ECE5884 Wireless Communications

Week 10: Multiple-user Systems and Cellular Systems

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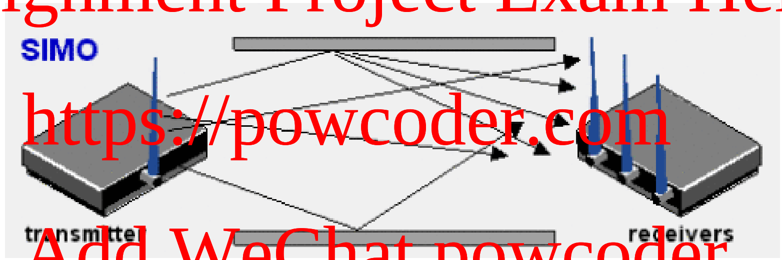
Course outline

This week: **Ref. Ch. 14 and Ch. 15 of [Goldsmith, 2005]**

- Week 1: Overview of Wireless Communications
- Week 2: Wireless Channel (Path Loss and Shadowing)
- Week 3: Wireless Channel Models
- Week 4: Capacity of Wireless Channels
- Week 5: Digital Modulation and Detection
- Week 6 : Performance Analysis
- Week 7: Equalization
- Week 8: Multicarrier Modulation (OFDM)
- Week 9: Multiple-Antenna Systems: Diversity Techniques
- Week 10: Multiple-User/Multiple-Antenna Systems (MIMO)
- Week 11: Guest Lecture "Multi-antenna systems: From theory to standardization in 5G-NR (New radio)"
- Week 12: Selected 4G/5G/6G Topics

Diversity for SIMO

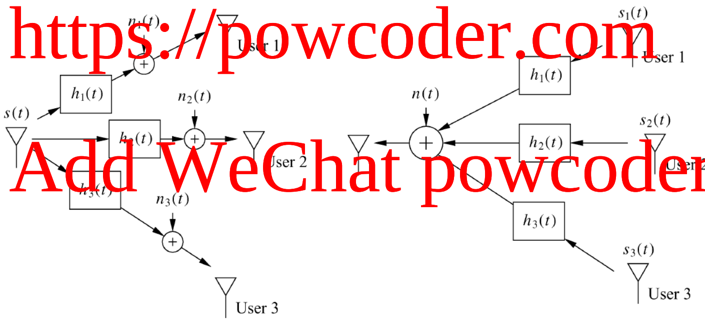
- Diversity: is to send the same data over independent fading paths/links



- SC, MRC, EGC or Threshold Combining
- Single-user pair with multiple antennas: simultaneous Tx is possible,no channel sharing.

Multiple-user system

- A "multiuser" channel is any channel that must be shared among multiple users.
  1. Downlink channel (broadcast channel or forward channel): one Tx sending to many Rxs
  2. Uplink channel (multiple access channel or reverse channel): many Txs sending to one Rx



Downlink Channel **Uplink Channel**

Downlink (DL) channel

- The signals transmitted to all users originate from the downlink Tx.

$$s(t) = \sum_{k=1}^{K} s_k(t); \text{ where } s_k(t) \text{ is the } k\text{th user signal} \tag{1}$$

- Examples: all radio and TV broadcasting, the transmission link from a satellite to multiple ground stations, and the transmission link from a base station to the mobile terminals in a cellular system.

- The total signaling dimensions and power of the transmitted signal must be divided among the different users.
- Synchronization of the different users is relatively easy.
- Both signal and interference are distorted by the same channel.

$$y_k(t) = \sum_{k=1}^{K} h_k s_k(t) + n(t); \tag{2}$$

$$SINR_k = \frac{|h_k|^2 P_{s_k}}{|h_k|^2 \sum_{j=1, j\neq k}^{K} P_{s_j} + N_o} \tag{3}$$

Uplink (UL) channel

- Many Txs sending signals to one Rx.
- Examples: laptop wireless LAN cards to a wireless LAN access point, from ground stations to a satellite, and from mobile terminals to a base station in cellular systems.
- Each signal must be within the total system bandwidth B.
- Each user may have an individual power constraint P_k associated with its transmitted signal $s_k(t)$.
- Synchronization is required.
- The uplink signals from different users are distorted by different channels.

$$y(t) = \sum_{k=1}^{K} h_k s_k(t) + n(t); \; s_k(t) \text{ is the } k\text{th user Tx signal} \tag{4}$$

$$SINR_k = \frac{|h_k|^2 P_{s_k}}{\sum_{j=1, j\neq k}^{K} |h_j|^2 P_{s_j} + N_o} \tag{5}$$

Interference

Most communication systems are bi-directional; and thus consist of both uplinks and downlinks – Interference

1. Duplexing (UL and DL inf.): bi-directional systems must separate the UL and DL channels into orthogonal signaling dimensions:
   - Time: time-division duplexing (TDD)
   - Frequency: frequency-division duplexing (FDD)
2. Multiple access (User inf.): dedicated channels are allocated to users - to create orthogonal channels (but not possible always!).
   - DL: $\gamma_k = \frac{|h_k|^2 P_{s_k}}{|h_k|^2 \sum_{j=1,j\neq k}^{K} P_{s_j} + N_o}$; UL: $\gamma_k = \frac{|h_k|^2 P_{s_k}}{\sum_{j=1,j\neq k}^{K} |h_j|^2 P_{s_j} + N_o}$
   - time-division multiple access (TDMA)
   - frequency-division multiple access (FDMA)
   - code-division multiple access (CDMA)
   - space-division multiple access (SDMA) - directional ant., beamforming

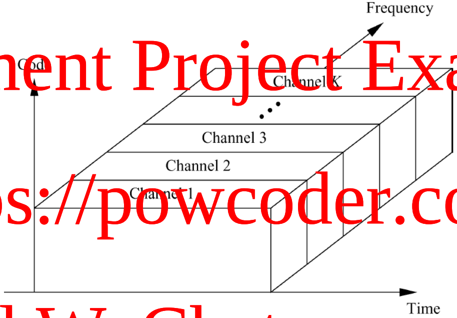
$$\gamma_k = \frac{|h_k|^2 P_{s_k}}{N_o} \tag{6}$$

$$C = \log_2(1 + \gamma_k)\ bits/sec/Hz \tag{7}$$

$$P_{out} = ??? \tag{8}$$

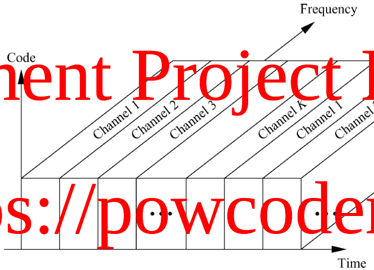
$$SER = ??? \tag{9}$$

Frequency-Division Multiple Access (FDMA)



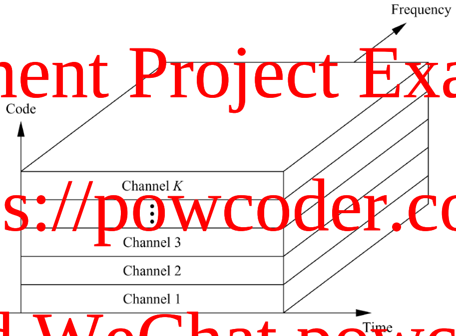
- Divided along the frequency axis into non-overlapping channels, and each user is assign a different frequency channel.
- The channels often have guard bands between them to avoid interference, etc.

Time-Division Multiple Access (TDMA)



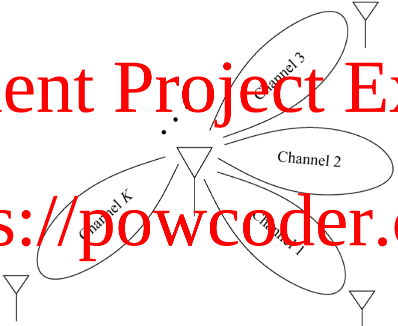
- Divided along the time axis into non-overlapping channels, and each user is assigned a different cyclically repeating time-slot.
- Occupy the entire system bandwidth.
- A major difficulty of TDMA, at least for uplink channels, is the requirement for synchronization among the different users.
- Used in the GSM.

Code-Division Multiple Access (CDMA)



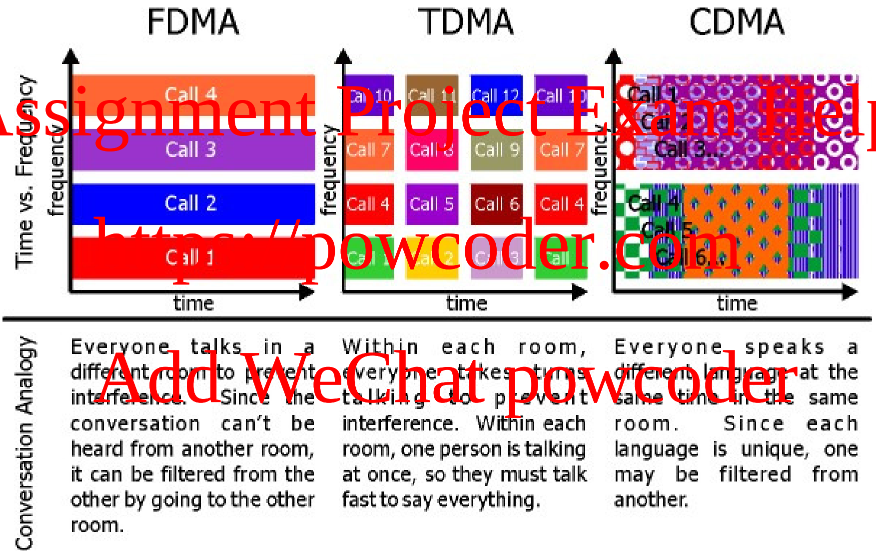
- The information signals of different users are modulated by orthogonal or non-orthogonal spreading codes.
- The resulting spread signals simultaneously occupy the same time and bandwidth.

Space-Division Multiple Access (SDMA)



- uses direction (angle) as another dimension in signal space, which can be channelized and assigned to different users -directional antennas/sectorized antenna arrays.
- TDMA or FDMA is used to channelize users within a sector.
- Hybrid Techniques!

TDMA/FDMA/CDMA



https://www.ccs.neu.edu/home/futrelle/teaching/com1204sp2001/uwash-intro/final.html

Cellular Systems

- A type of infrastructure-based network that make efficient use of spectrum by reusing it at spatially separated locations.
- Exploit the power falloff with distance of signal propagation in order to reuse the same channel at spatially separated locations.
- A given spatial area (a city) is divided into non-overlapping cells.

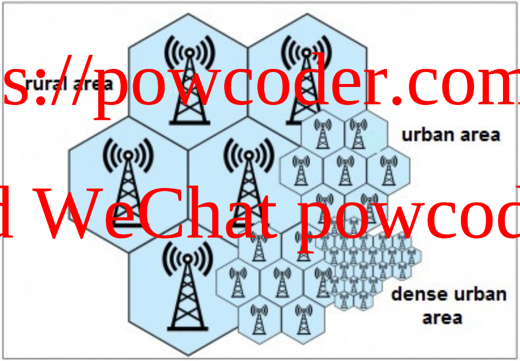
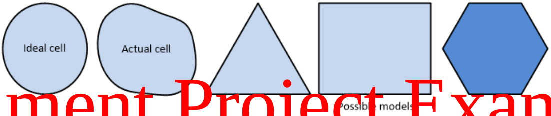


Figure 1: Cellular system.

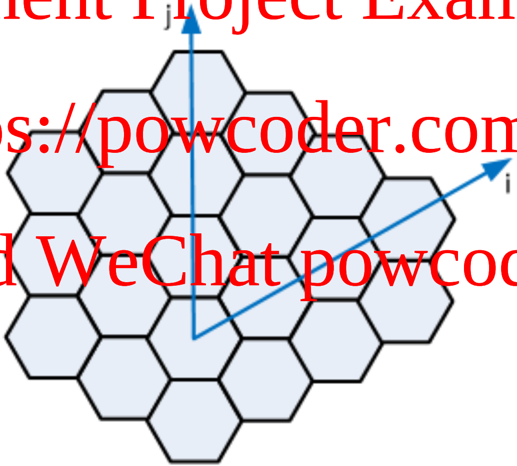
“Cell”ular Structure



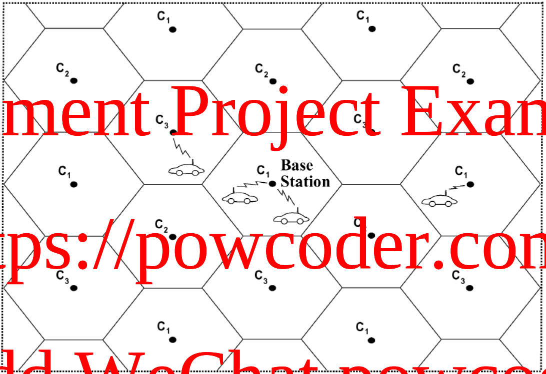
- The hexagon is an ideal choice for representing cellular coverage areas, because it closely approximates a circle and offers a wide range of tessellating reuse cluster sizes.
- Typical cells: Femto-, Pico-, Micro-, Macro-cells
- Cluster size: $N = i^2 + ij + j^2$; $i \geq j \geq 0 \Rightarrow N = 1, 3, 4, 7, 9, \cdots$

"Cell"ular Structure

- Cluster size: $N = i^2 + ij + j^2$; $i \geq j \geq 0 \Rightarrow N = 1, 3, 4, 7, 9, \cdots$
- i= no. of cells (center to center) along any chain of hexagon
- j= no. of cells in 60 degree counter-clockwise of i

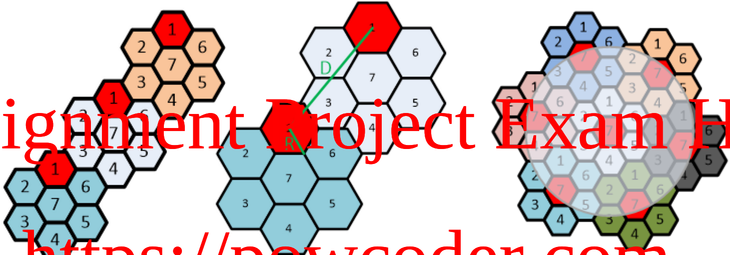


Cellular System Fundamentals



- Every cell is then assigned a channel set, and these sets can be reused at spatially separated locations – frequency reuse or channel reuse, e.g., Channel set C_n where $n = 1, 2, 3$.
- Cells that are assigned the same channel set, called co-channel cells, must be spaced far enough apart (to minimize interference).
- Handed off: When a mobile moves between two cells.

Co-channels in cellular systems



- Use the same frequency channels.
- Co-channel reuse factor: the ratio of the co-channel reuse distance (D) between cells using the same set of carrier frequencies and the radius of the cells (R)

$$\frac{D}{R} = \sqrt{3N} \tag{10}$$

- Co-channel interference: signals from cells that share same channel(s) cause co-channel interference.
- See figure for the First Tier interfering cells.

Interference in Cellular Systems

1. Intercell or co-channel interference: interference from outside the cell (e.g., due to reuse).
2. Intracell interference: interference from within a cell (e.g., non-orthogonal channelization).
3. Signal-to-interference-plus-noise power ratio (SINR):

$$SINR = \frac{P_r}{P_I + N_0} \tag{11}$$

   where P_r is the received desired signal power, and P_I is the received power associated with both intracell and intercell interference.
4. Interference-limited system: the interference power is much larger than the noise power - Signal-to-interference-power ratio (SIR) or carrier-to-interference-power ratio (CIR)

$$CIR = SIR = \frac{P_r}{P_I} \tag{12}$$

Co-channel interference (CCI)

- In a fully equipped hexagonal-shaped system, the number of interfering channels in the first tier is always 6.

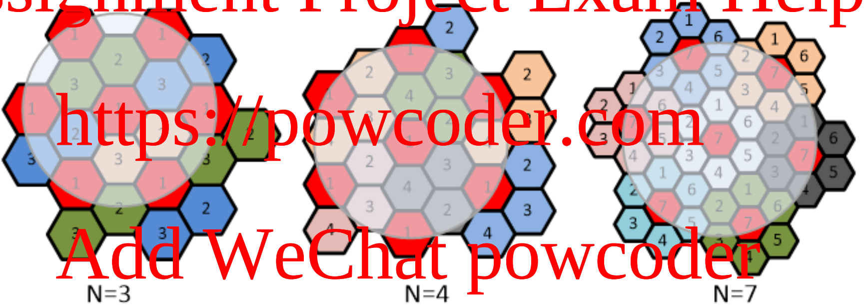
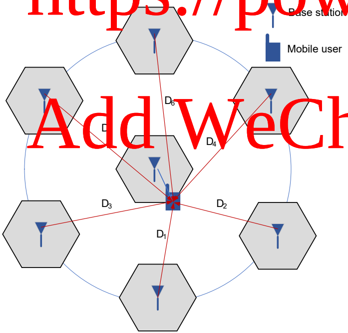


Figure 2: The first tier interfering cells.

1. DL: The BS to the mobile user.
2. The worst case: the mobile user is far away from the desired BS (and more closer to interfering BSs)
   - Assume that the BS antennas are all the same height and all BSs transmit with the same power.
   - Ignore the effects of shadowing and multipath fading, and assume that the propagation path-loss is described by the inverse law or the simplified model.



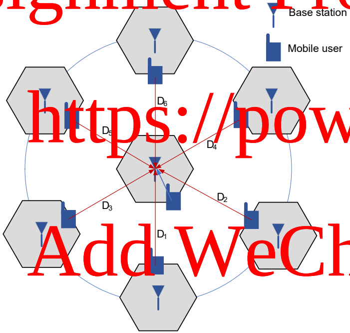
$$P_r(d) = P_i(d) = P_t K \left(\frac{d_r}{d}\right)^{\alpha} \quad (13)$$

Carrier-to-interference ratio (C/I):

$$\frac{C}{I} = \frac{P_r}{\sum_{i=1}^{6} P_i} = \frac{P_t K \left(\frac{d_r}{R}\right)^{\alpha}}{\sum_{i=1}^{6} P_t K \left(\frac{d_r}{D_i}\right)^{\alpha}} = \frac{R^{-\alpha}}{\sum_{i=1}^{6} D_i^{-\alpha}} \quad (14)$$

UL worst case CCI

1. UL: The mobile user to the BS.
2. The worst case: the mobile user is far away from the desired BS; and interfering mobile users are closer to the desired BS.



$$\frac{C}{I} = \frac{P_r}{\sum_{i=1}^{6} P_i} \tag{15}$$

$$= \frac{P_t K \left(\frac{d_r}{R}\right)^{\alpha}}{\sum_{i=1}^{6} P_t K \left(\frac{d_r}{D_i}\right)^{\alpha}}$$

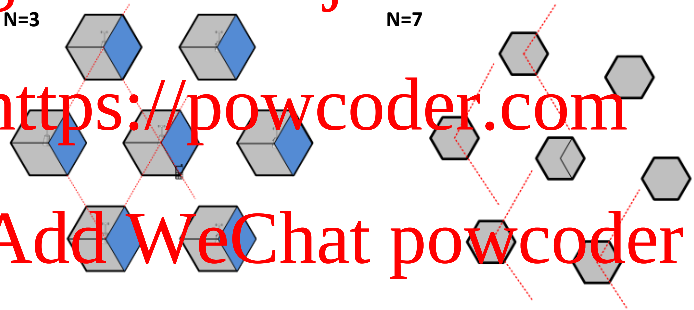
$$= \frac{R^{-\alpha}}{6D^{-\alpha}} \quad \text{where } D \equiv D_i \; \forall i \tag{16}$$

3. You may use this for network design:

$$\frac{D}{R} = \sqrt{3N} \tag{17}$$

Cell Sectoring

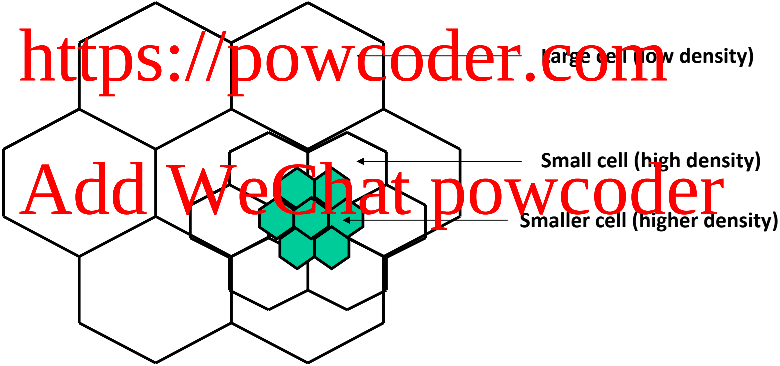
1. Cell sectoring reduces the number of co-channel base stations
   - 120^o sectoring: 2 or 3 co-channel cells cause interference
   - 60^o sectoring: 1 or 2 co-channel cells cause interference



2. Example: For $N = 7$, 120^o cell sectoring yields an approximately 6 dB C/I improvement over Omni-cells.

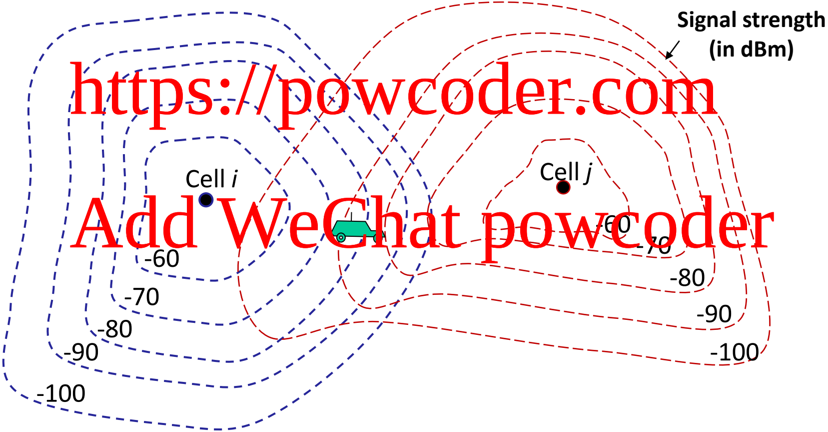
Cell Splitting

1. Depending on traffic patterns, the smaller cells may be activated/deactivated in order to efficiently use cell resources.
   - subdividing a congested cell into smaller cells (Femto, Pico).
   - Each has its own base station, and use reduced transmission power.
   - Channel borrowing



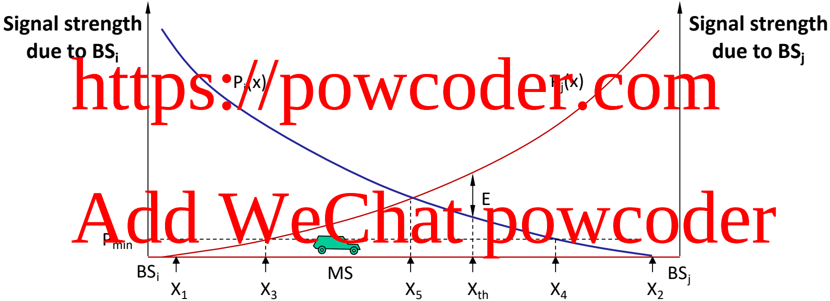
Signal Strength

- Signal strength contours indicating actual cell tiling. This happens because of
  - terrain
  - presence of obstacles
  - signal attenuation in the atmosphere, etc...



Handoff

- Handoff - when crossing a cell boundary while continuing the call.
- By looking at the variation of signal strength from BSs, it is possible to decide on the optimum area where handoff can take place.
- When to initiate handoff, e.g., the mean signal (over some predetermined time) is below some threshold.



1. Hard handoff - A user on the edge of a cell is either assigned to one cell or the other but not both.
2. Soft handoff - A user on the edge of a cell can receive or transmit signals to two or more BSs to improve reception.

References

A. Goldsmith, *Wireless Communications*, Cambridge University Press, USA, 2005.

Thank You!

See you again ☺