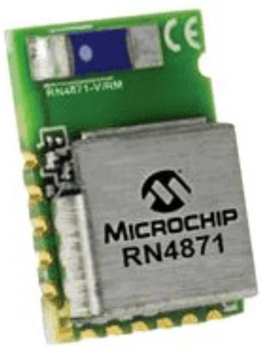
Cellular Networks

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

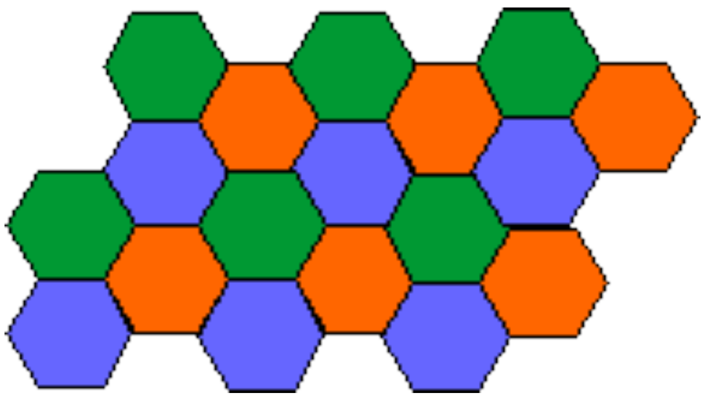
WiFi

Cellular

Cellular Concept

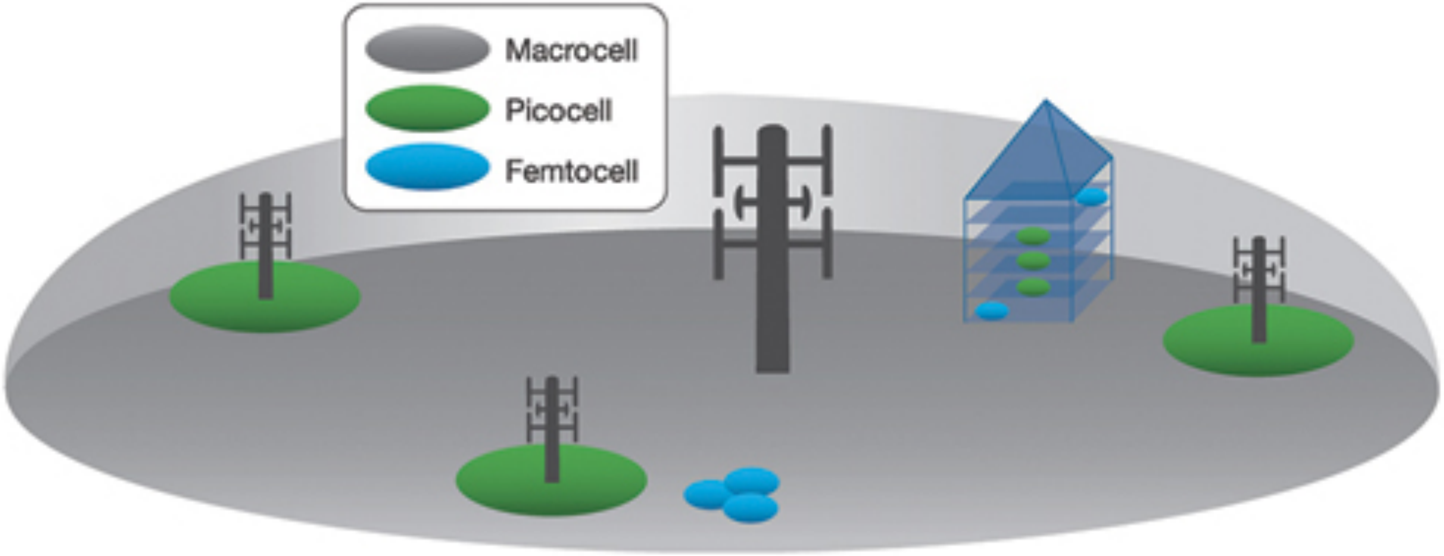
- First proposed in ‘70s; commercial services offered early ‘80s
- A large geographic service area is divided into many smaller cells; no matter where you are located, you are always within a cell
- Each cell has a base station to connect users within the cell; all base stations are in turn connected 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



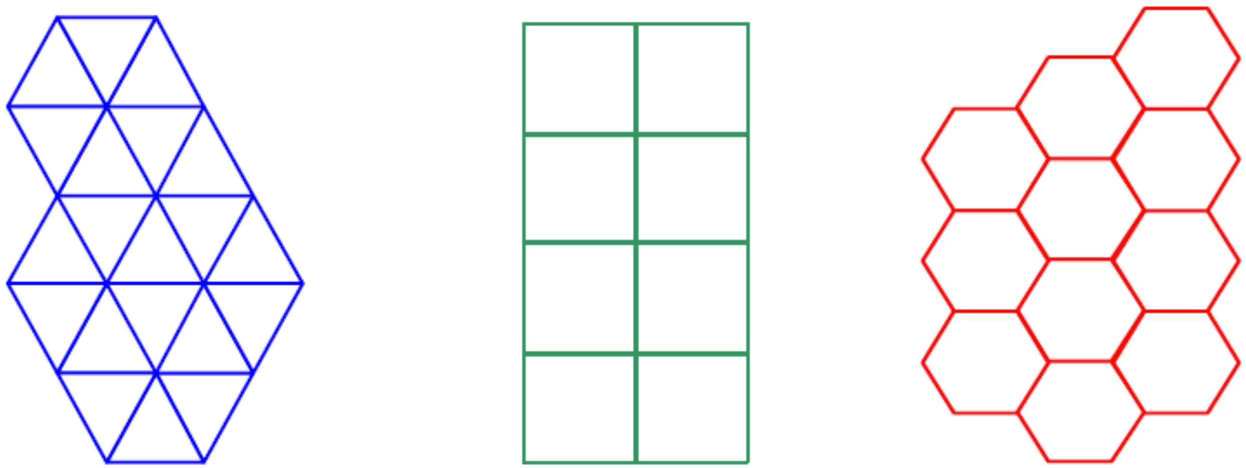
How large are the cells?
Macro, Micro, Pico, Femto Cells

- 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

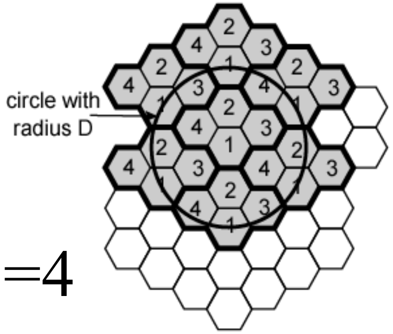


Frequency reuse and clustering

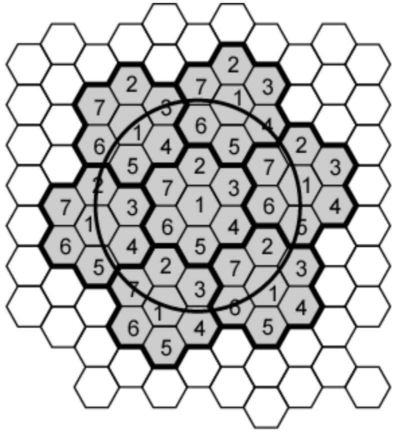
- Adjacent cells cannot use the same channel due to interference
- All cells in the service area are grouped into many clusters; the total spectrum is divided into sub-bands that are distributed among the cells within a cluster; the spatial distribution of sub-bands within the cluster should make sure 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

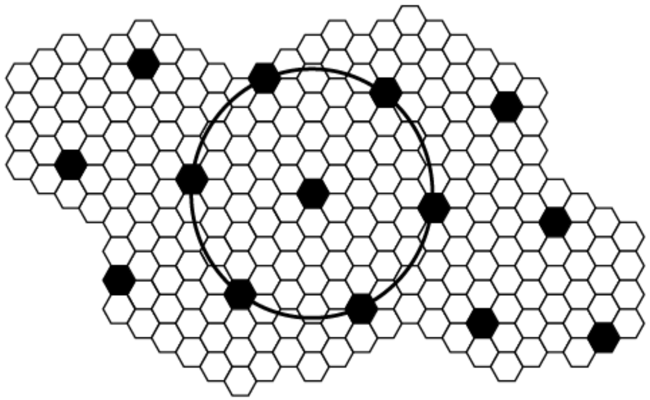


Cluster Size =4



Cluster Size =7

(a) Frequency reuse pattern for N = 4 (b) Frequency reuse pattern for N = 7

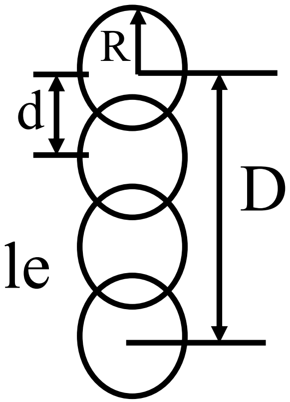


Cluster Size =19

(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 ($d = R\sqrt{3}$)
  - $d < 2R$ 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
  - $N = I^2 + J^2 + (I \times J)$, $I, J = 0, 1, 2, 3, \ldots$
- Possible values of N are 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, …
- Reuse Ratio = Distance/Radius = $D/R = \sqrt{3N}$
- $D/d = \sqrt{N}$

Example

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?

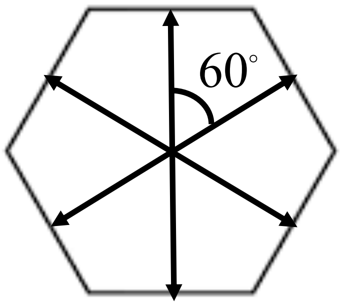
Sol. R = 1 km, N = 12

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

$D = (3\times12)^{1/2} \times 1$ km

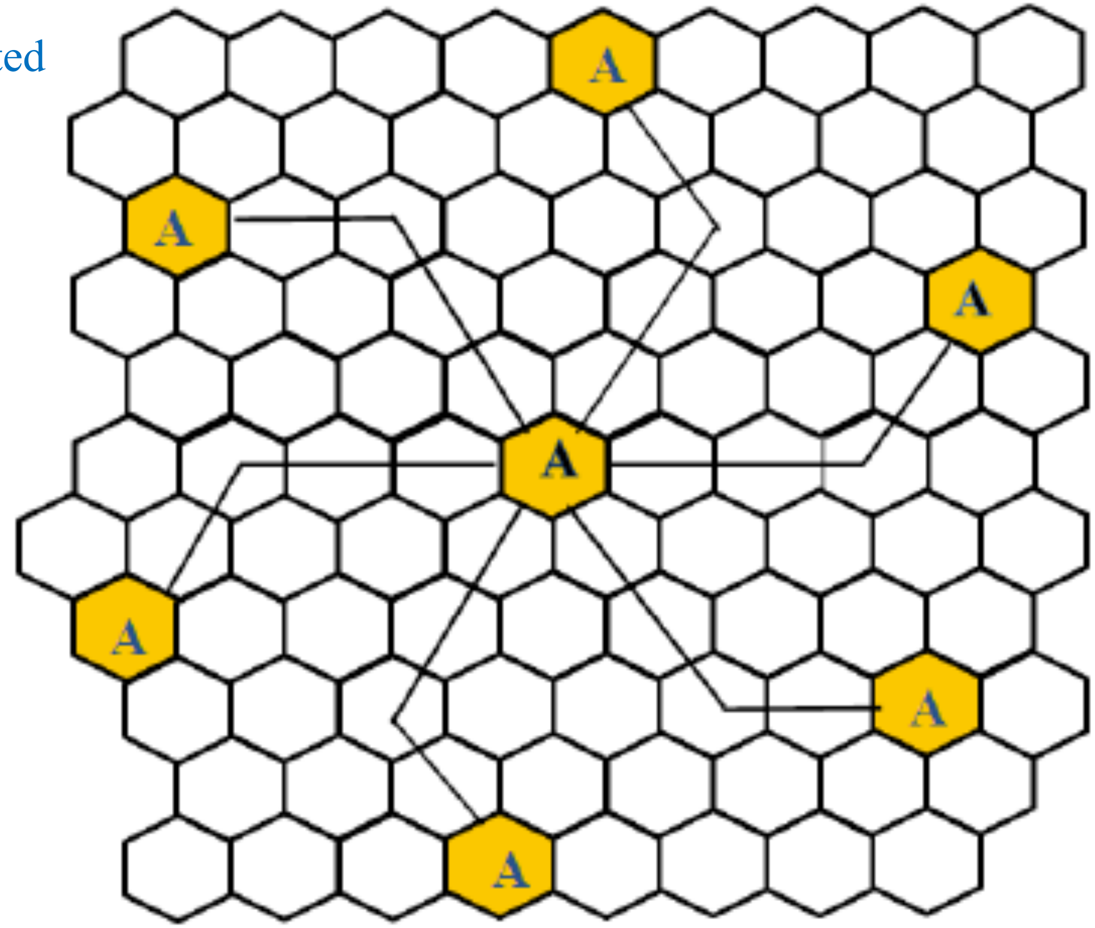
$= 6$ km

Locating Co-channel Cells



6 directions of a hexagon, separated by 60 degrees

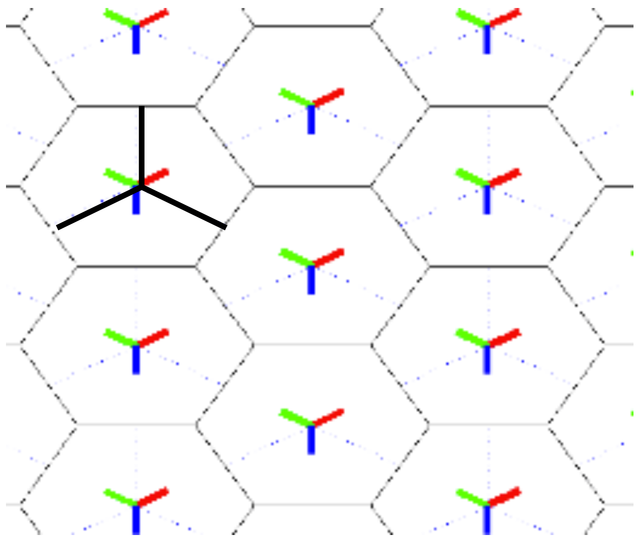
- Move i cells in any direction
- Turn 60° counter-clock and move j cells



i=3, j=2; N=19

How to distribute channels among cells within a cluster?

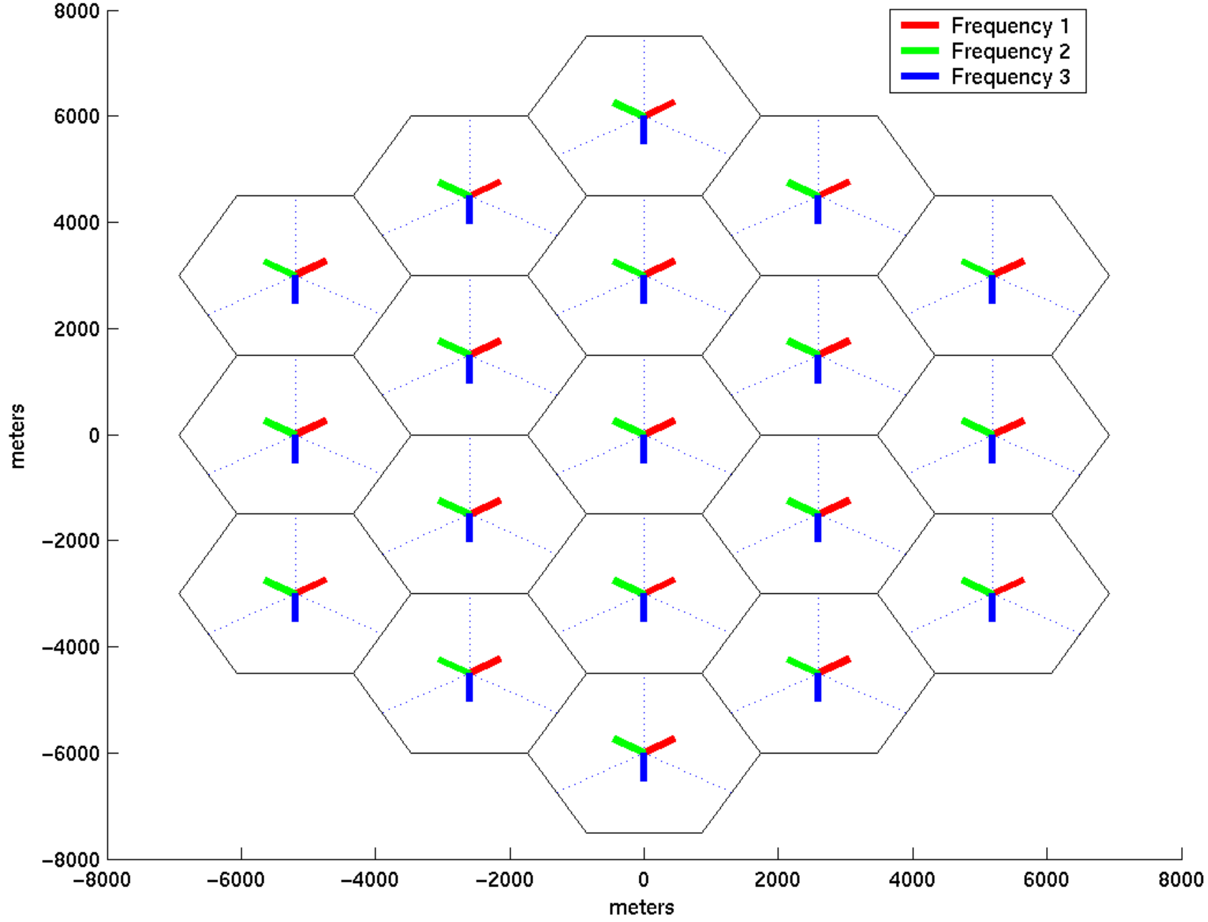
- For simplicity, it is assumed that the total spectrum is divided equally among all cells in the cluster
  - T (total channels), N (cluster size), K (number of channels per cell)
  - K = T/N
- Cells are usually divided into sectors; channels allocated to a cell is then further sub-allocated to different 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

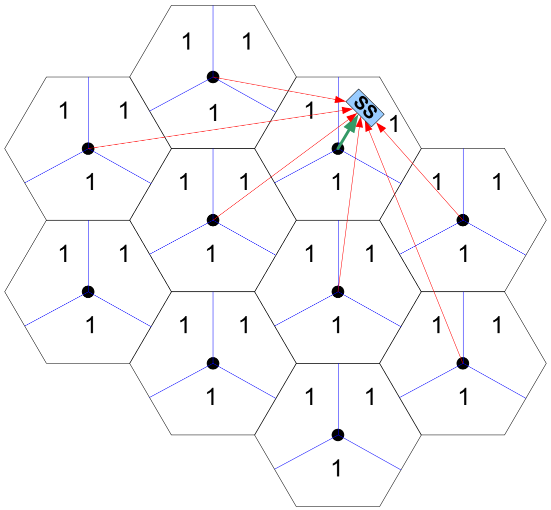
1X3X3



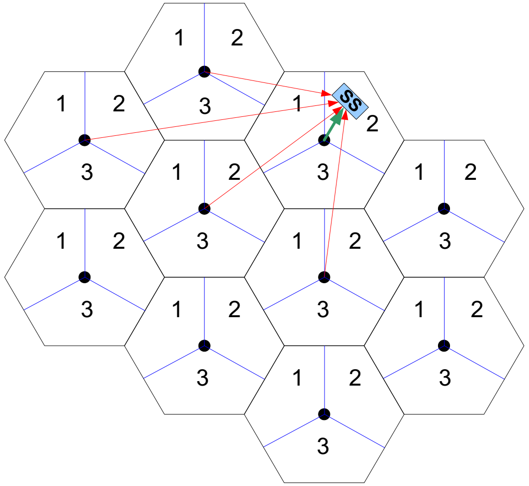
In this case, K is evenly distributed among all sectors. Uneven allocations can address uneven demands in different sectors. NxSxK notation does not capture the frequency distribution among sectors.

Frequency Reuse Notation (Cont)

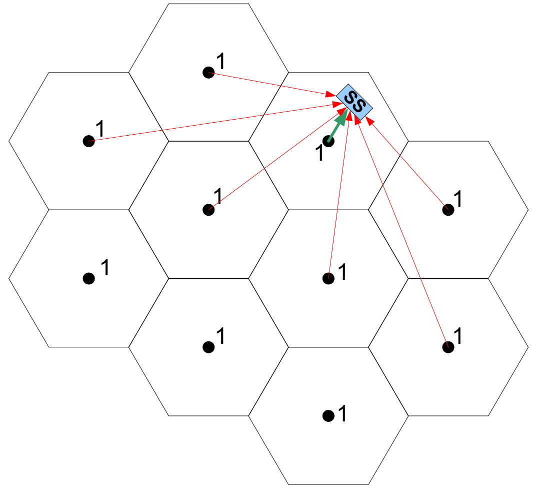
1x3x1

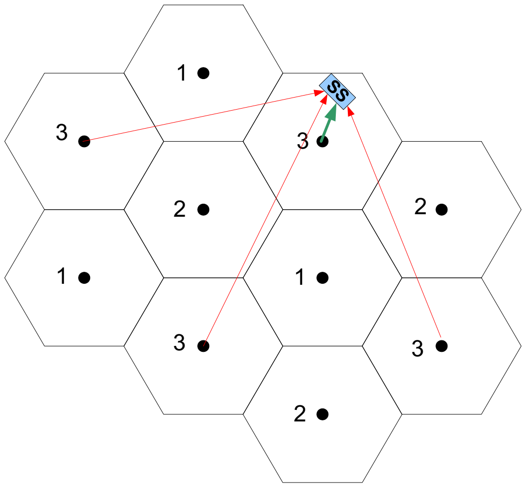


1x3x3

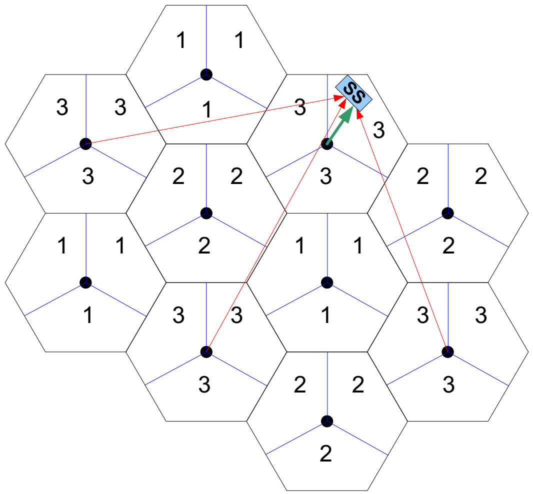


1x1x1

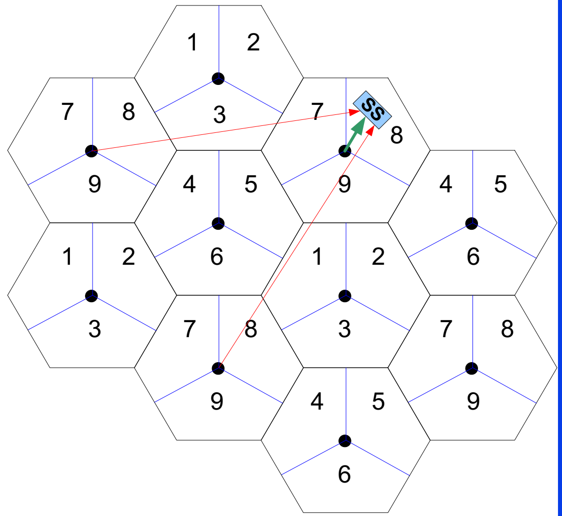




3x1x1



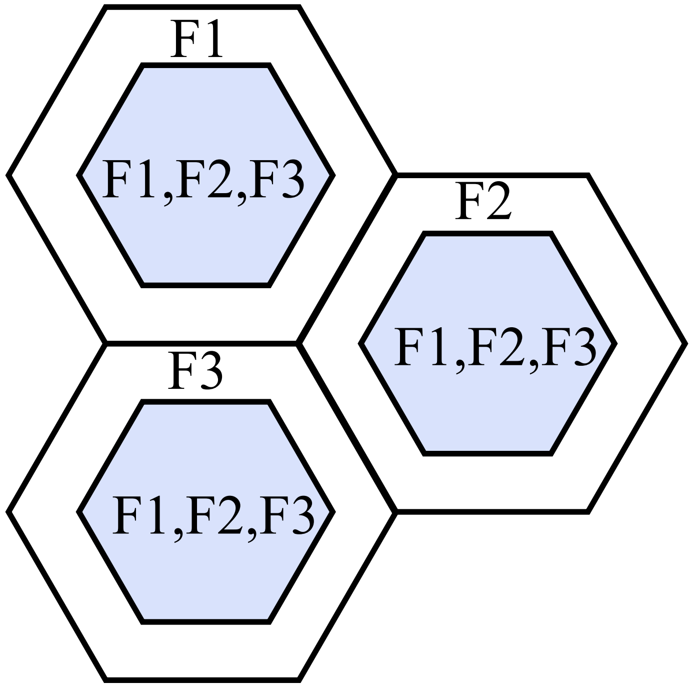
3x3x1



3x3x3

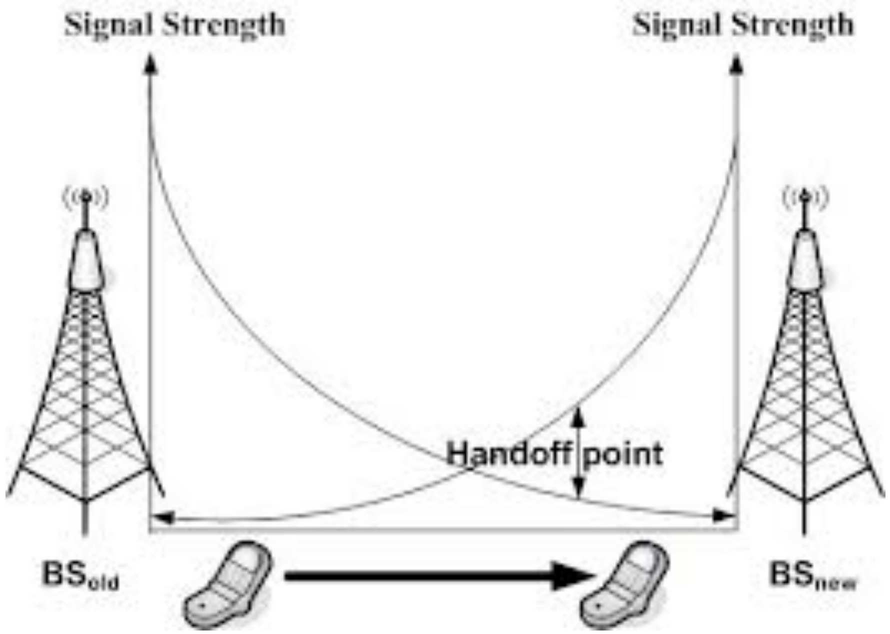
Fractional Frequency Reuse

- 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.

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)

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- A. Using FDMA/FDD:

1. How much bandwidth is available per cell using FDD?

   49 MHz/7 = 7 MHz/cell

   FDD $\Rightarrow$ 3.5 MHz/uplink or downlink

2. How many users per cell can be supported using FDMA?

   10 kbps/user = 10 kHz $\Rightarrow$ 350 users per cell

3. What is the cell area?

   100 users/sq km $\Rightarrow$ 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 $\Rightarrow$ 10 users/channel

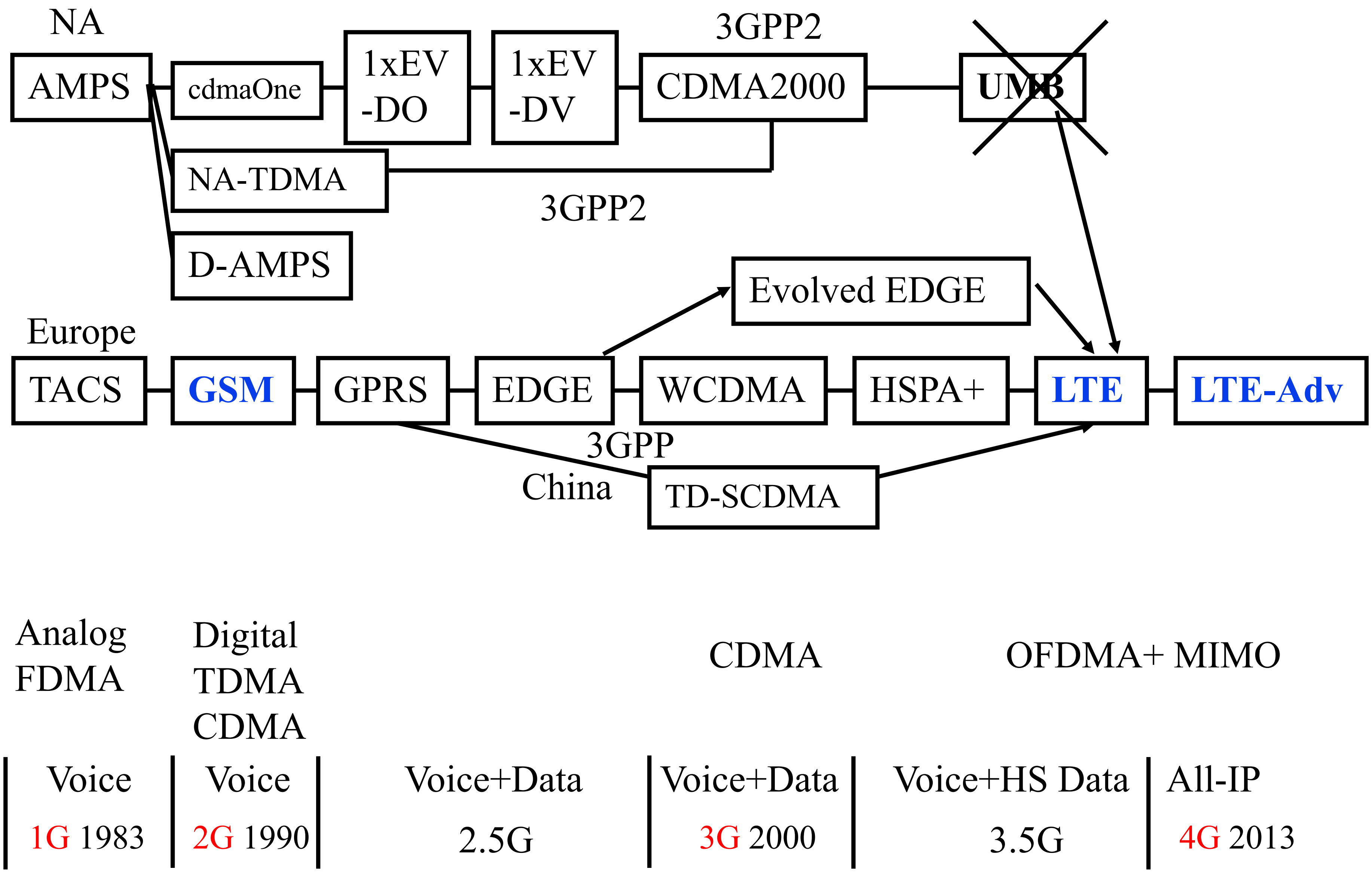
3. If the TDMA frame is 10ms, how long is each user slot in the frame?

   10 ms/10 = 1ms

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

   1 ms x 100 kbps = 100 b/slot

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 (3rd 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/4G

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)
   ⇒ 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.

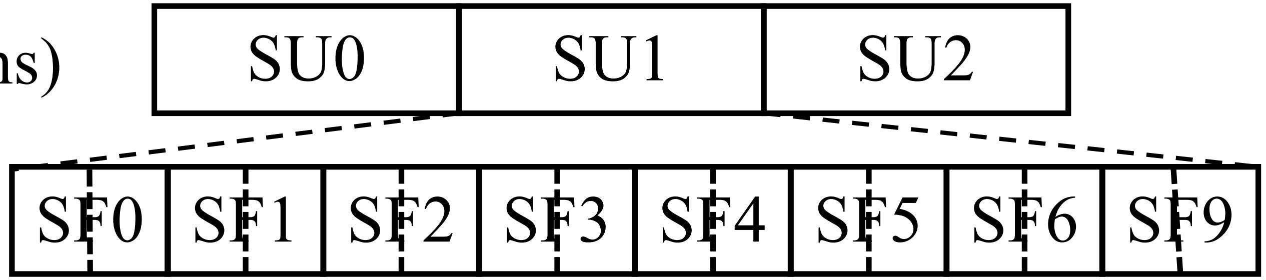
LTE: Key Features (Cont)

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

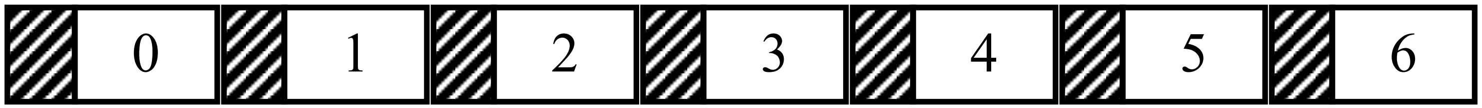
LTE Frame Structure

Superframes (10 ms)

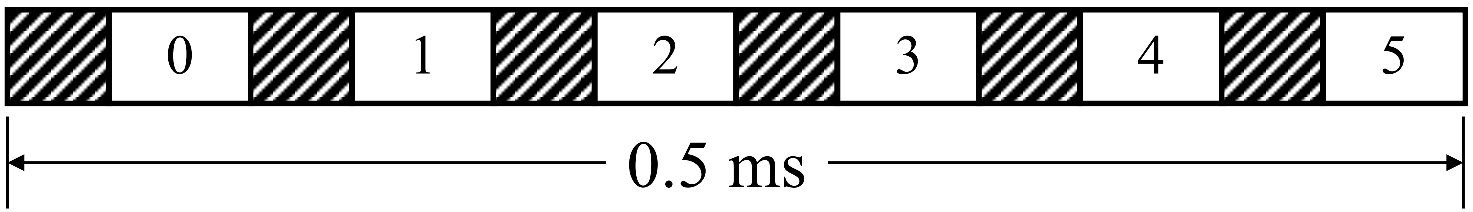
Subframes (1ms)



- 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

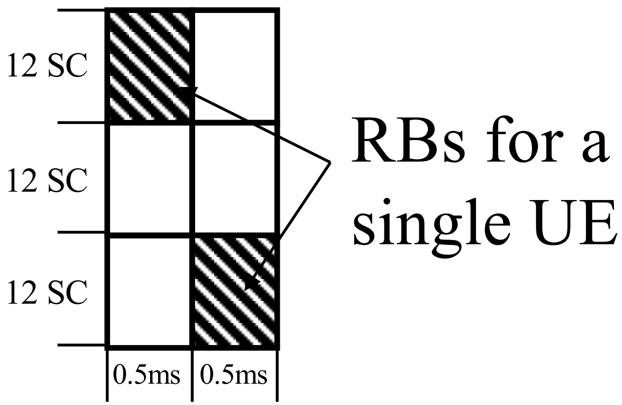


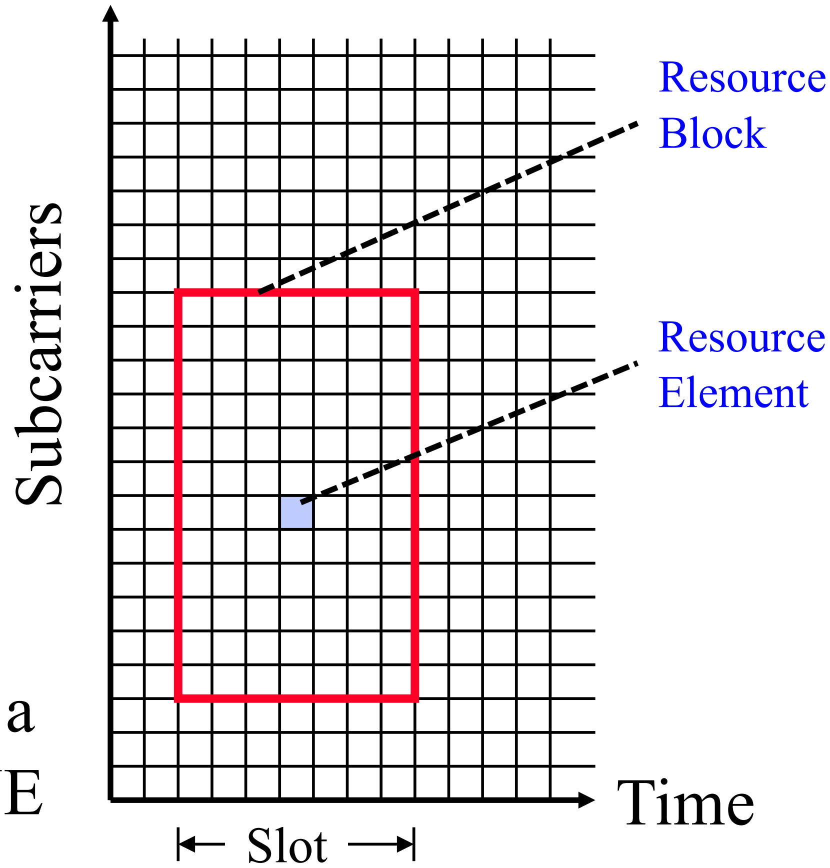
- Extended Cyclic Prefix: for larger networks. 16.7 μs each



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





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)

5G

5G Promise

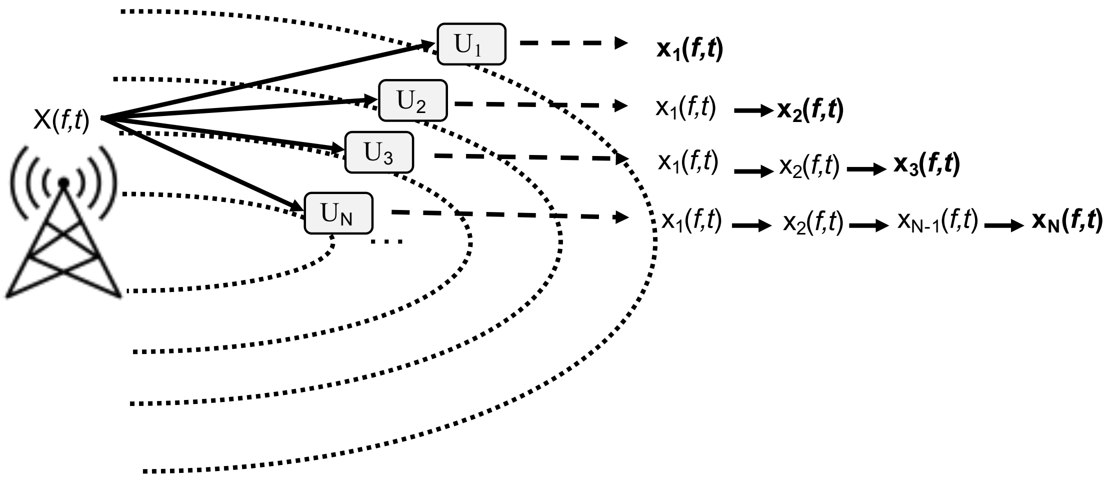
- Deployment started in 2019/2020
- Designed to improve not only the data rates, but many other things
- Key 5G targets
  - **1. Data Rate:** While 4G offered the maximum data rate of 1Gbps per user under ideal conditions, 5G promises 20Gbps under the same conditions.
  - **2. Latency:** ~100ms with 3G and ~30ms in 4G. 5G promises 1ms.
  - **3. Connection Density:** 4G could connect 100 thousand devices per km^2, 5G promises to connect 1 million/ km^2.
- 5G Applications
  - **Enhanced broadband:** fixed wireless (no cable/wire coming to homes), new videos standards (4K/8K, 360°), wireless VR, blazing photo/video upload, …
  - **Ultra-reliable low latency communications:** autonomous driving, remote medical procedures, and so on.
  - **IoT:** will connect billions of devices at low energy, long distance, hard-to-reach areas

3 Fundamental Dimensions for Cellular Enhancements

- **Increase bps/Hz or spectral efficiency:** develop new coding and modulation techniques as well as new spectrum sharing methods to squeeze more bits out of the given spectrum. Increases capacity linearly.
- **Reduce cell radius or increase spectral reuse:** Smaller cells allow higher spectrum reuse in the service area. The most effective method to increase capacity. Cell sizes have been consistently reduced over the 4 generations. 5G will continue to follow this trend.
- **Use new spectrum:** Eventually we will need new spectrum to cope with the increasing demand for mobile traffic. 5G will be the first generation to use millimeter wave bands.

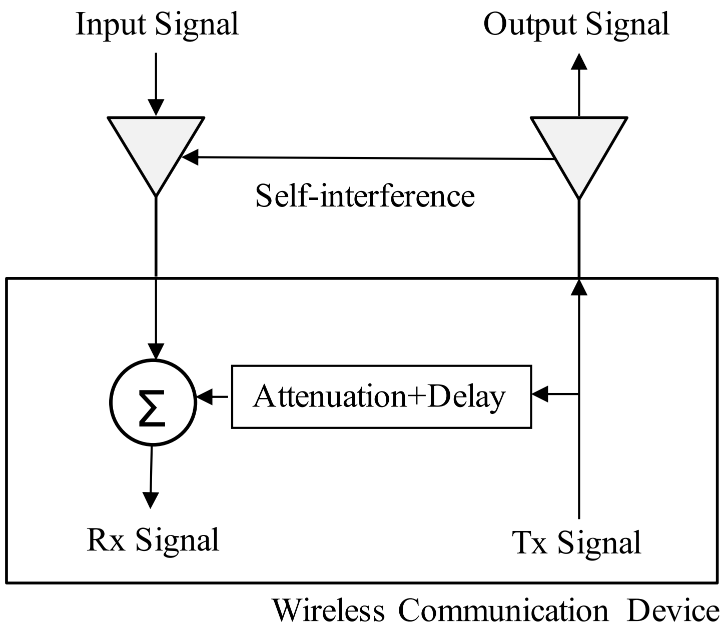
NOMA

- Use power as the 4th dimension of multiplexing
- Allows use of the same frequency at the same time for all users
- BS transmits combined signal with the highest power for the farthest user's signal
- Devices decodes the highest – power signal first by treating all other as noise; then removes it from the combined signal; stops when own signal is received (successive interference cancellation or SIC)



Full-duplex Wireless

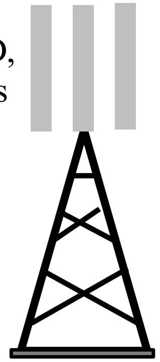
- Full-duplex in wireless has not been possible so far due to self-interference
- Half-duplex reduces capacity and increases latency
- With advanced processing, attenuation+delay circuits within the radio hardware can cancel self-interference and achieve full-duplex



Massive MIMO and 3D Beamforming

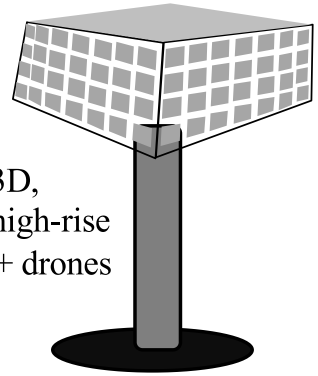
- Existing BSs use vertical antennas; good for serving grounds users
- 5G BS will have planar array antennas with many (>100) antenna elements; 3D beams formed by adjusting phase and amplitude of each antenna element

Good for 2D, ground users

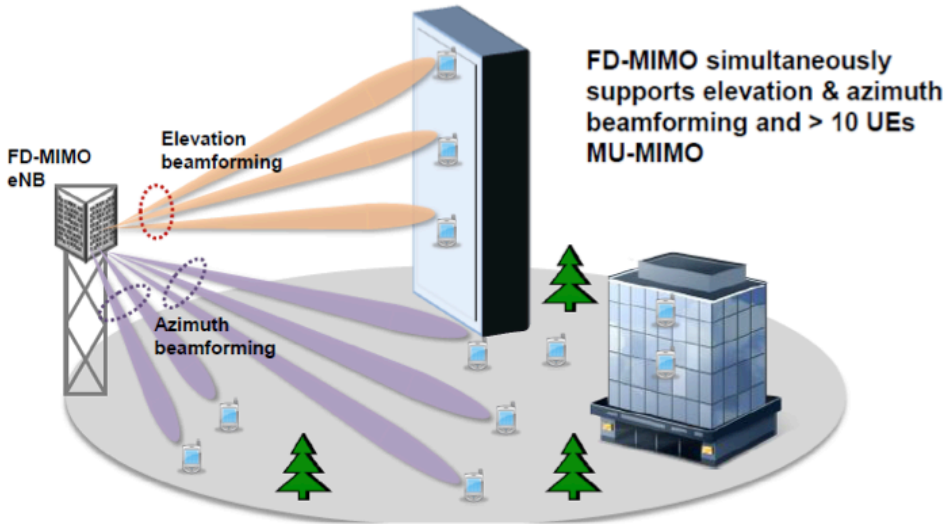


4G Sector Antenna

Good for 3D, ground + high-rise apartment+ drones

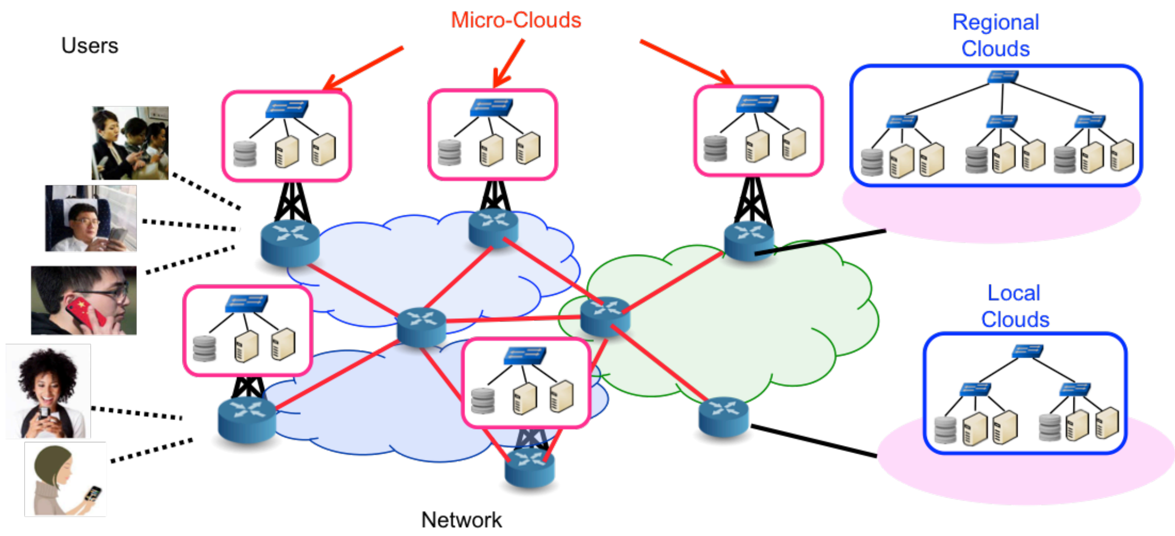


5G Massive MIMO



Mobile Edge Computing

- Future handsets will need many computations not feasible within the device (e.g., natural language processing, augmented reality, etc.); cloud computing will increase latency
- Provision mini-clouds in each radio tower (at the edge) to provide computing power with low latency and energy cost



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.
- 5G is being launched in 2020 promising to offer ultra-high data rates, ultralow latency, and massive connectivity for Internet of Things
- 5G will use NOMA as a new access technology that enables serving multiple users over the same frequency at the same time; NOMA uses power as a new dimension to differentiate users.
- 5G promises full-duplex wireless communications where both the Tx and Rx antennas can function at the same time.
- 5G base stations will use planar array antennas for massive MIMO and 3D beamforming.
- 5G base stations will host computing and storage resources to reduce latency for applications requiring cloud support.
- 5G will use new spectrum in the mmWave band.