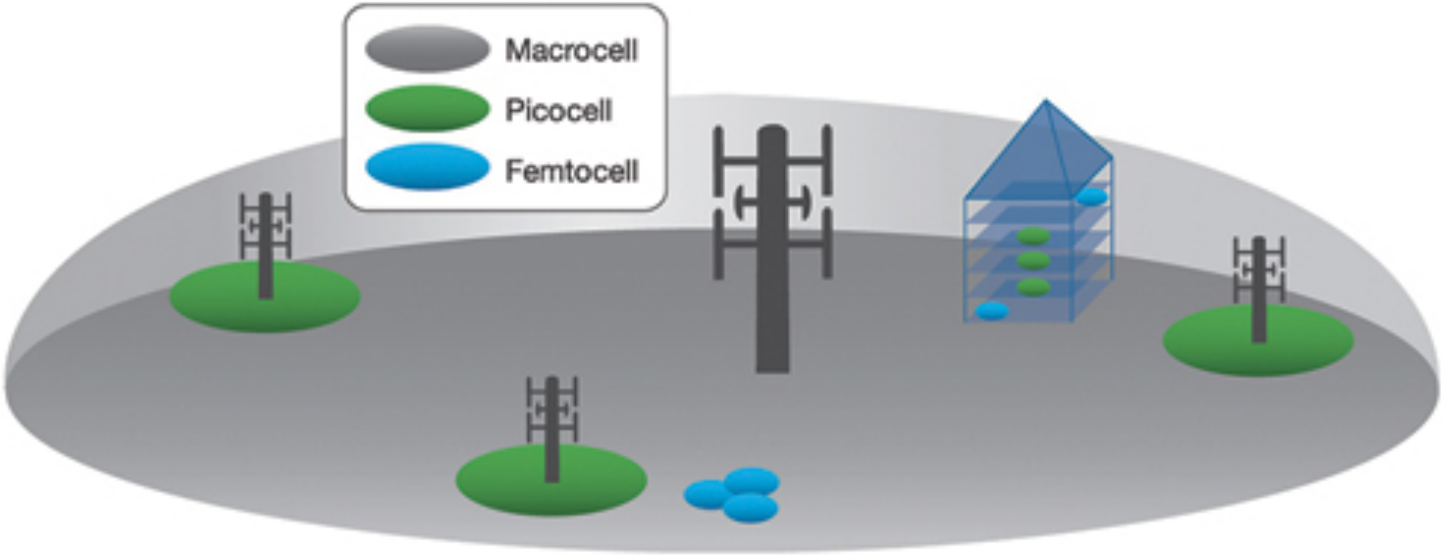
- First proposed in '70s; commercial services offered early '80s
- A large geographic service area is divided into many smaller cells; no matter where you are located, you are always within a cell
- Each cell has a base station to connect users within the cell; all base stations are in turn connected to a central control system
- Adjacent cells must not use the same frequency to avoid interference
- The same frequency can be reused by a `distant' base station increase reuse the spectral resources and increase system capacity

3 frequencies, red, green, and blue, reused by distant cells



How large are the cells?
Macro, Micro, Pico, Femto Cells

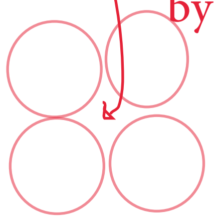
- Macro: Sections of a city, more than 1 km radius
- Micro: Neighborhoods, less than 1 km
- Pico: Busy public areas: Malls, airports, …, 200 m
- Femto: Inside a home, 10 m

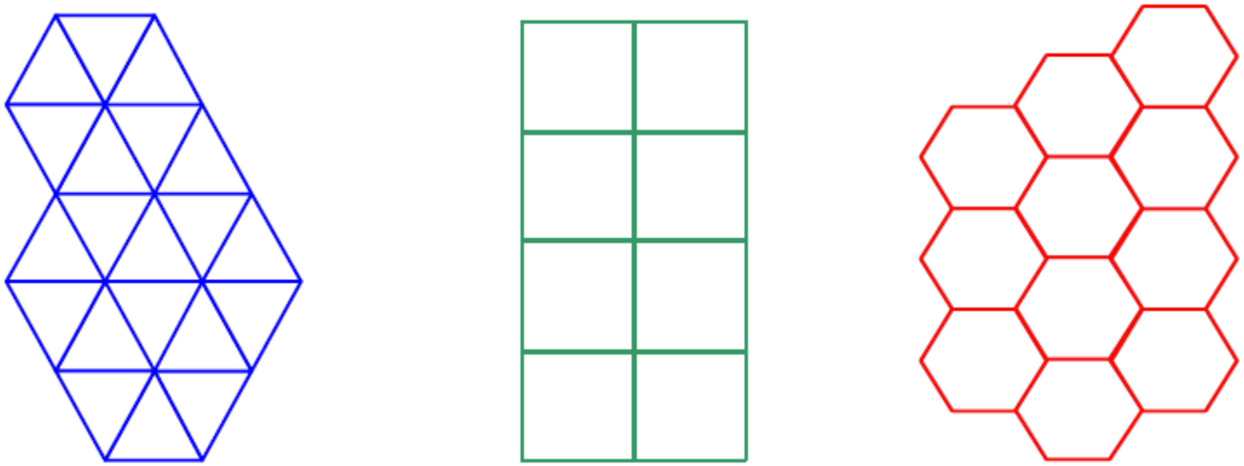


Cell Geometry

- Although there is no regular cell geometry in practice due to natural obstacles to radio propagations, a model is required for planning and evaluation purposes
- Simple model: All cells have identical geometry and should *tessellate* perfectly to avoid any coverage gaps in the service area
  - Radio propagation models lead to circular cells, but circles do not tessellate!
- Three options for tessellation: equilateral triangle, square, regular hexagon
- Hexagon has the largest area among the three; hence its typical use

not covered
by any BS!





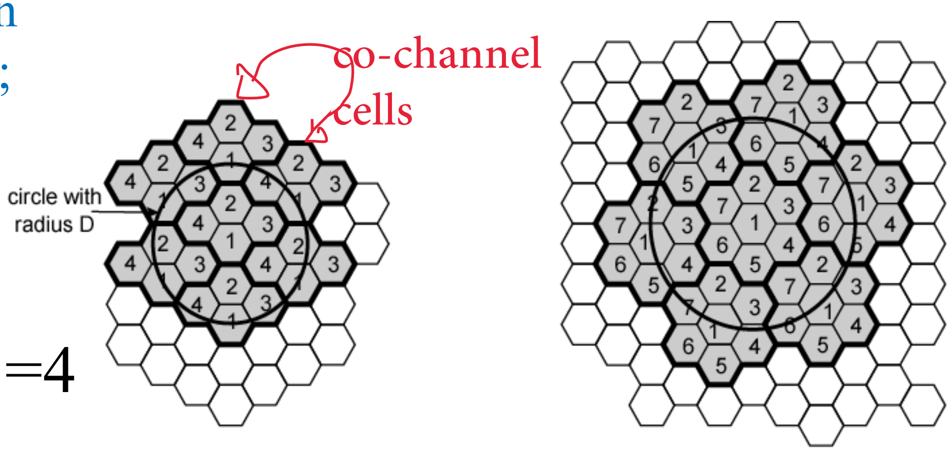
Frequency reuse and clustering

- Adjacent cells cannot use the same channel due to interference
- All cells in the service area are grouped into many clusters; the total spectrum is divided into sub-bands that are distributed among the cells within a cluster; the spatial distribution of sub-bands within the cluster should make sure that adjacent cells do not share the same sub-band
- A cluster of cells together use the entire spectrum
- By dividing the service area into many clusters, the operator can reuse the allocated spectrum spatially over the entire service area

Cluster Size

Clusters are shown with solid borders; N represents cluster size

co-channel cells

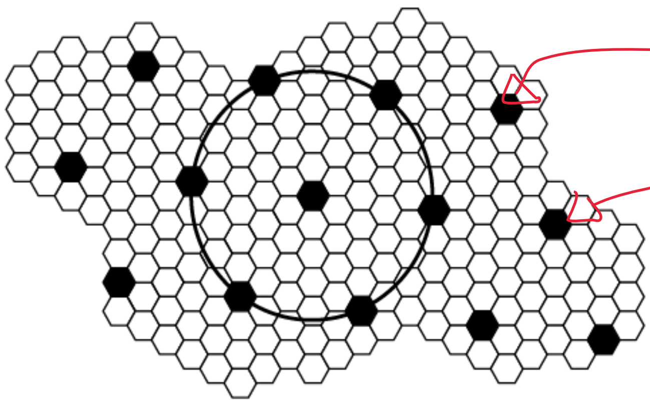


Cluster Size =4

Cluster Size =7

(a) Frequency reuse pattern for N = 4

(b) Frequency reuse pattern for N = 7



co-channels are further apart

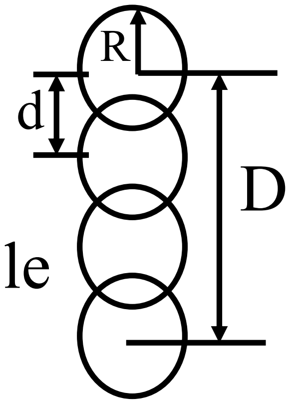
Cluster Size =19

(c) Black cells indicate a frequency reuse for N = 19

Characterizing Frequency Reuse

- D = minimum distance between centers of cells that use the same band of frequencies (called co-channels)
- R = radius of a cell
- d = distance between centers of adjacent cells (d = R√3)
  - d < 2R due to *overlapping* cells
- N = number of cells in repetitious pattern (**Cluster**)
  - Frequency Reuse Factor = 1/N
  - Each cell in cluster uses unique band of frequencies
- For hexagonal cells, following values of N are possible
  - $N = I^2 + J^2 + (I \times J)$, I, J = 0, 1, 2, 3, …
- Possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, …
- Reuse Ratio = Distance/Radius = $D/R = \sqrt{3N}$
- $D/d = \sqrt{N}$

i = 2
j = 0



Example

distance between co-channel cells (D)

Q. What would be the minimum distance between the centers of two cells with the same band of frequencies if *cell radius* is 1 km and the *reuse factor* is 1/12?

Sol. R = 1 km, N = 12

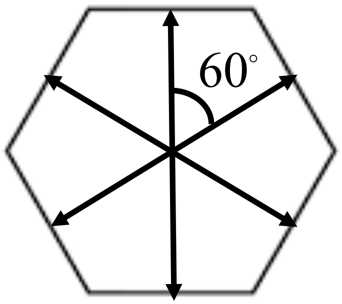
$D/R = \sqrt{3N}$

$D = (3 \times 12)^{1/2} \times 1$ km

$= 6$ km

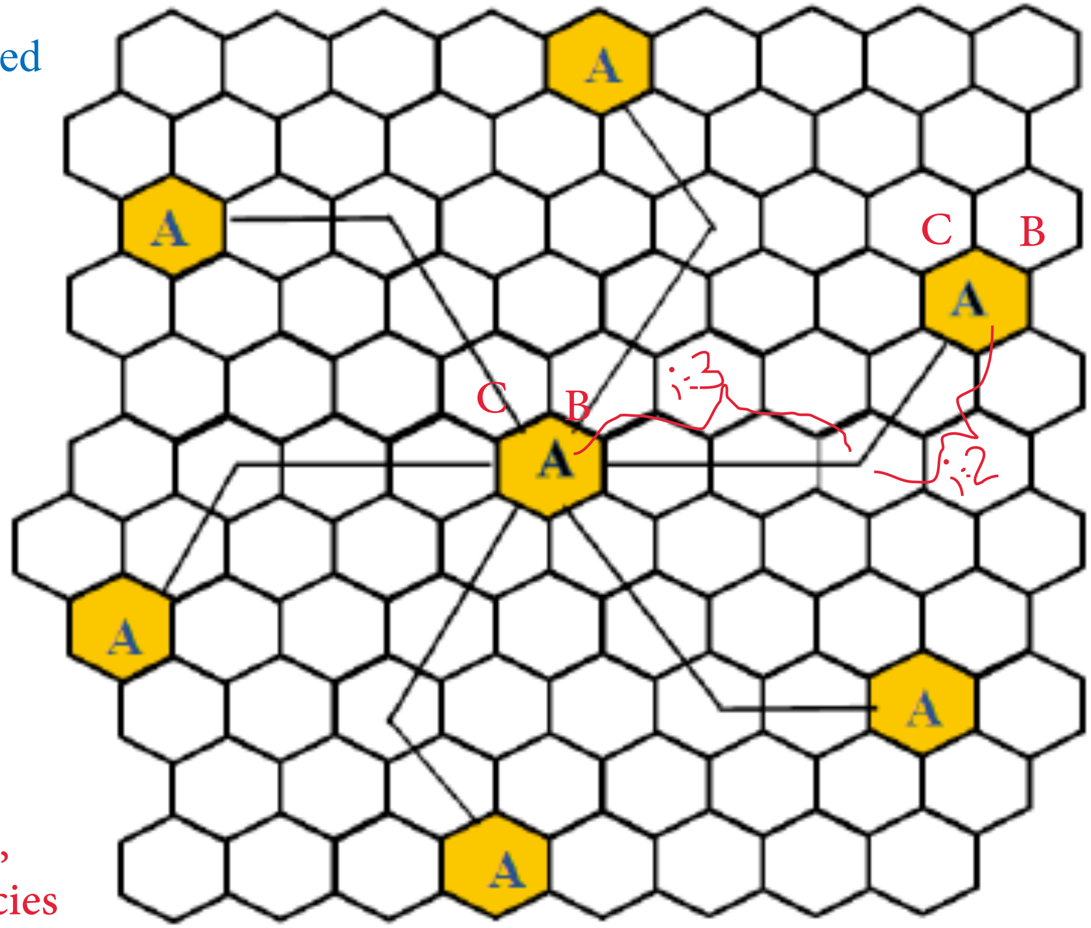
you cannot reuse the spectrum before 6km

Locating Co-channel Cells



6x60 = 360 degrees

6 directions of a hexagon, separated by 60 degrees

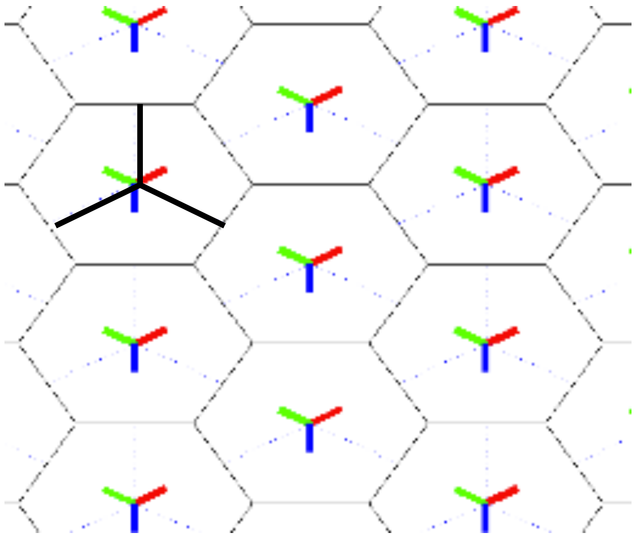


- Move i cells in any direction
- Turn 60° counter-clock and move j cells

if you switch the values of i and j,
the physical locations of frequencies
will be slightly different, but you will still
have the same frequency re-use factor in your system i=3, j=2; N=19

How to distribute channels among cells within a cluster?

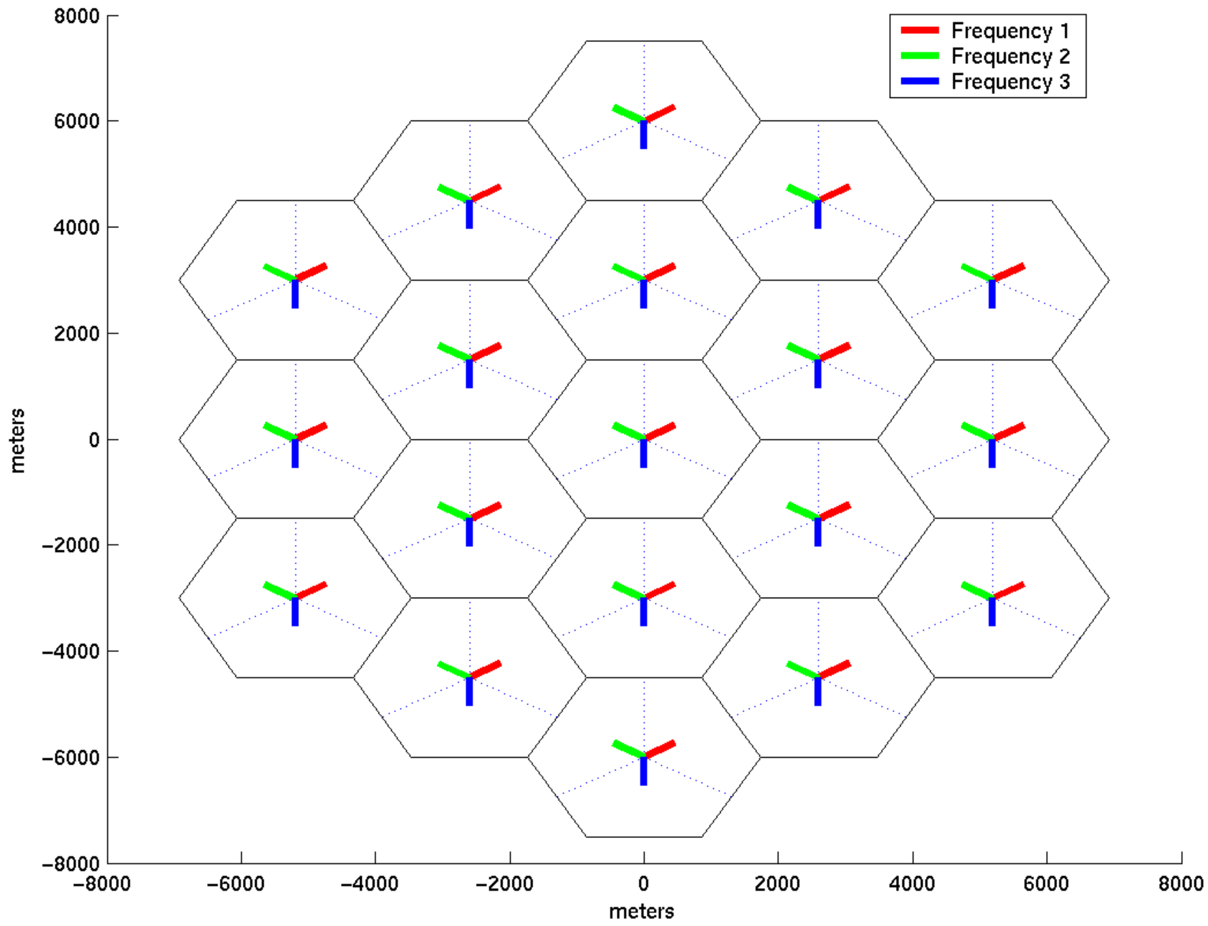
- For simplicity, it is assumed that the total spectrum is divided equally among all cells in the cluster
  - T (total channels), N (cluster size), K (number of channels per cell)
  - K = T/N
- Cells are usually divided into sectors; channels allocated to a cell is then further sub-allocated to different sectors according to the load/demand in each sector; spatial allocation of channels to sectors should try to minimize interference/overlap with the adjacent cell sectors



Frequency Reuse Notation

- N × S × K frequency reuse pattern
- N=Number of cells per cluster
- S= Number of sectors in a cell
- K = Number of frequency/channel allocations per cell

1X3X3

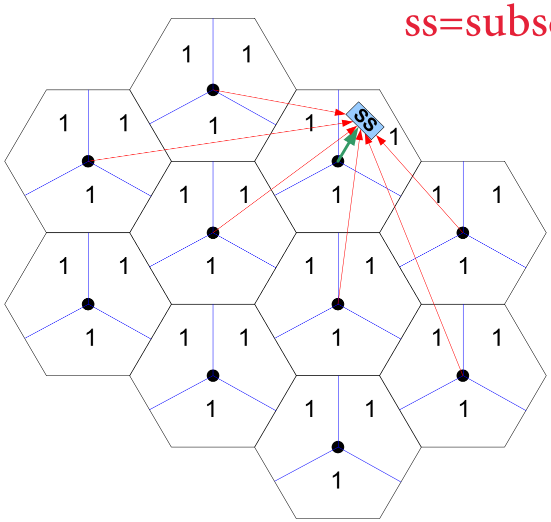


In this case, K is evenly distributed among all sectors. Uneven allocations can address uneven demands in different sectors. NxSxK notation does not capture the frequency distribution among sectors.

Frequency Reuse Notation (Cont)

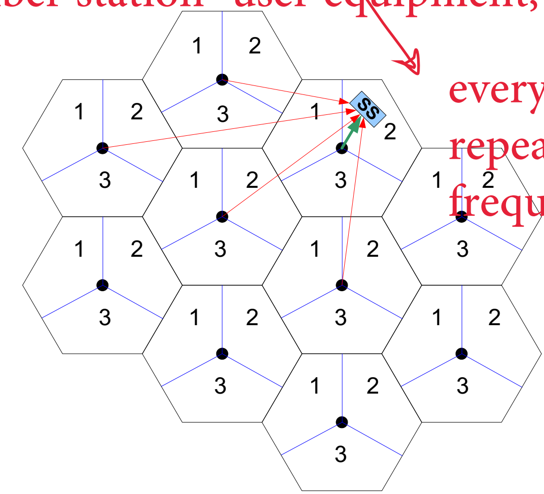
ss=subscriber station=user equipment, e.g., your mobile phone

1x3x1

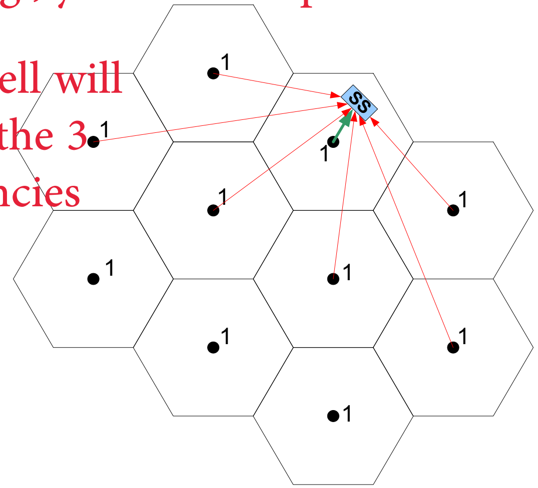


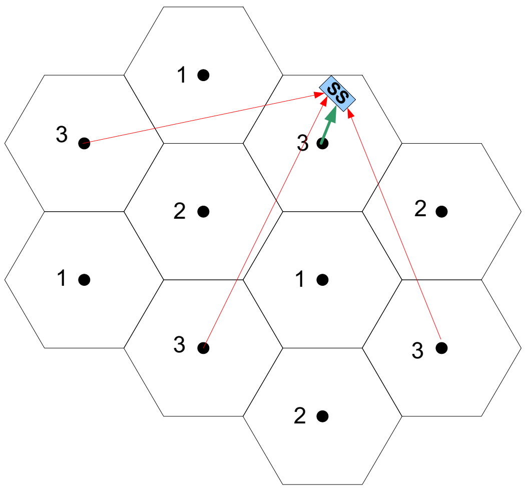
1x3x3

every cell will repeat the 3 frequencies

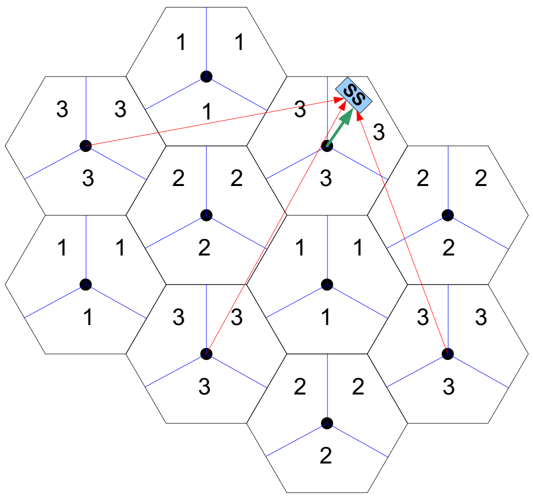


1x1x1

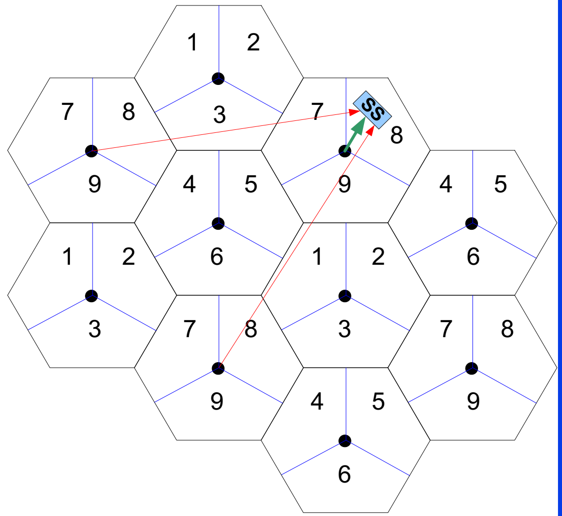




3x1x1



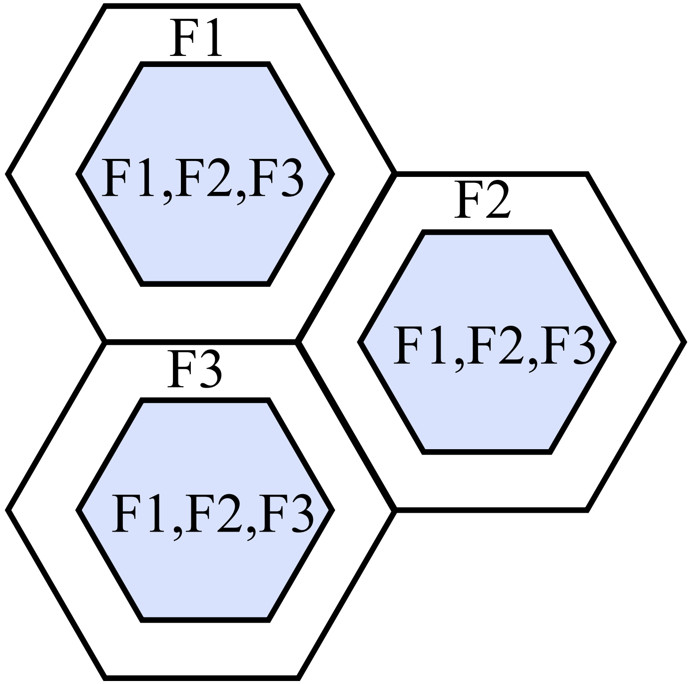
3x3x1



3x3x3

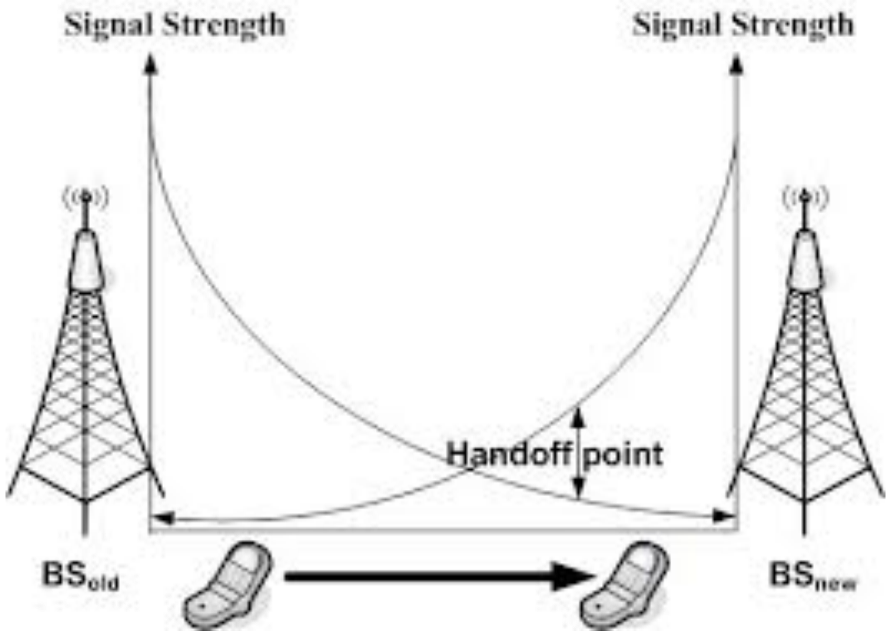
Fractional Frequency Reuse

- Users close to the BS use all frequencies
- Users at the cell boundary use only a fraction of available frequencies
- Border frequencies are designed to avoid interference with adjacent cells;



Handoff

- User mobility poses challenges for cellular networks; cannot remain connected to the same BS; as the RSS becomes too weak, the mobile device must connect to a new BS with a stronger RSS
- Disconnecting from one and connecting to a new BS during an on-going session is called handoff



Frequency Allocation for Handoff

- To handoff successfully, the new BS must have available channels to support the on-going call; otherwise the call will be dropped
- Dropping an ongoing call is worse than rejecting a new call
- BSs therefore usually reserve some channels, called guard channels, exclusively for supporting handoff calls
- Unfortunately, guard channels increases blocking probability of new calls
- The number of guard channels is left to the operators to optimize (not part of the standard)

Cellular System Capacity Example

- A particular cellular system has the following characteristics: cluster size =7, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-949 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code rate = 1 bps/Hz.

DL=BS-->mobile
UL=mobile--> BS

A. Using FDMA/FDD:
   1. How much bandwidth is available per cell using FDD?
   2. How many users per cell can be supported using FDMA?
   3. What is the cell area?
   4. What is the cell radius assuming circular cells?

B. If the available spectrum is divided in to 35 channels and TDMA is employed within each channel:
   1. What is the bandwidth and data rate per channel?
   2. How many time slots are needed in a TDMA frame to support the required number of users?
   3. If the TDMA frame is 10ms, how long is each user slot in the frame?
   4. How many bits are transmitted in each time slot?

Cellular System Capacity (Cont)

- A particular cellular system has the following characteristics: cluster size =7, uniform cell size, user density=100 users/sq km, allocated frequency spectrum = 900-949 MHz, bit rate required per user = 10 kbps uplink and 10 kbps downlink, and modulation code rate = 1 bps/Hz.
- A. Using FDMA/FDD:
  1. How much bandwidth is available per cell using FDD?

     49 MHz/7 = 7 MHz/cell

     FDD ⇒ 3.5 MHz/uplink or downlink
  2. How many users per cell can be supported using FDMA?

     10 kbps/user = 10 kHz ⇒ 350 users per cell

     3.5 MHz / 10kHz
  3. What is the cell area?

     100 users/sq km ⇒ 3.5 Sq km/cell
  4. What is the cell radius assuming circular cells?

     $\pi r^2 = 3.5 \Rightarrow r = 1.056$ km

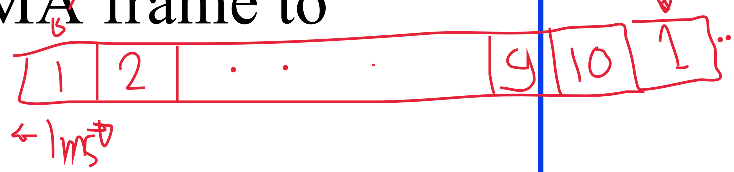
Cellular System Capacity (Cont)

B. If the available spectrum is divided in to 35 channels and TDMA is employed within each channel:

1. What is the bandwidth and data rate per channel?

   3.5 MHz/35 = 100 kHz/Channel = 100 kbps

2. How many time slots are needed in a TDMA frame to support the required number of users?



   10 kbps/user ⇒ 10 users/channel

3. If the TDMA frame is 10ms, how long is each user slot in the frame?

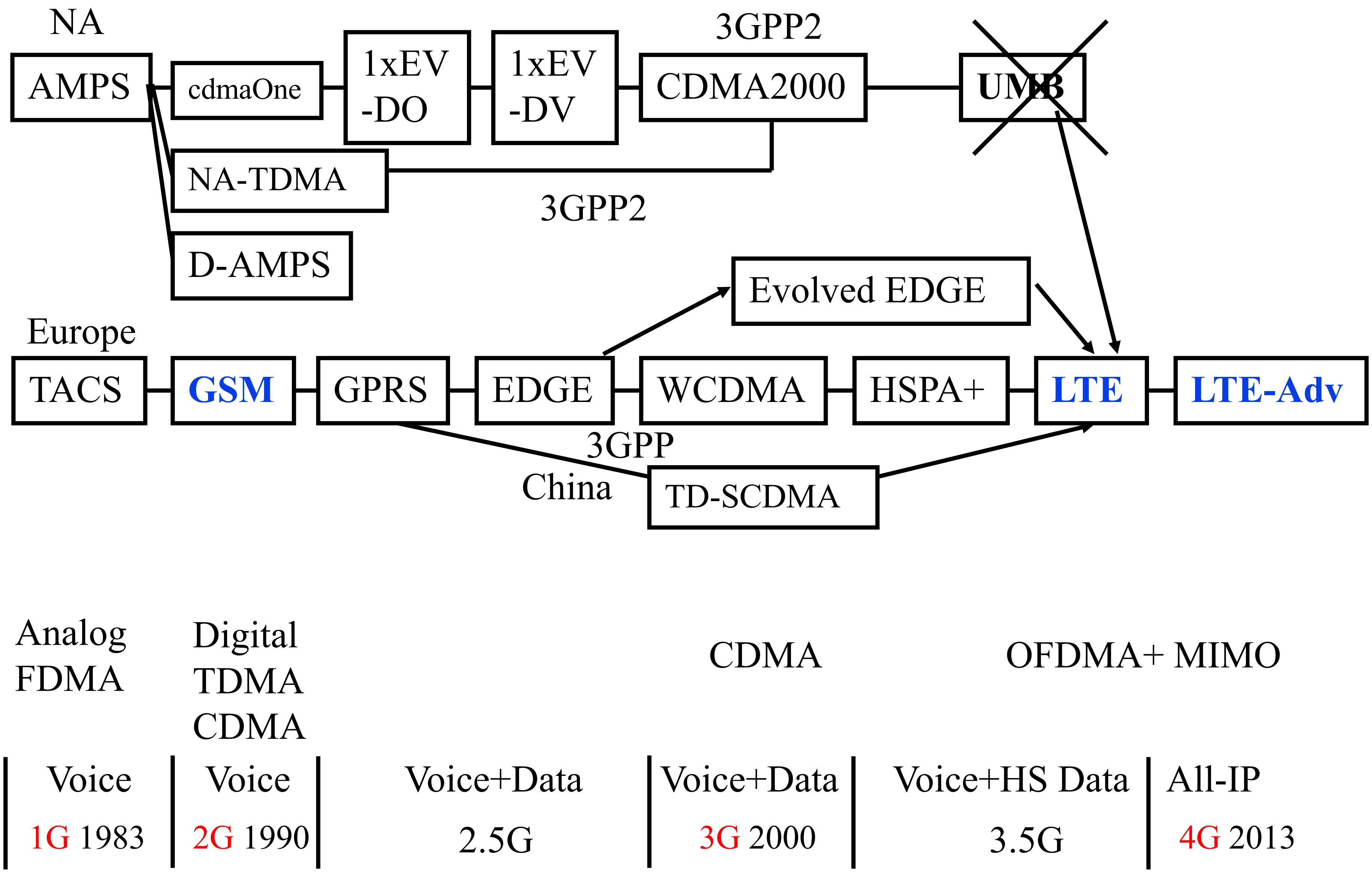
   10 ms/10 = 1ms

4. How many bits are transmitted in each time slot?

   1 ms x 100 kbps = 100 b/slot = 100 b/ms = ?

   = 100b/10ms = 10 kbps

Cellular Telephony Generations



Cellular Generations (Cont)

- **1G: Analog Voice. FDMA. 1980s**
  - AMPS: Advanced Mobile Phone System
  - TACS: Total Access Communications System
- **2G: Digital Voice. TDMA. 1990**
  - cdmaOne: Qualcomm. International Standard IS-95.
  - NA-TDMA
  - Digital AMPS (D-AMPS)
  - **GSM**: Global System for Mobile Communications
- **2.5G: Voice + Data. 1995.**
  - 1xEV-DO: Evolution Data Optimized
  - 1xEV-DV: Evolution Data and Voice
  - General Packet Radio Service (GPRS)
  - Enhanced Data Rate for GSM Evolution (EDGE)

Cellular Generations (Cont)

- **3G: Voice + High-speed data. All CDMA. 2000.**
  - CDMA2000: Qualcomm. International Standard IS-2000.
  - W-CDMA: Wideband CDMA
  - TD-SCDMA: Time Division Synchronous Code Division Multiple Access (Chinese 3G)
  - 384 kbps to 2 Mbps
- **3.5G: Voice + Higher-speed data**
  - EDGE Evolution
  - High-Speed Packet Access (HSPA)
  - Evolved HSPA (HSPA+)
  - Ultra Mobile Broadband (UMB)

Cellular Generations (Cont)

- Two Tracks for 1G/2G/3G:
  - Europe 3GPP (3^{rd} Generation Partnership Project)
  - North America 3GPP2
- **3.9G: High-Speed Data. VOIP. OFDMA.**
  - Long Term Evolution (LTE)
- **4G: Very High-Speed Data. 2013.**
  - LTE-Advanced
  - 100 Mbps – 1 Gbps
- **5G: Ultra High-Speed Data. 2020.**
  - IP based

LTE: Key Features

Long Term Evolution. 3GPP Release 8, 2009.

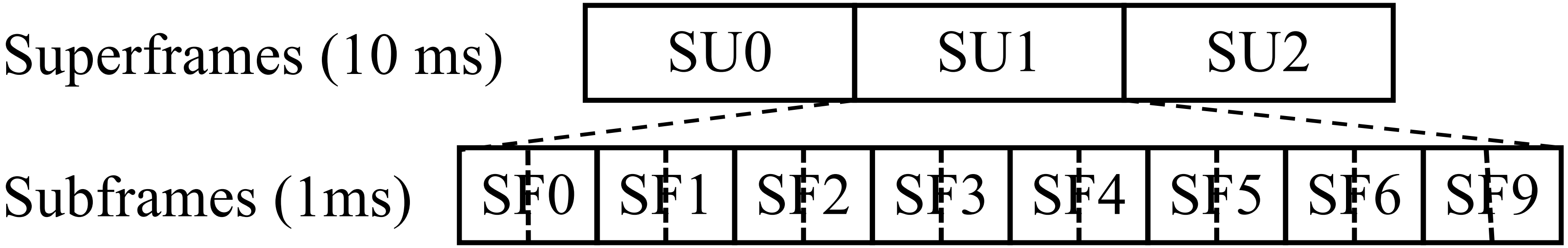
1. **Many different bands**: 700/1500/1700/**2100**/2600 MHz
2. **Flexible Bandwidth**: 1.4/3/5/10/15/20 MHz
3. Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD)
   $\Rightarrow$ Both *paired* and *unpaired* spectrum
4. 4x4 MIMO, Multi-user collaborative MIMO
5. Beamforming in the downlink

Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp. Safari book.

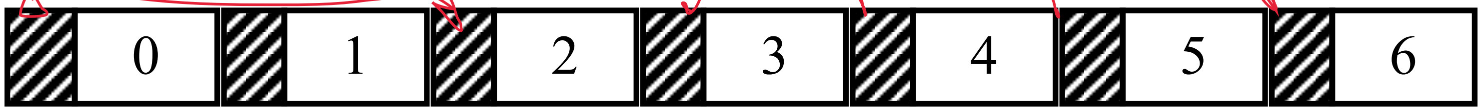
LTE: Key Features (Cont)

8. Data Rate: 326 Mbps/down 86 Mbps up (4x4 MIMO 20 MHz)
9. Modulation: OFDM with QPSK, 16 QAM, 64 QAM
10. **OFDMA** downlink,
    Single Carrier Frequency Division Multiple Access (**SC-FDMA**) uplink
11. **Hybrid ARQ** Transmission
12. Short **Frame Sizes** of 10ms and 1ms ⇒ faster feedback and better efficiency at high speed
13. **Persistent scheduling** to reduce control channel overhead for low bit rate voice transmission.
14. **IP based** flat network architecture

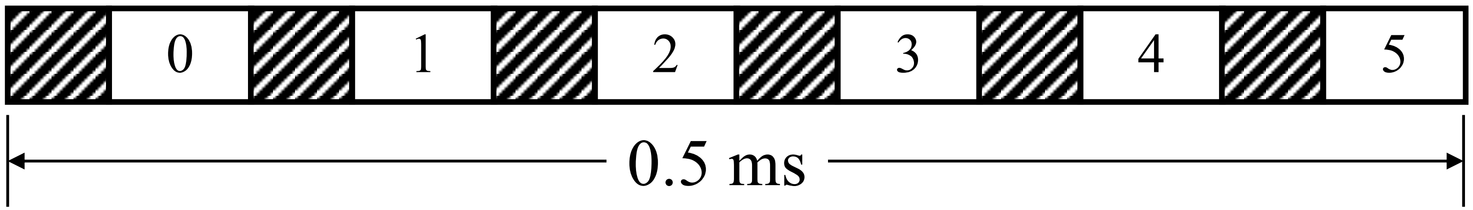
LTE Frame Structure



- Subframe = 2 slots of 0.5 ms each
- Slot = 6 or 7 symbols of 66.7 μs (1/15 kHz) each
- Normal Cyclic Prefix: 5.2 μs for 1st symbol, 4.7 μs for others

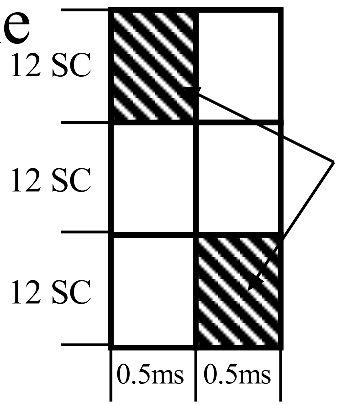


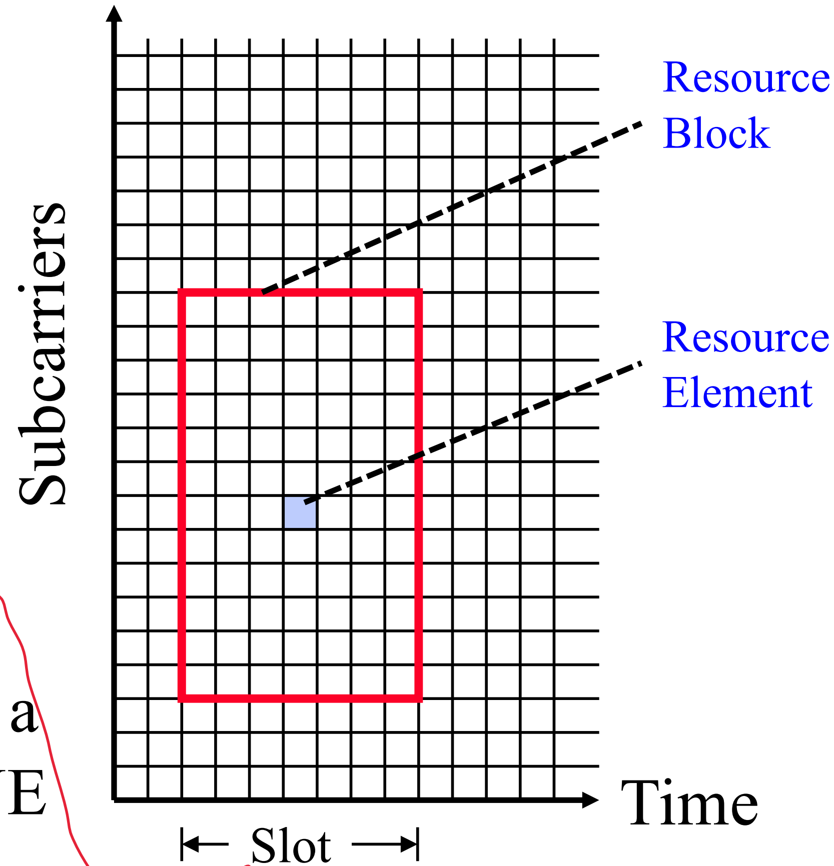
- Extended Cyclic Prefix: for larger networks. 16.7 μs each



Resource Allocation

- **Time slot:** 0.5 ms
  6 or 7 OFDM symbols
- **Subcarriers:** 15 kHz
- **Physical Resource Block (RB):** 12 subcarriers (180 kHz) over 1 time slot
- **Minimum Allocation**: 2 RBs per subframe





a slot here has 7 symbols

Ref: A. Ghosh, J. Zhang, J. G. Andrews, R. Muhamed, "Fundamentals of LTE," Prentice Hall, 2010, ISBN: 0137033117, 464 pp.

Example

- For *normal* cyclic prefix (CP), how many resource elements (REs) are there in 2 RBs?
- Solution
  - With normal CP, we have 7 symbols per slot
  - Number of REs per RB = 12 x 7 = 84
  - Number of REs in 2 RB = 2 x 84 = 168

LTE Transmission Bandwidth

- For downlink, LTE does not use all subcarriers
- Transmission bandwidth < Channel bandwidth

Channel bandwidth [MHz]	1.4	3	5	10	15	20
Transmission bandwidth [MHz]	1.08	2.7	4.5	9	13.5	18
Transmission bandwidth [RB]	6	15	25	50	75	100

http://www.viavisolutions.com/sites/default/files/technical-library-files/LTE_PHY_Layer_Measurement_Guide_0.pdf

Example

- What is the *transmission bandwidth* for a resource allocation of 10 RBs?
- Solution
  - Each RB = 180 kHz
  - Transmission Bandwidth = 10 x 180 = 1.8 MHz

Example

- What is the *peak data rate* of DL LTE?
- Solution
  - For peak data rate, we assume best conditions, i.e., 64 QAM (6 bits per symbol), short CP (7 symbols per 0.5 ms slot), and 20 MHz channel
  - Each symbol duration = 0.5 ms / 7 = 71.4 μs
  - Number of RB for 20 MHz = 100
  - Number of subcarriers per RB = 12
  - Number of subcarriers for 20 MHz channel = 100 x 12 = 1200
  - Number of bits transmitted per symbol time = 6 x 1200 bits
  - Data rate = (6 x 1200 bits) / (71.4 μs) = 100.8 Mbps (without MIMO)

What is 4G?

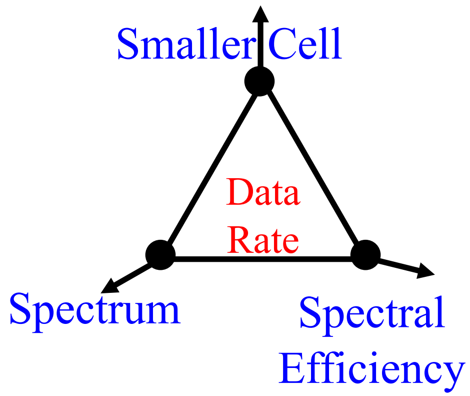
- International Mobile Telecommunication (IMT) Advanced
- Requirements in ITU M.2134-2008
- IP based packet switch network
- 1.0 Gbps peak rate for fixed services with 100 MHz
- 100 Mbps for mobile services. High mobility to 500 km/hr

Feature	Cell	Cell Edge	Peak
DL Spectral Efficiency (bps/Hz)	2.2	0.06	15
UL Spectral Efficiency (bps/Hz)	1.4	0.03	6.75

- Seamless connectivity and global roaming with smooth handovers
- High-Quality Multimedia

LTE Advanced Techniques

- **Three dimensions of data rates**: Spectrum (Band, Bandwidth), Spectral Efficiency (coding/modulation, MIMO), and Cell sizes (spatial re-use of spectrum)



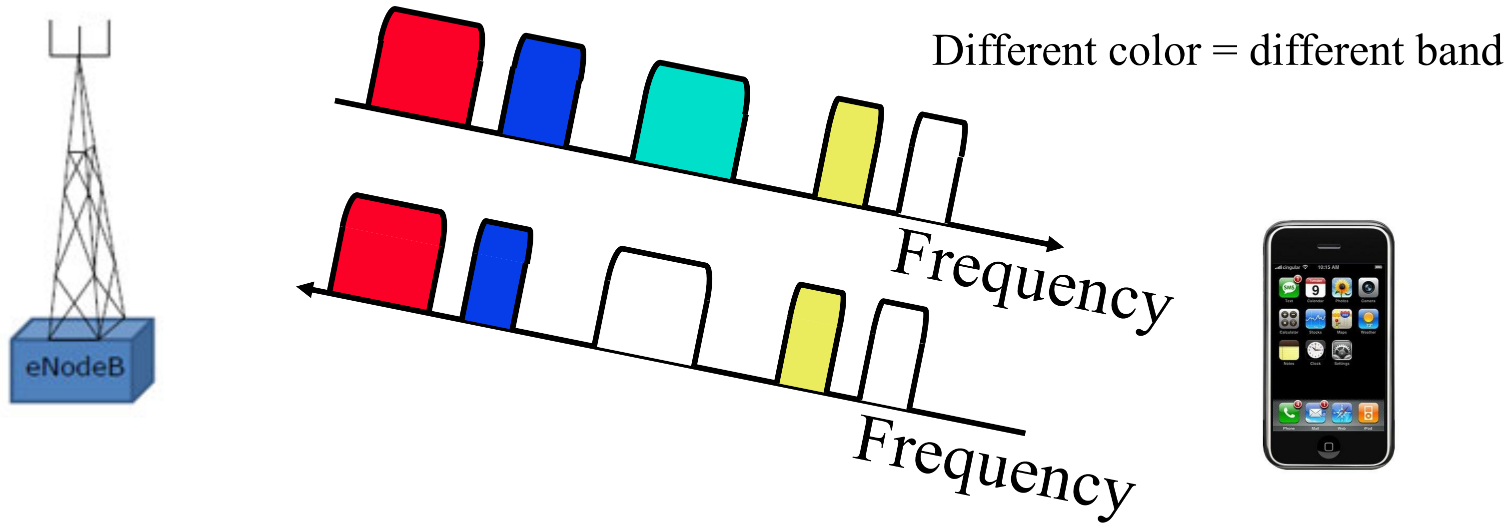
- **Bandwidth**: 100 MHz using carrier aggregation
  5 carriers allowed now. 32 in future.

- **Cell Sizes and Spectrum Re-use**:
  - Smaller cells
  - Frequency Reuse Factor of 1

- **Spectral Efficiency**:
  - Higher order MIMO (8x8 DL, 4x4 UL)
  - New MIMO Techniques: Single-user uplink MIMO
  - Inter-Cell Interference Co-ordination and cancellation

Carrier Aggregation

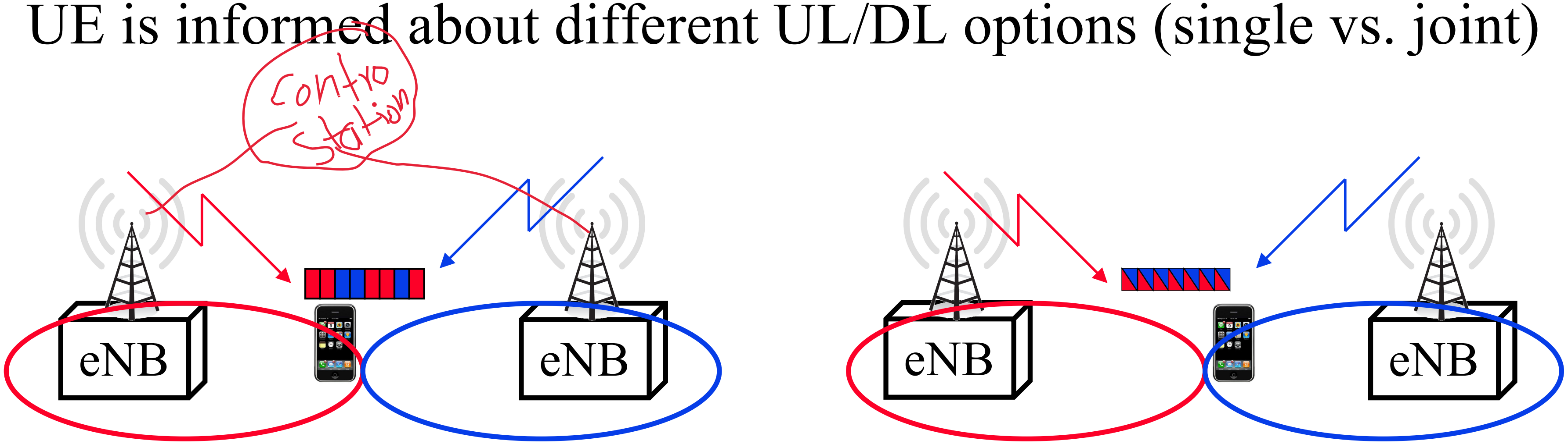
- Aggregation = Combine multiple bands (Component Carriers)



- Backward compatible with LTE (Single carrier)
  ⇒ Each band can be 1.4, 3, 5, 10, or 20 MHz
- Maximum 5 component carriers ⇒ 100 MHz max
- Each component can be different width
- Number of components in DL and UL can be different, but
  Number of components in DL ≥ Number of components in UL

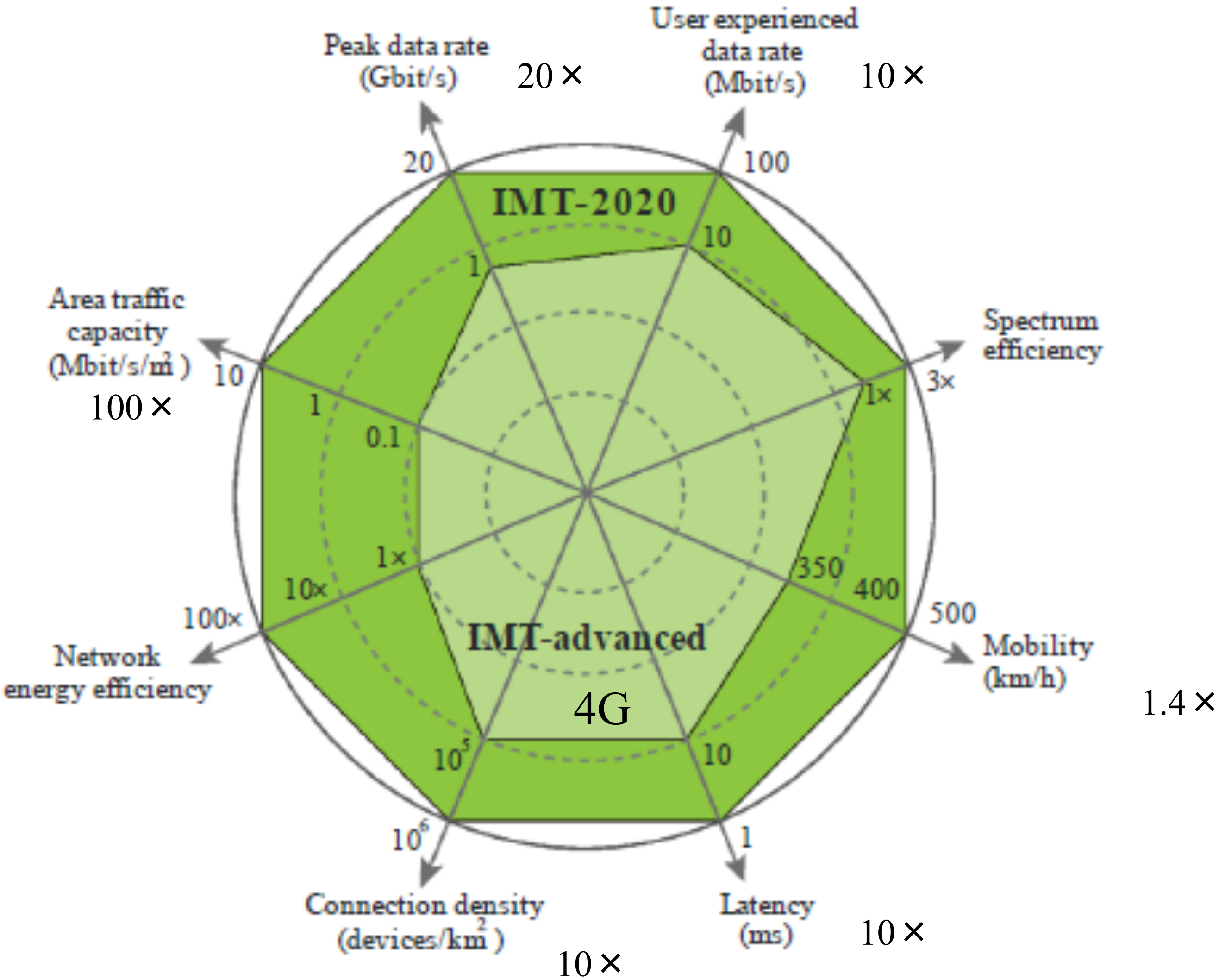
Coordinated Multipoint Operation (CoMP)

- To improve performance at cell edge
- Base stations coordinate transmissions and reception
- Single Tx (DL): Only one BS transmits in each subframe
- Joint Tx (DL): Multiple transmitters in the same subframe
- Joint Reception (UL): Multiple BSs receive the signal from one UE and combine
- UE is informed about different UL/DL options (single vs. joint)



(a) Single transmission (b) Joint Transmission

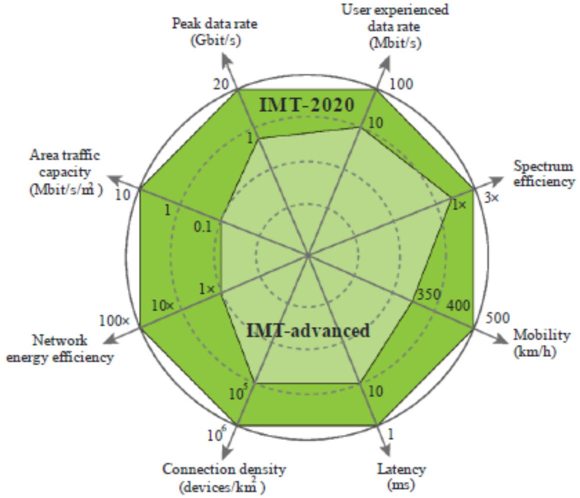
5G Definition



Ref: ITU-R Recommendation M.2083-0, "IMT Vision – Framework and overall objectives of the future development of IMT for 2020 and beyond," Sep. 2015, 21 pp., https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf

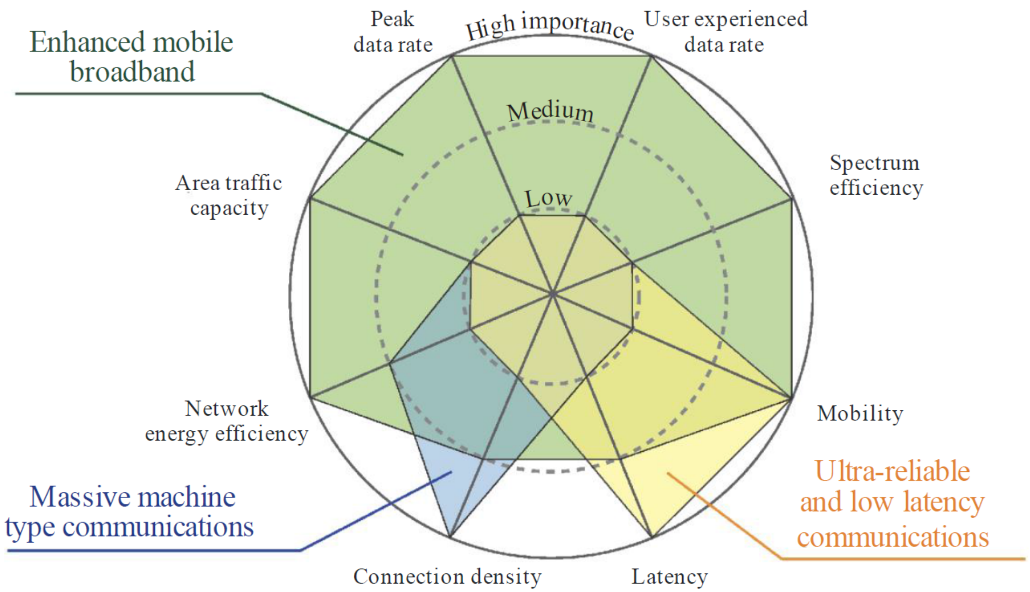
5G Definition (Cont)

1. Peak Data Rate: max rate per user under ideal conditions. 10 Gbps for mobiles, 20 Gbps under certain conditions.
2. User experienced Data Rate: Rate across the coverage area per user. 100 Mbps in urban/suburban areas. 1 Gbps hotspot.
3. Latency: Radio contribution to latency between send and receive
4. Mobility: Max speed at which seamless handover and QoS is guaranteed
5. Connection Density: Devices per km^2
6. Energy Efficiency: Network bits/Joule, User bits/Joule
7. Spectrum Efficiency: Throughput per Hz per cell
8. Area Traffic Capacity: Throughput per m^2



Importance

- Three Key Application Areas:
  - Enhanced Mobile Broadband
  - Ultra-Reliable and Low Latency: Real-time, safety
  - Massive Machine Type Communications (IoT)



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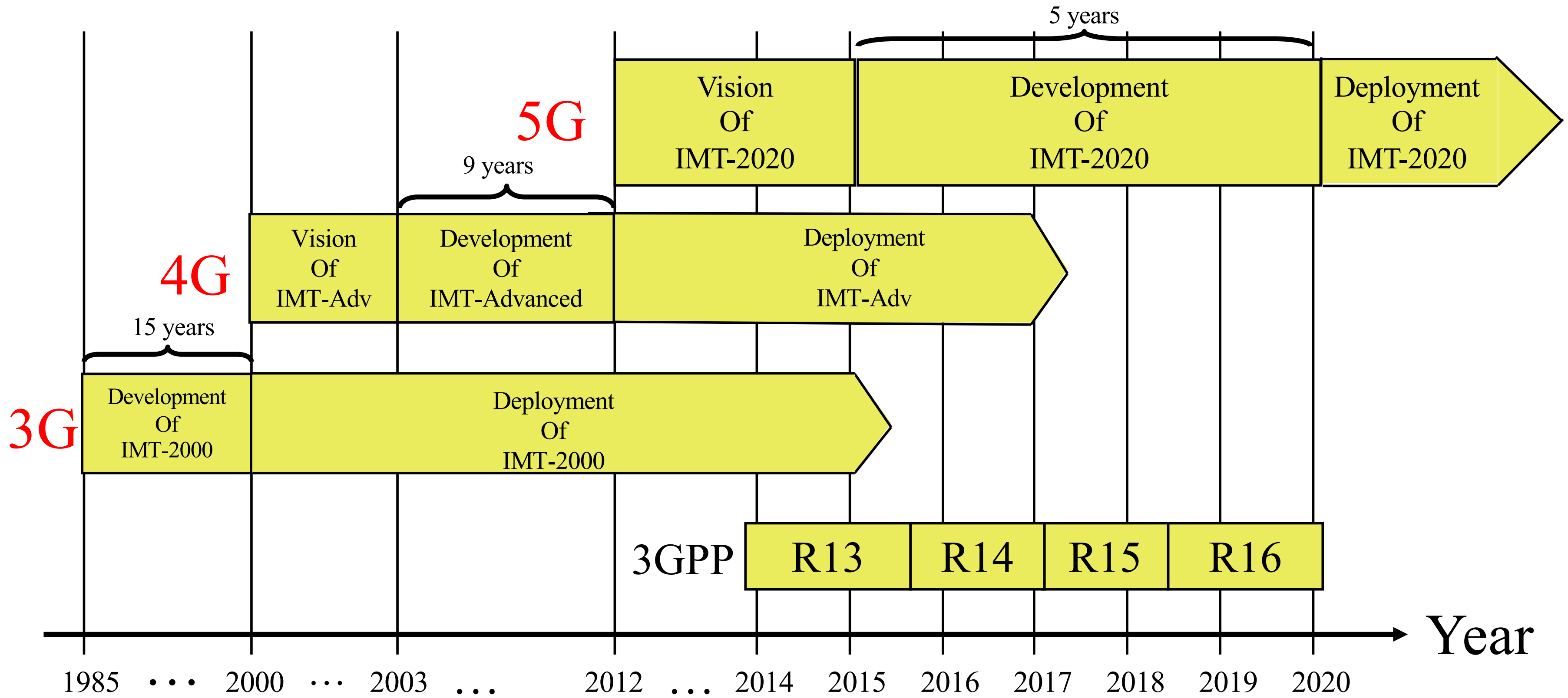
Timeline

- 3G: IMT-2000 started in 1985, first release in 2000
- 4G: IMT-Advanced, vision in 2003, first release in 2012
- 5G: IMT-2020, vision in 2015, first release in 2020



Ref: ITU-R, "Workplan, timeline, process and deliverables for the future development of IMT," 4pp.,

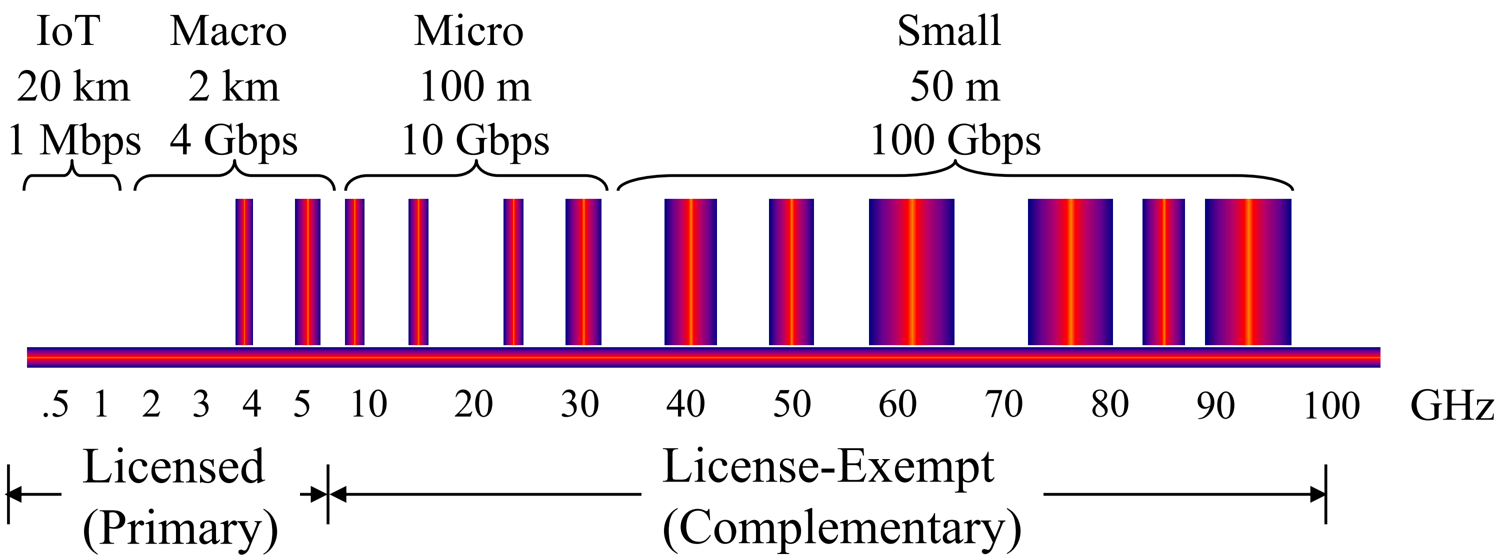
How?

5G

- **New Radio Multiplexing Techniques** [Spectrum Filtered OFDM (f-OFDM), Filtered Bank Multicarrier (FBMC), Non-Orthogonal Multiple Access (NOMA), Pattern Division Multiple Access (PDMA), Low Density Spreading, (LDS), Sparse Code Multiple Access (SCMA), Interleave-Division Multiple Access (IDMA)]
- **New Efficient Spectrum Usage** [3D Beamforming and Massive MIMO, FDD-TDD Carrier Integration, Distributed Antenna Systems (DAS), Simultaneous Transmission and Reception, Dynamic TDD, License Assisted Access (LAA), Multimode Base Stations, Intelligent Multi-Mode RAT Selection, Higher order modulations in small cells]
- **New Spectrum**
- **New Energy Saving** [Discontinuous Transmission (DTX), Antenna Muting, Cell on/off switching, Power Save Mode for IoT]
- **CapEx/OpEx Reduction** [Software Defined Networking (SDN), Network Function Virtualization (NFV), Mobile Edge Computing (MEC), Cloud Radio Access Network (C-RAN)]
- **Application Specific Improvements** [HTTP-based Video, Narrow-band IoT]

New Spectrum

- ITU estimates 900-1420 MHz required for 4G/5G by 2020 and 440-540 MHz required for 2G/3G and their enhancements



Ref: P. Zhu, "5G Enabling Technologies," PIMRC, Sep 2014, 20 slides, http://www.ieee-pimrc.org/2014/2014-09-03%205G%20Enabling%20Technologies%20PMIRC%20Huawei_Final.pdf

Ref: ITU-R M.2290-0, "Future Spectrum Requirements estimate for Terrestrial IMT," Dec 2013, http://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-M.2290-2014-PDF-E.pdf

Huawei, "White Paper on Spectrum," February 2013, http://www.huawei.com/us/others/index-cdf_en_group_white_book.htm

Above 6 GHz

- Free-space loss increases in proportion to square of frequency and square of distance. 88 dB loss with 30 GHz at 20 m $\Rightarrow$ 10-100 m cell radius
- Outdoor-to-Indoor: Glass windows add 20-40 dB
- Mobility: Doppler shift is proportional to frequency and velocity. Multipath results in varying Doppler shifts $\Rightarrow$ Lower mobility
- Wide Channels: Duplex filters cover only 3-4% of center frequency $\Rightarrow$ Need carrier aggregation.
- Antenna: 8x8 array at 60 GHz is only 2cm x 2cm. A/D and D/A converters per antenna element may be expensive
- 2 Gbps up to 1 km may be feasible using mm waves

Summary

- In a cellular cluster of size N, the minimum distance between cells with same frequencies is $D = R\sqrt{3N}$. Here R is the cell radius.
- 1G was analog voice with FDMA
- 2G was digital voice with TDMA. Most widely implemented 2G is GSM. Data rate was improved by GPRS and EDGE.
- 3G was voice+data with CDMA. Most widely implemented 3G is W-CDMA using two 5 MHz FDD channels. Data rate was improved later using HSPA and HSPA+.
- LTE uses a **super-frame** of 10 subframes of 1 ms each. Each **subframe** has one 0.5 ms **slot** for uplink and downlink each.
- LTE Advanced truly meets 4G requirements; supports up to 100 MHz channels by aggregating bandwidth from the same or different carriers
- 5G is being launched in 2020 promising to offer ultra-high data rates, ultra-low latency, and massive connectivity for Internet of Things; it will use new spectrum in the millimeter wave band and deploy new techniques for improving spectrum efficiency and energy savings.