Introduction to Wireless and Mobile Networking

Lecture 3: Multiplexing, Multiple Access, and Frequency Reuse

Hung-Yu Wei
National Taiwan University

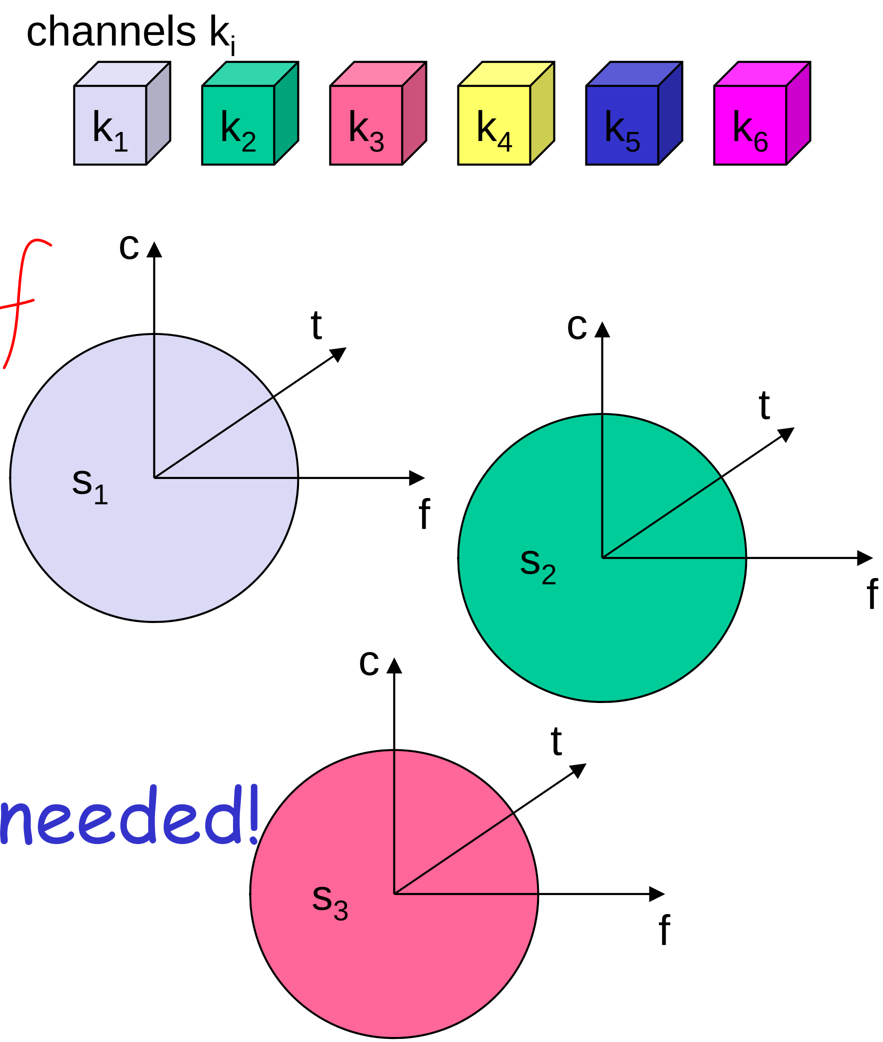
Multiplexing/Multiple Access

Multiplexing

- Multiplexing in 4 dimensions
  - space (s_i)
  - time (t)
  - frequency (f)
  - code (c)

f_1 f_2

f

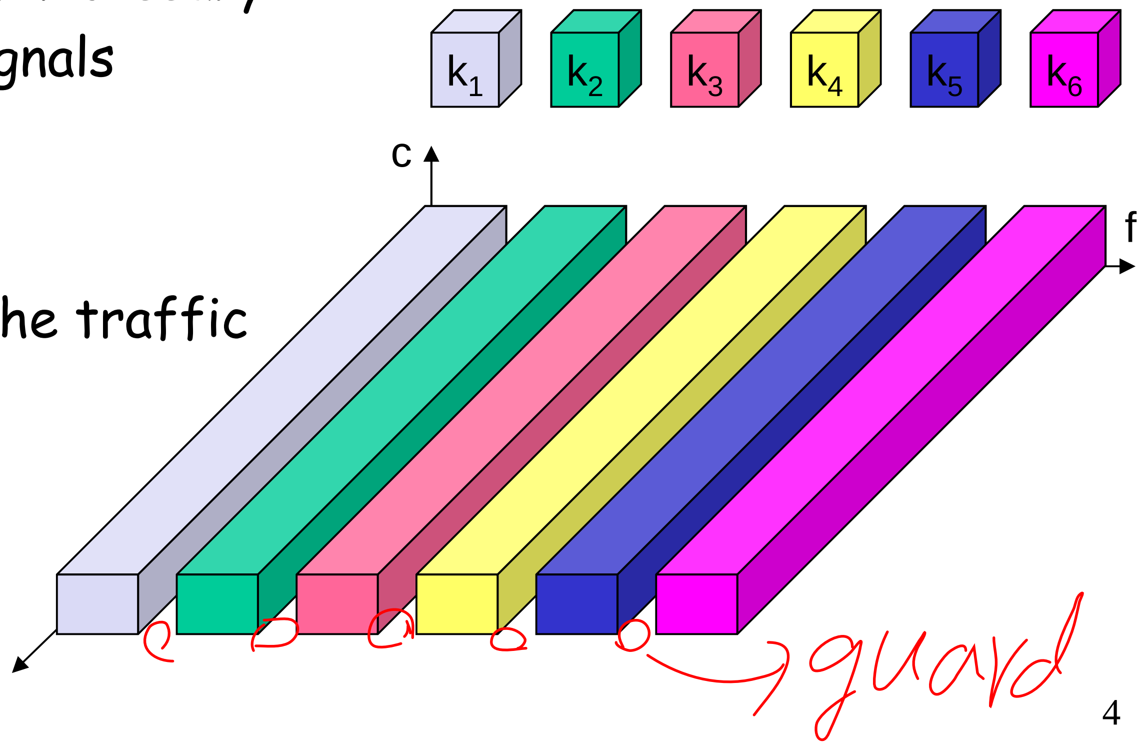


- Goal: multiple use of a shared medium

- Important: guard spaces needed!

Frequency multiplex

- Separation of the whole spectrum into smaller frequency bands
- A channel gets a certain band of the spectrum for the whole time
- Advantages:
  - no dynamic coordination necessary
  - works also for analog signals
- Disadvantages:
  - waste of bandwidth if the traffic is distributed unevenly
  - inflexible
  - guard spaces

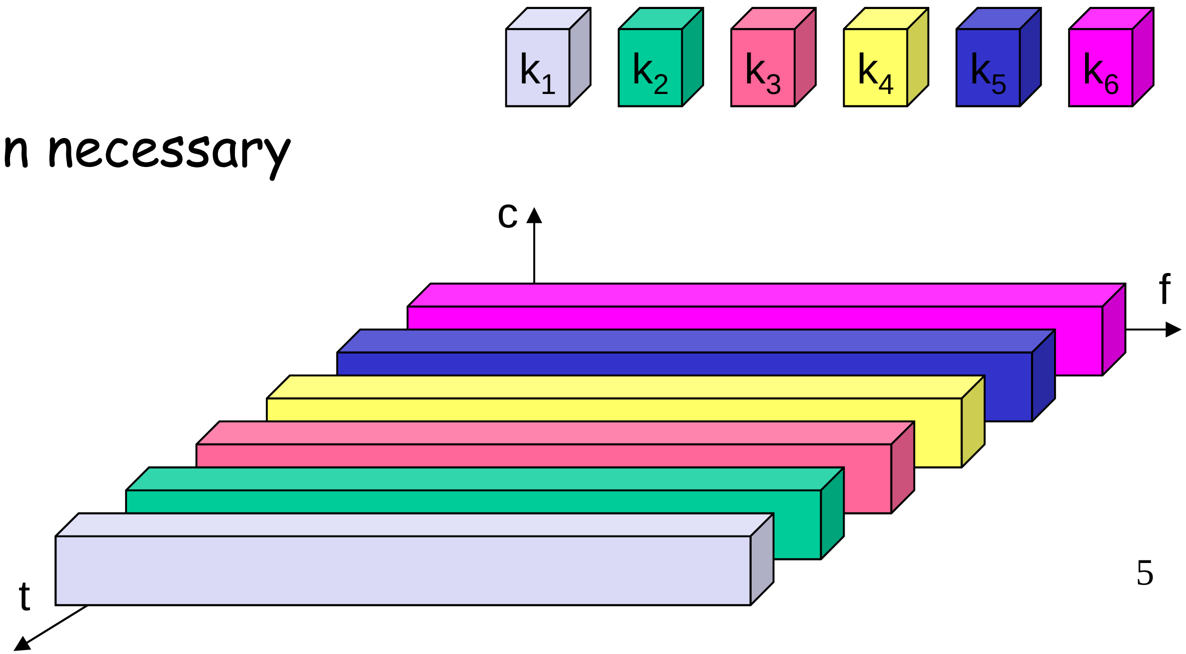


Time multiplex

- A channel gets the whole spectrum for a certain amount of time

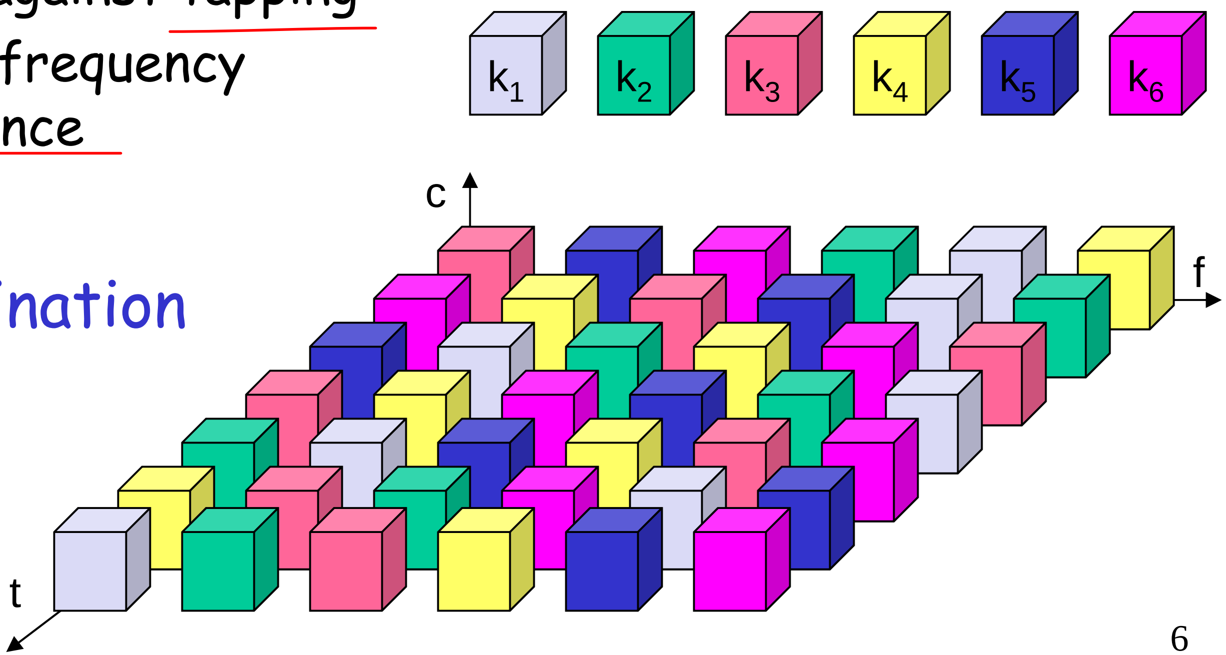
- Advantages:
  - only one carrier in the medium at any time
  - Flexibility in time-domain scheduling

- Disadvantages:
  - Precise synchronization necessary



Time and frequency multiplex

- Combination of both methods
- A channel gets a certain frequency band for a certain amount of time
- Example: GSM LTE
- Advantages: for sercurity
  - better protection against tapping
  - protection against frequency selective interference

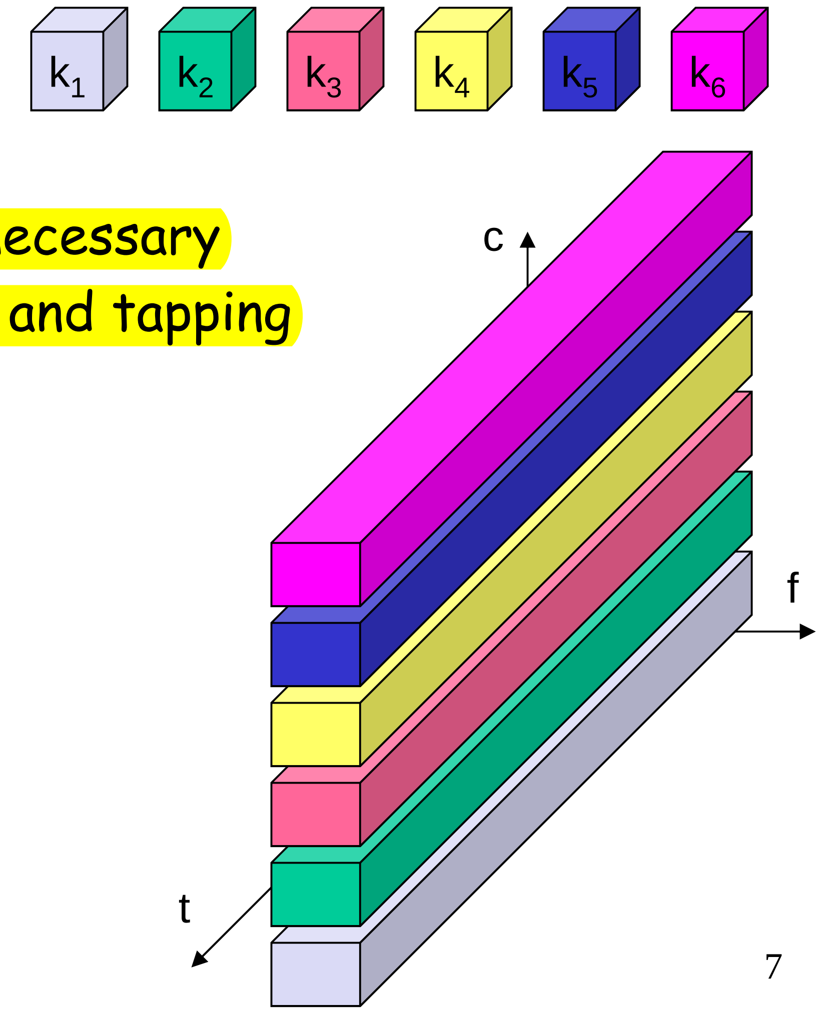


- but: precise coordination required

Code multiplex

time diversity
frequency

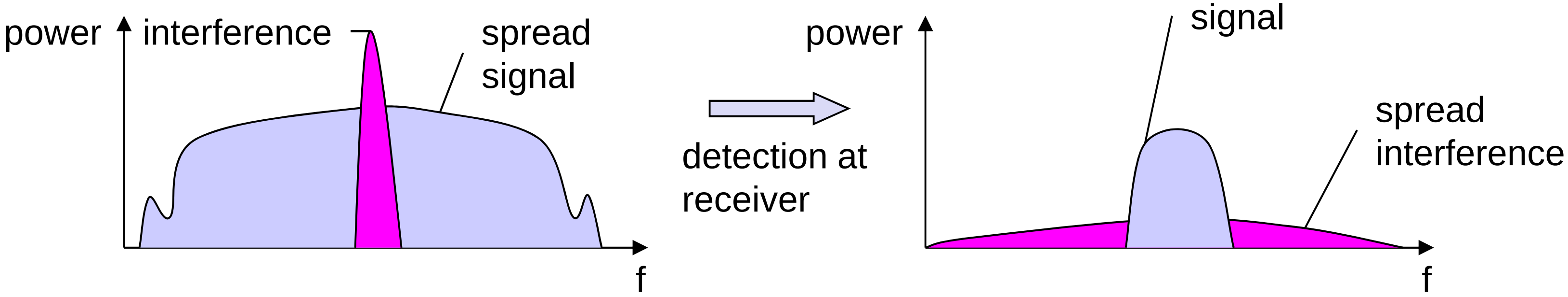
- Each channel has a unique code
- All channels use the same spectrum at the same time
- Advantages:
  - bandwidth efficient
  - no coordination and synchronization necessary
  - good protection against interference and tapping
- Disadvantages:
  - lower user data rates
  - more complex signal regeneration
- Implemented using spread spectrum technology



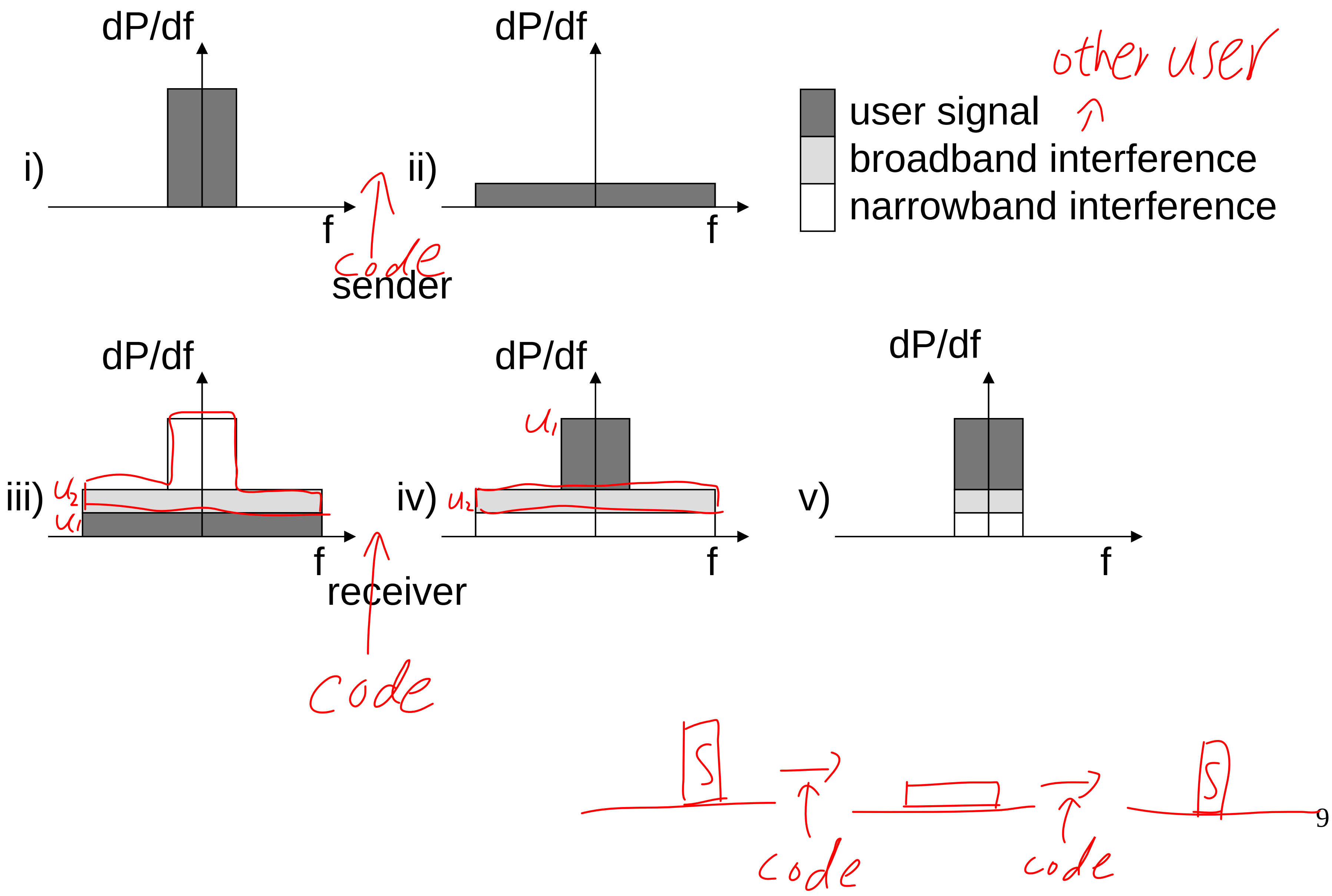
$$SINR = \frac{S_1}{S_2 + S_3 + \cdots S_n}$$

Spread spectrum technology

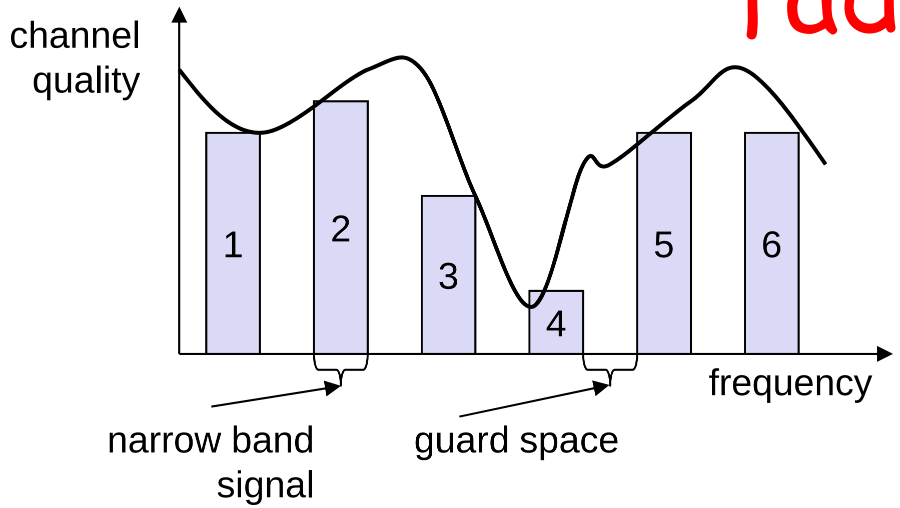
- Problem of radio transmission: frequency dependent fading can wipe out narrow band signals for duration of the interference
- Solution: spread the narrow band signal into a broad band signal using a special code
- protection against narrow band interference



Effects of spreading and interference

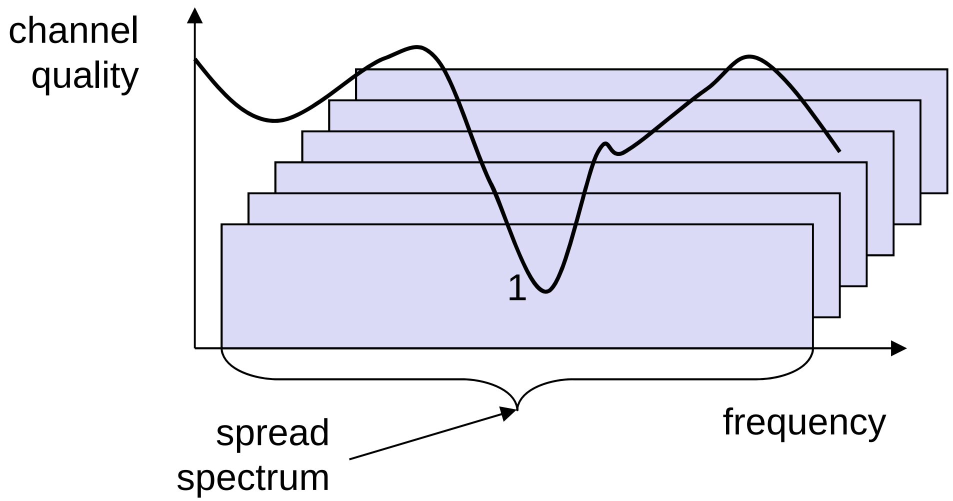


Spreading and frequency selective fading



diversity

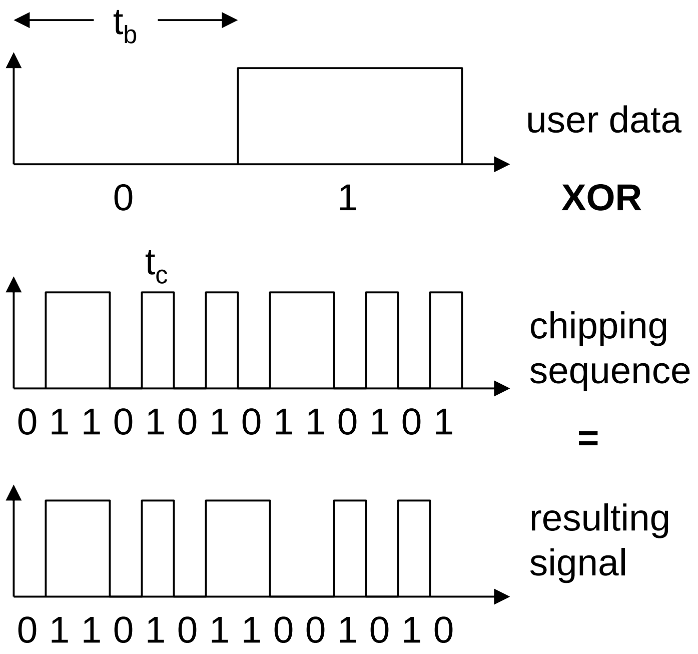
narrowband channels



spread spectrum channels

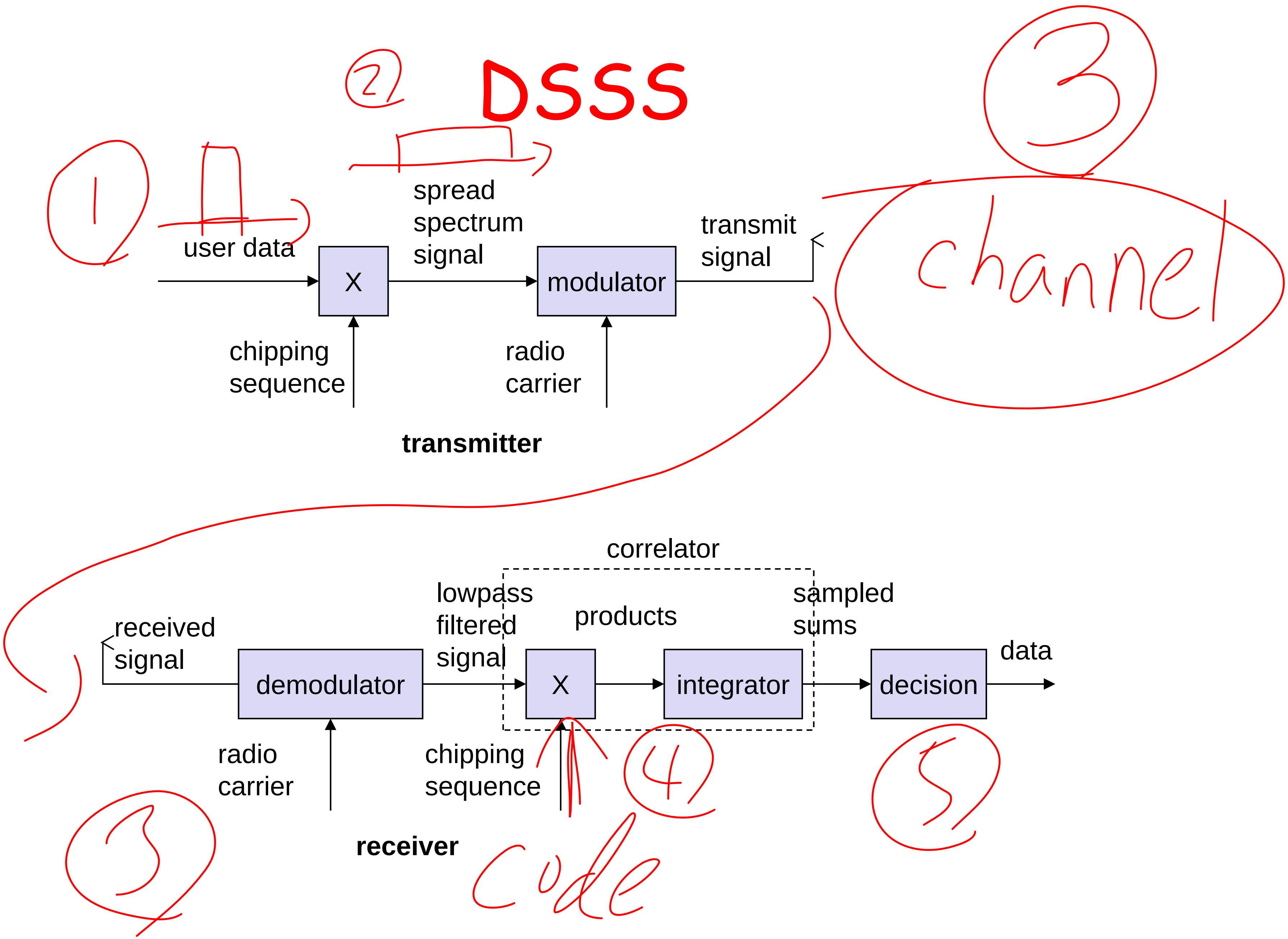
DSSS (Direct Sequence Spread Spectrum)

- XOR of the signal with pseudo-random number (chipping sequence)
  - many chips per bit (e.g., 128) result in higher bandwidth of the signal
- Advantages
  - reduces frequency selective fading
  - in cellular networks
    - base stations can use the same frequency range
    - several base stations can detect and recover the signal
    - soft handover
- Disadvantages
  - precise power control necessary



t_b: bit period
t_c: chip period

DSSS



user data
X
spread spectrum signal
modulator
transmit signal
chipping sequence
radio carrier
transmitter
channel
correlator
received signal
demodulator
lowpass filtered signal
X
products
integrator
sampled sums
decision
data
radio carrier
chipping sequence
receiver
code

FHSS (Frequency Hopping Spread Spectrum)

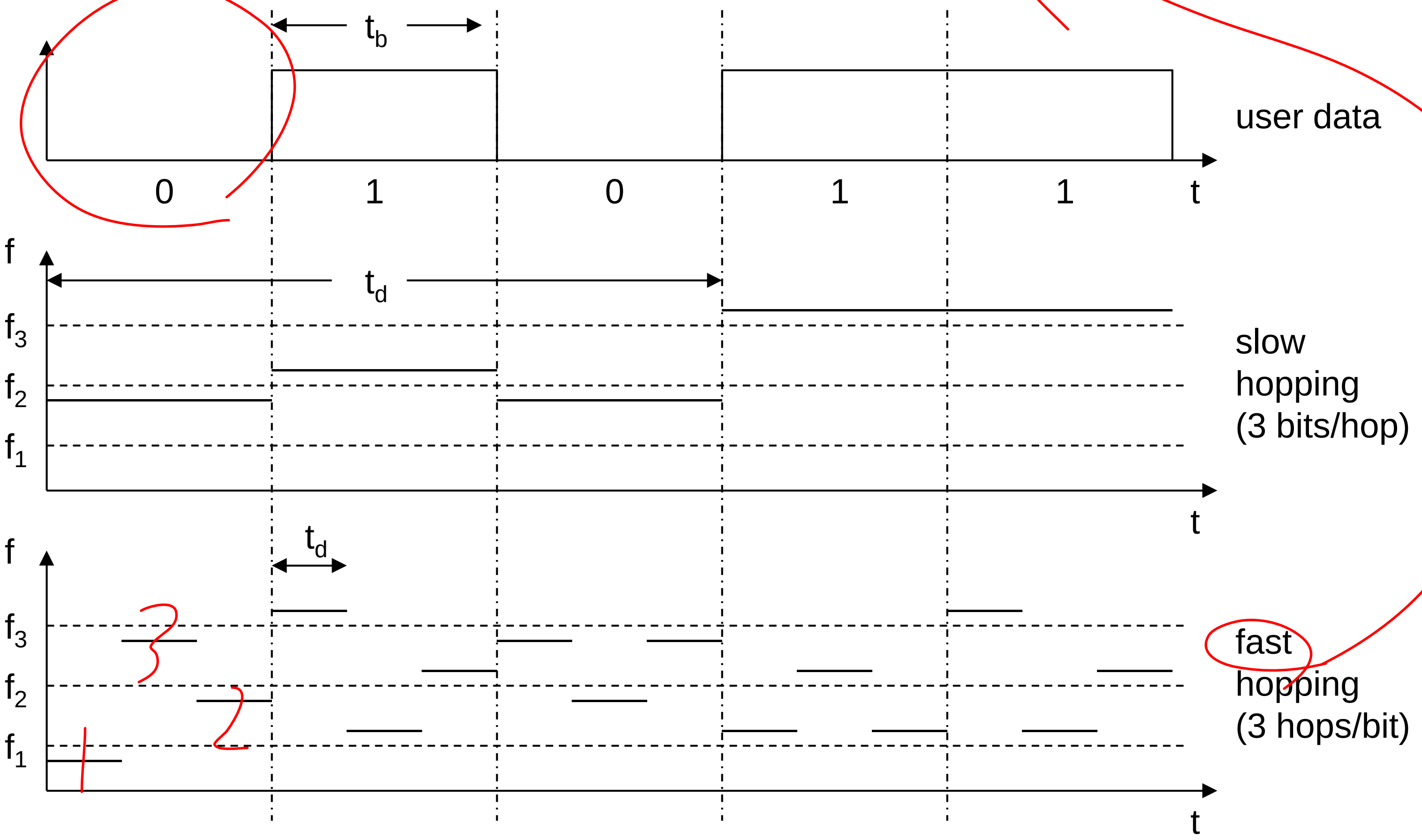
- Discrete changes of carrier frequency
  - sequence of frequency changes determined via pseudo random number sequence
- Two versions
  - Fast Hopping:
    several frequencies per user bit
  - Slow Hopping:
    several user bits per frequency

diversity

- Advantages
  - frequency selective fading and interference limited to short period
  - simple implementation → DSSS
  - uses only small portion of spectrum at any time
- Disadvantages
  - not as robust as DSSS
  - simpler to detect

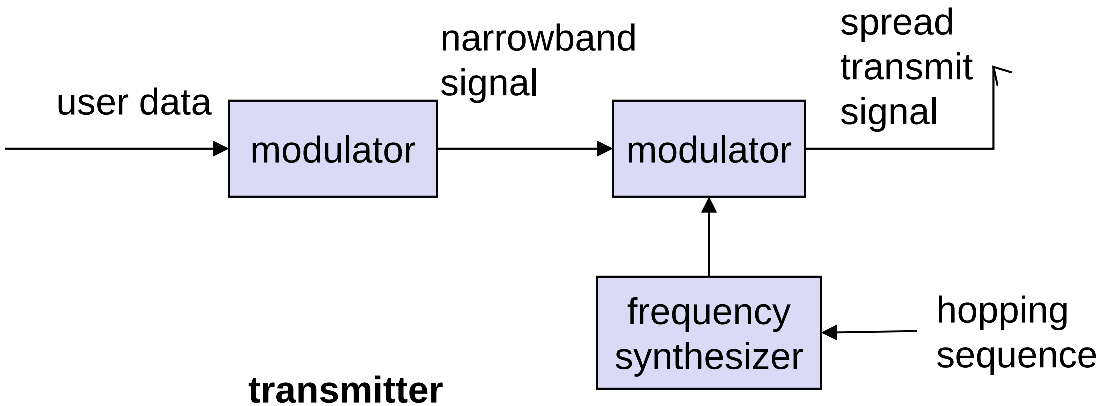
data bit

FHSS

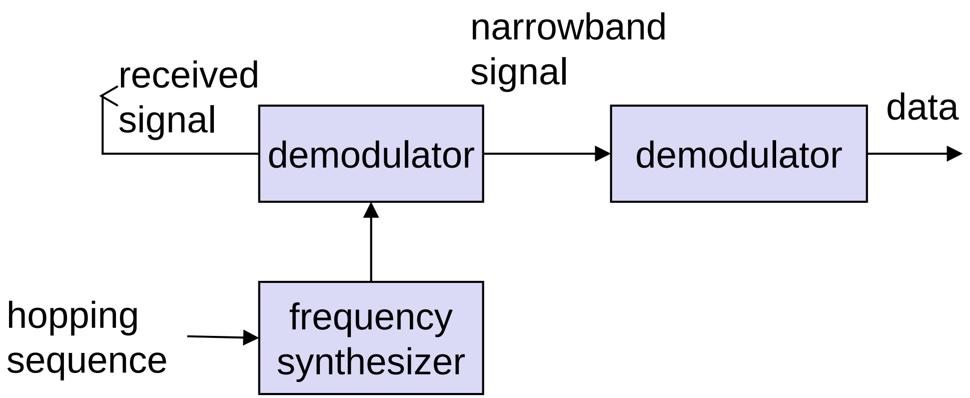


t_b: bit period t_d: dwell time

FHSS



transmitter



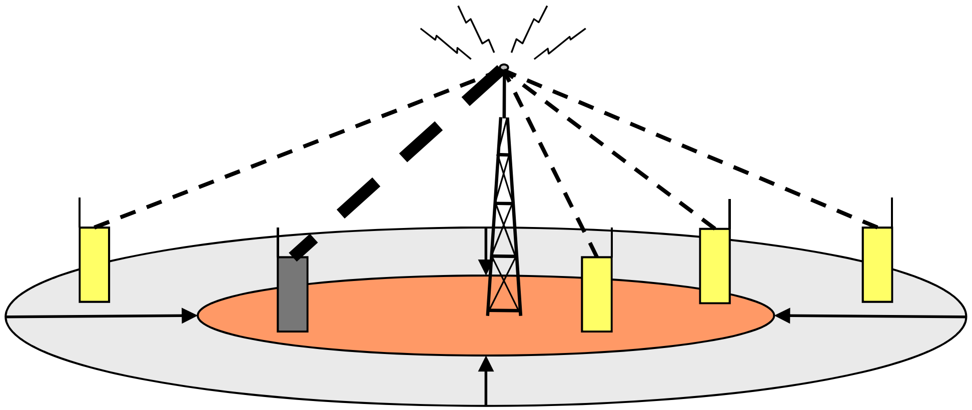
receiver

Cell breathing

DSSS

- CDM systems: cell size depends on current load
- Additional traffic appears as noise to other users
- If the noise level is too high users drop out of cells

SINR ≥ threshold



$P_{rx} = G_{tx} \cdot G_{rx} \cdot P_{tx} \cdot$ ≥ threshold

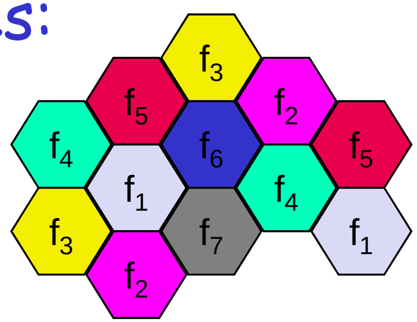
Cell structure

- Implements space division multiplex: base station covers a certain transmission area (cell)
- Mobile stations communicate only via the base station

- Advantages of cell structures:
  - higher capacity, higher number of users
  - less transmission power needed
  - more robust, decentralized
  - base station deals with interference, transmission area etc. locally
- Problems:
  - fixed network needed for the base stations
  - handover (changing from one cell to another) necessary
  - interference with other cells
- Cell sizes from some 100 m in cities to, e.g., 35 km on the country side (GSM) - even less for higher frequencies

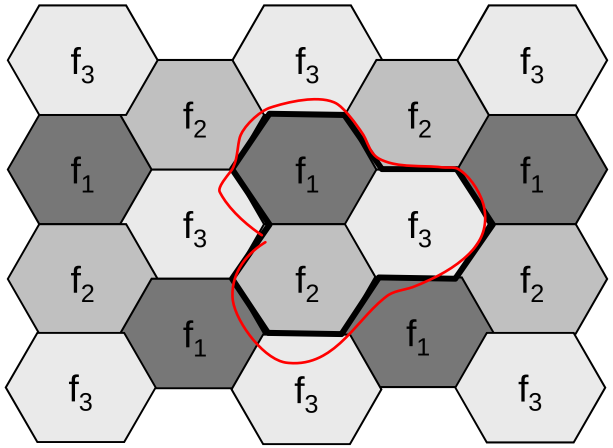
Frequency planning

- Frequency reuse only with a certain distance between the base stations
- Standard model using 7 frequencies:

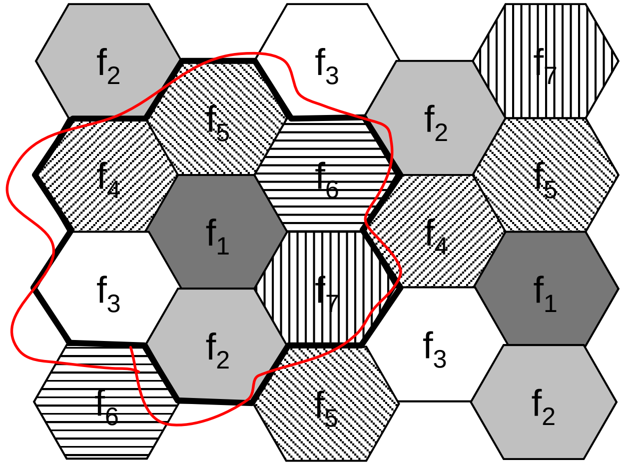


- Fixed frequency assignment:
  - certain frequencies are assigned to a certain cell
  - problem: different traffic load in different cells
- Dynamic frequency assignment:
  - base station chooses frequencies depending on the frequencies already used in neighbor cells
  - more capacity in cells with more traffic
  - assignment can also be based on interference measurements

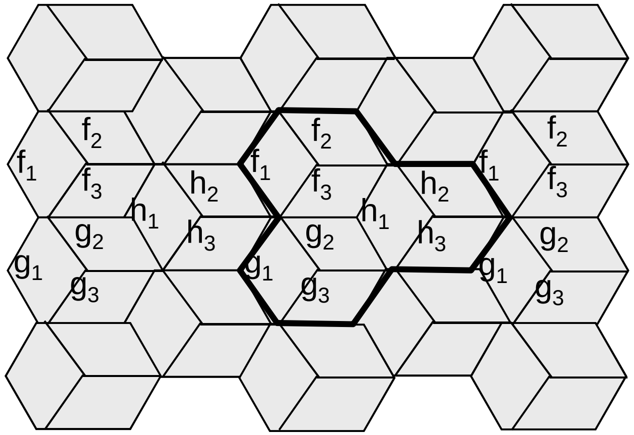
Frequency planning



3 cell cluster



7 cell cluster



3 cell cluster
with 3 sector antennas

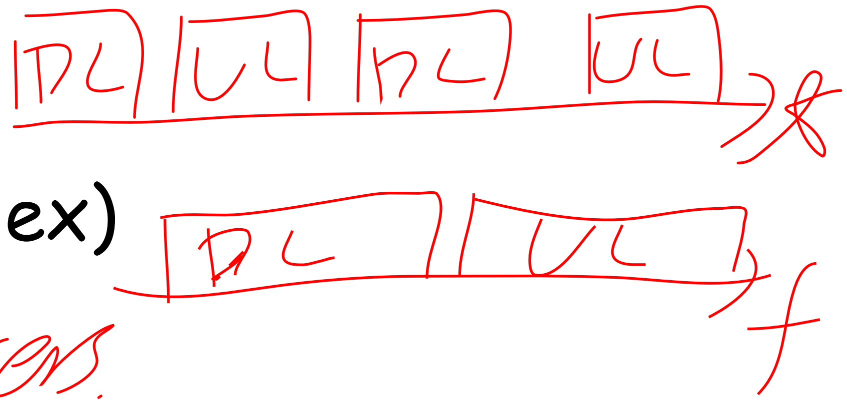
Clarification on Terminologies

Similar (but confusing) terms

- MAC (medium access control) protocol
  - A protocol that control which user should access the medium at a given moment
- Multiple Access
  - Multiple users access network simultaneously
- Multiplexing
  - Combine multiple signals/transmissions into 1 transmission

Similar (but confusing) terms

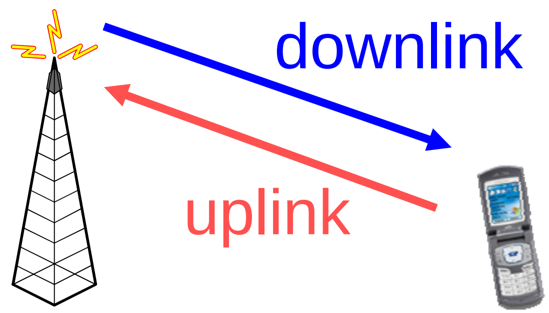
- Duplex
  - TDD (time division duplex)
  - FDD (frequency division duplex)

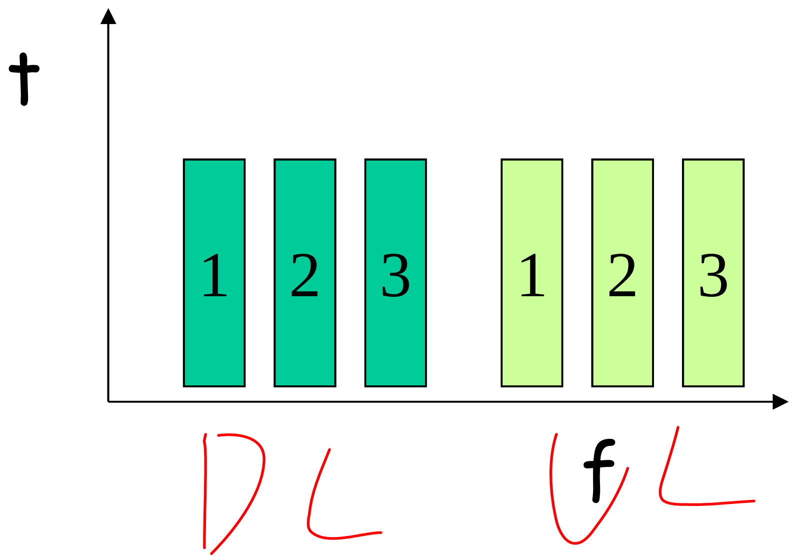


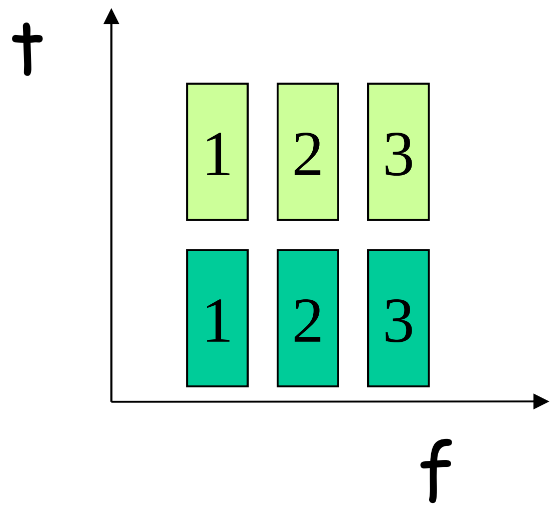
- Multiple access multiple users.
  - TDMA (time division multiple access)
  - FDMA (frequency division multiple access)
- Multiplexing
  - TDM (time division multiplexing)
  - FDM (frequency division multiplexing)

Examples

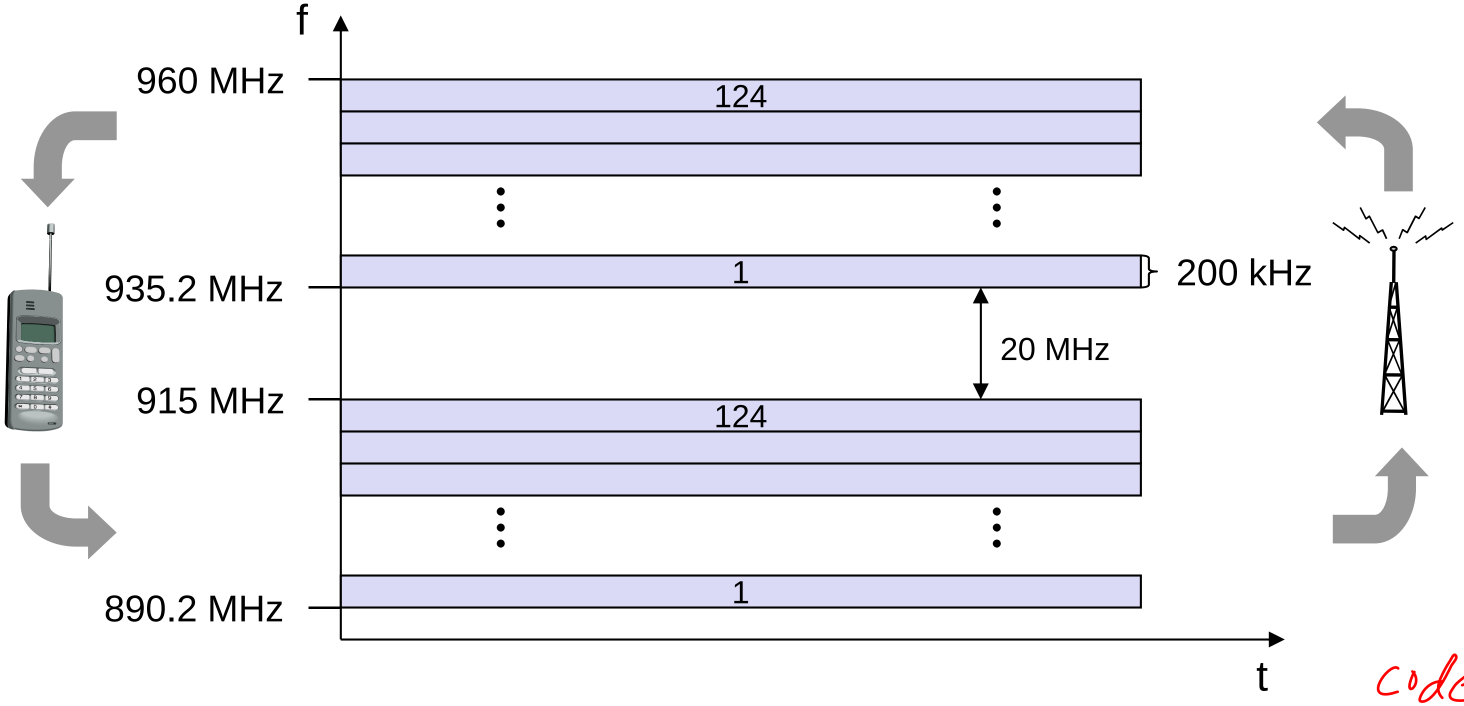
- FDMA/FDD
  - E.g. AMPS
- FDMA/TDD
  - E.g. CT-2



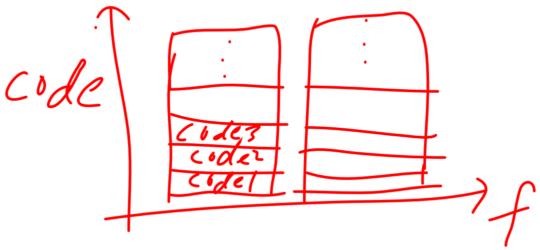




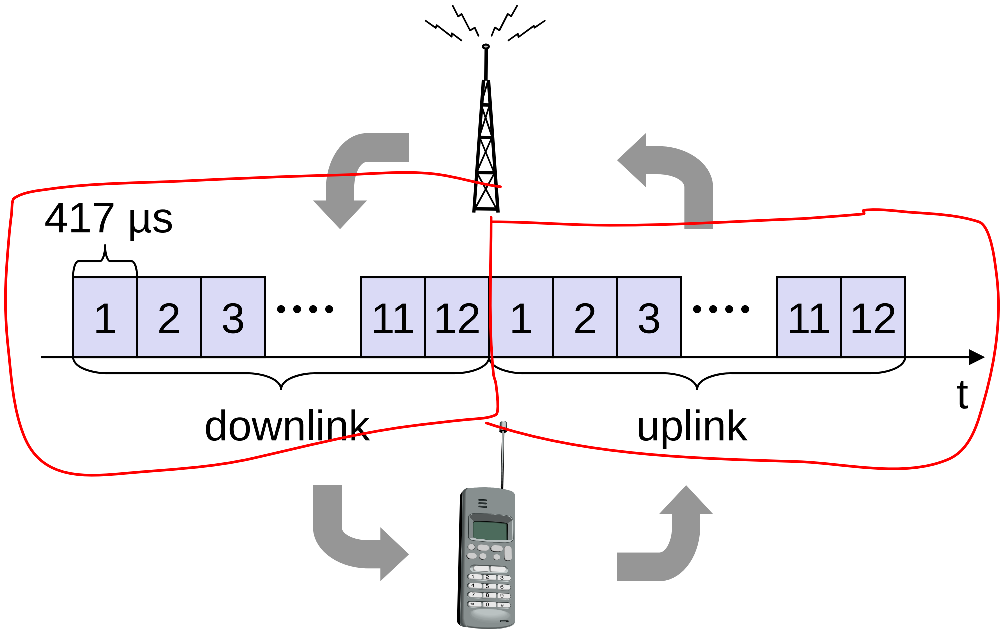
FDD/FDMA
Example GSM



FDD/CDMA



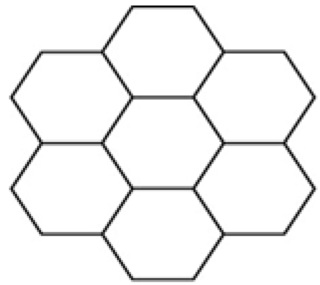
TDD/TDMA
Example DECT



Frequency Reuse in Cellular System

Review: Basic Cellular Concept

- "Cell"
  - Typically, cells are hexagonal
  - In practice, it depends on available cell sites and radio propagation conditions
- Spectrum reuse
  - Reuse the same wireless spectrum in other geographical location
  - Frequency reuse factor



Frequency Reuse

- Frequency reuse
  - Spatial reuse
  - Spectral reuse

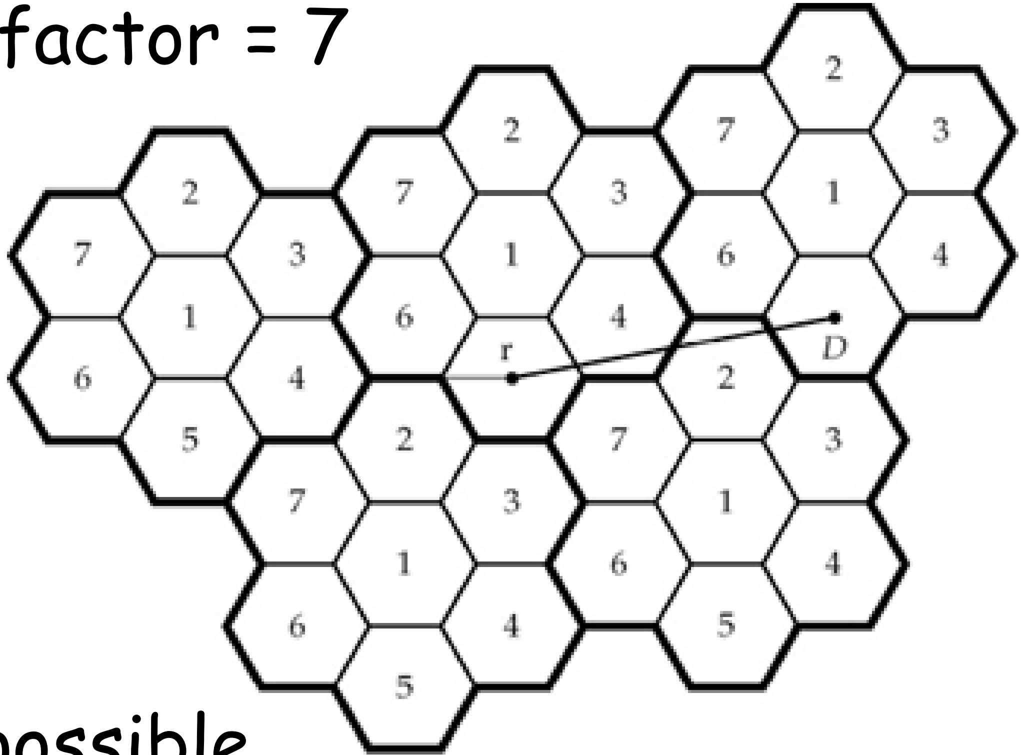
spectrum

- Cluster
  - A group of cells
- Frequency reuse factor
  - (Total # of channels in a cluster) / (Total # of channels in a cell)

TDMA/FDMA Spatial Reuse

A frequency reuse example

- Example
  - Frequency reuse factor = 7
  - Cluster size =7



- Question
  - What are other possible frequency reuse patterns?

Cluster

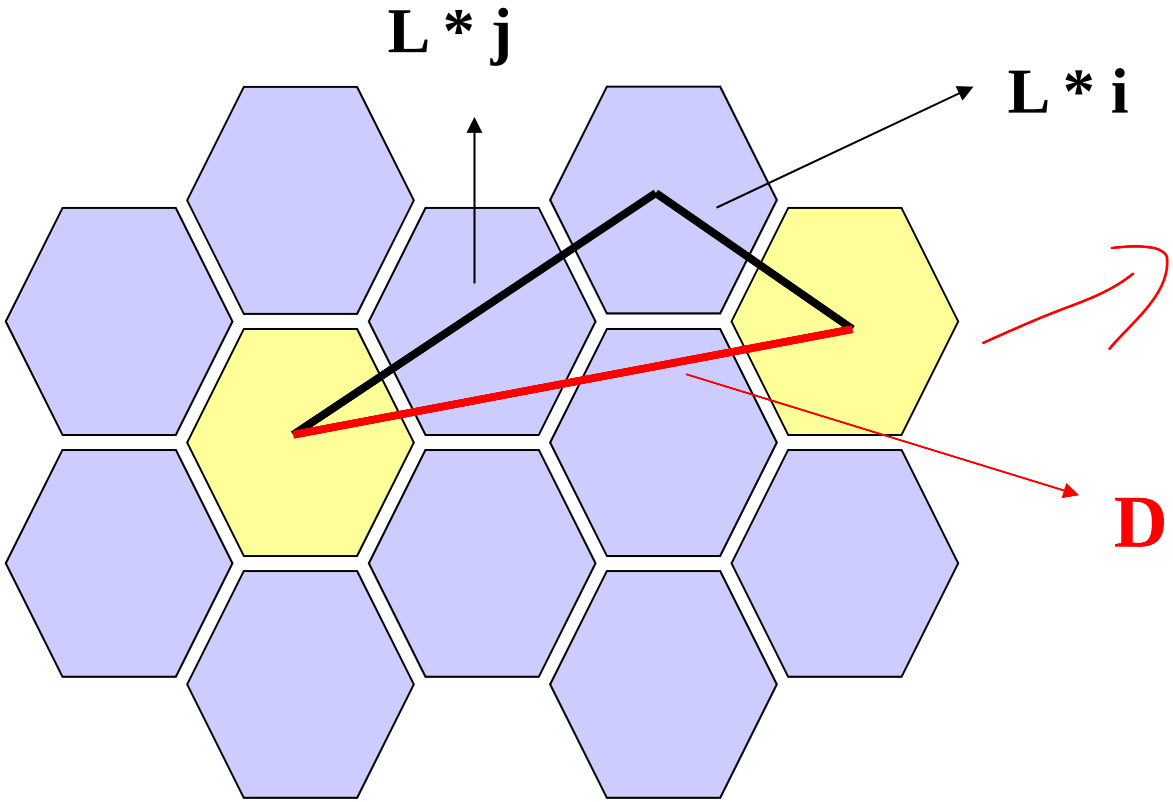
- The hexagon is an ideal choice for macrocellular coverage areas, because it closely approximates a circle and offers a wide range of tessellating reuse cluster sizes.
- A cluster of size N can be constructed if,
  - $N = i^2 + ij + j^2$. $i, j \in [0, 1, 2, \ldots]$
  - i,j are positive integer
- Allowable cluster sizes are
  - $N = 1, 3, 4, 7, 9, 12, \ldots$

Determine frequency reuse pattern

- Co-channel interference [CCI]
  - one of the major factors that limits cellular system capacity
  - CCI arises when the same carrier frequency is used in different cells.
- Determine frequency reuse factor
  - Propagation model
  - Sensitivity to CCI

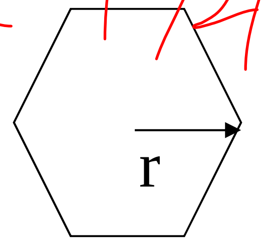
Reuse distance

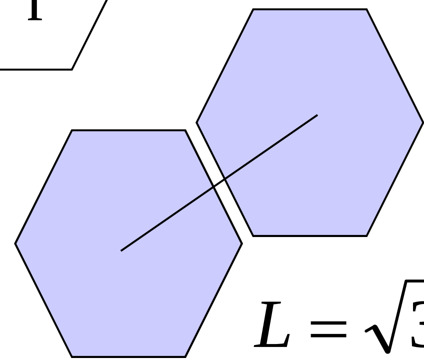
- Notations
  - D :Reuse distance
    - Distance to cell using the same frequency
  - r : Cell radius
  - N : Frequency reuse factor
- Relationship between D and r
  - D/r=(3N)^0.5
  - $N = i^2 + ij + j^2$
- Proof?



In this case: j=2, i=1

斜角座標





$L = \sqrt{3}r$

$$D^2 = (L \cdot i)^2 + (L \cdot j)^2 - 2(L \cdot i)(L \cdot j)\cos(2\pi/3)$$

$$D^2 = L^2 \cdot i^2 + L^2 \cdot j^2 - 2L^2 \cdot i \cdot j \cdot (-0.5)$$

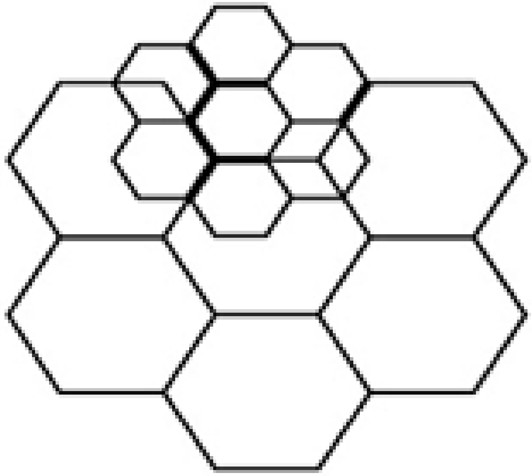
$$D^2 = L^2(i^2 + j^2 + ij)$$

$$D/r = \sqrt{3(i^2 + j^2 + ij)} = \sqrt{3N}$$

Compute D based on “law of cosine”

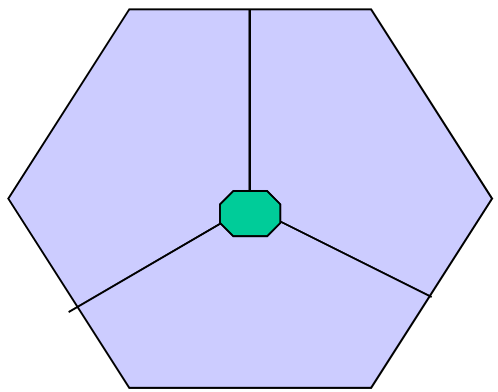
Cell splitting

- Smaller cells have greater system capacity
  - Better spatial reuse
- As traffic load grows, larger cells could split into smaller cells



Sectors

- Use directional antenna reduces CCI
  - Why? Think about it!
- 1 base station could apply several directional antennas to form several sectors
- 3-sector cell



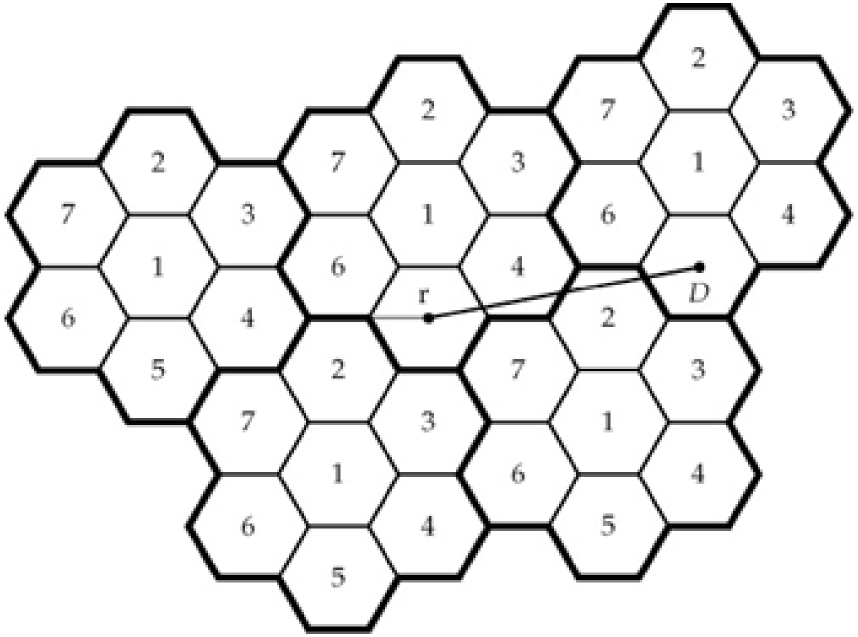
More about cellular

Cell size & FRF

- Cell size should be proportional to 1/(subscriber density)
- Co-channel interference is proportional to
  - 1/D
  - r
  - 1/N^0.5
  - Path-loss model
- Total system capacity is proportional to
  - 1/N
    - N : Frequency reuse factor

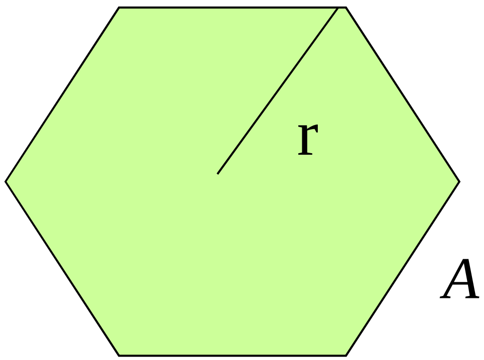
Example: N=7

- Frequency reuse factor N=7
  - $N = i^2 + ij + j^2$
  - (i,j)=(1,2) or (2,1)
- Other commonly used patterns
  - N=3
    - (1,1)
  - N=4
    - (2,0); (0,2)
- N=1 is possible
  - CDMA



Compute total system capacity

- Example
  - Total coverage area = 100 mile^2 = 262.4 km^2
  - Total 1000 duplex channels
  - Cell radius = 1km
  - N=4 or N=7
- What's the total system capacity for N=4 and N=7?

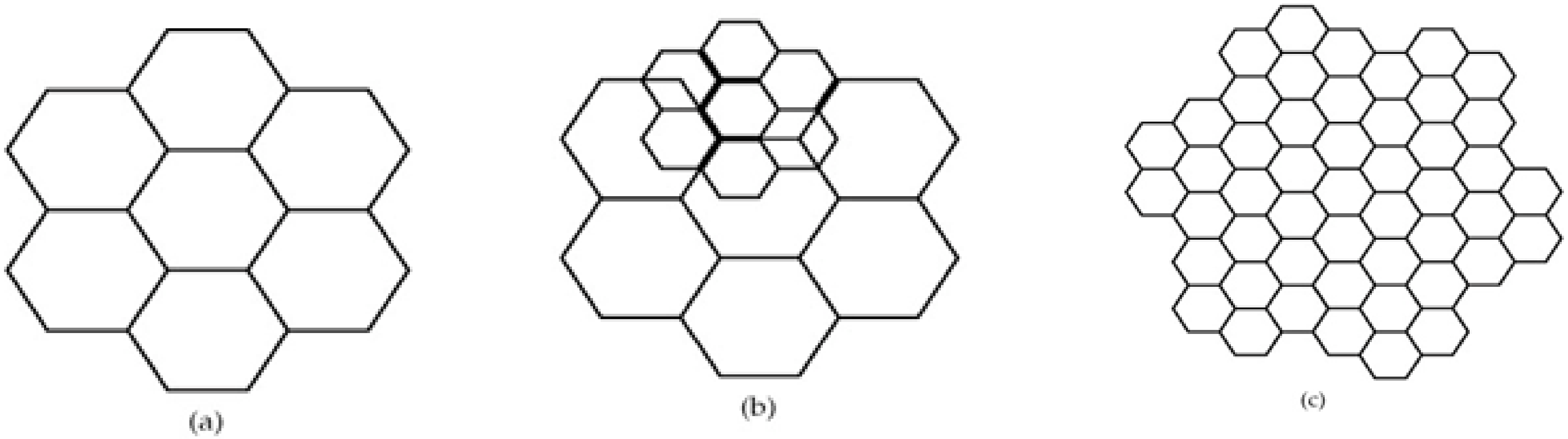


$$A = \frac{3\sqrt{3}}{2} r^2 = 2.6 r^2$$

Compute total system capacity

- # of cells = 262.4/2.6=100 cells
- # of usable duplex channels/cell
  - S=(# of channels)/(reuse factor)
  - S_4=1000/4=250
  - S_7=1000/7=142
- Total system capacity (# of users could be accommodated simultaneously)
  - C=S*(# of cells)
  - C_4=250*100=25000
  - C_7=142*100=14200

Evolving deployment



Early stage Intermediate stage Late stage

- Multiple stages of deployment
- Deployment evolves with subscriber growth

Practical deployment issues

- Location to setup antenna
  - Antenna towers are expensive
  - Local people do not like BSs
    - Antenna/BS does not look like antenna/BS
- Antenna
  - Omni-directional
  - Directional antenna

Wireless QoS

- Quality of Service (QoS)
  - Achieving satisfactory wireless QoS is an important design objective
- Quality measures
  - Channel availability (wireless network is available when users need it)
    - Blocking probability
    - Dropping probability
  - Coverage: probability of receiving adequate signal level at different locations
  - Transmission quality: fidelity/quality of received signals
    - BER
    - FER
- Application-dependent
  - Voice
  - Data
  - Multimedia

Wireless QoS

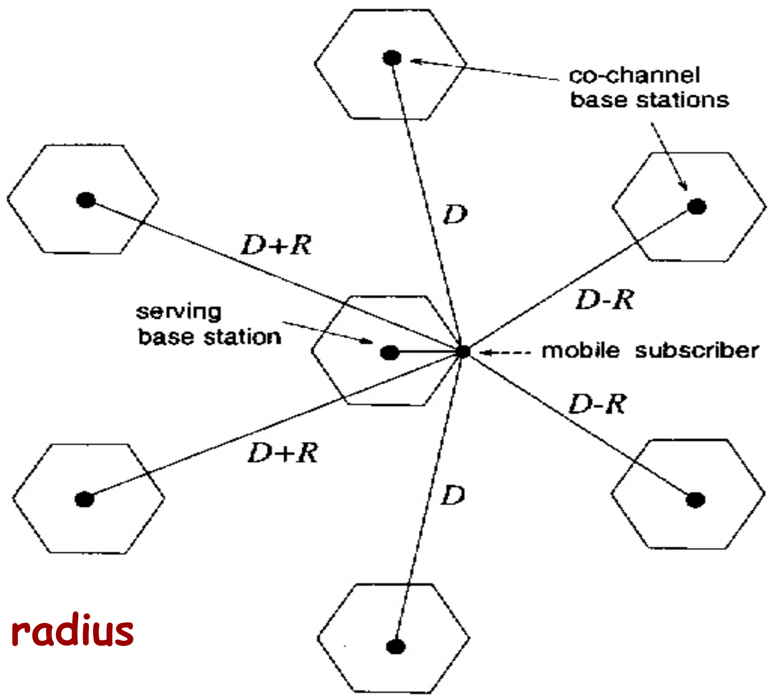
- Admission control
  - Blocking
  - Poor reception quality
- Co-channels
  - Frequency reuse factor
  - Cell planning
    - Frequency planning

Worst-Case CCI on the Forward Channel

- Co channel interference [CCI] is one of the prime limitations on system capacity. We use the propagation model to calculate CCI.

- There are six first-tier, co-channel BSs, two each at (approximate) distances of D-R, D, and R+D and the worst case (average) Carrier-to-(Co-Channel) Interference [CCI] is

$$\Lambda = \frac{1}{2}\frac{R^{-\beta}}{(D-R)^{-\beta} + D^{-\beta} + (D+R)^{-\beta}}$$



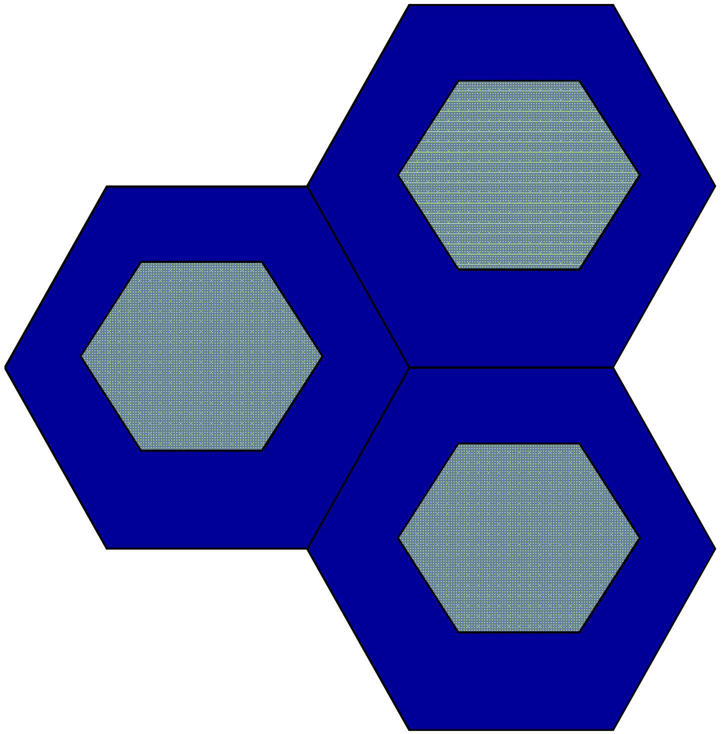
Worst case CCI on the forward channel

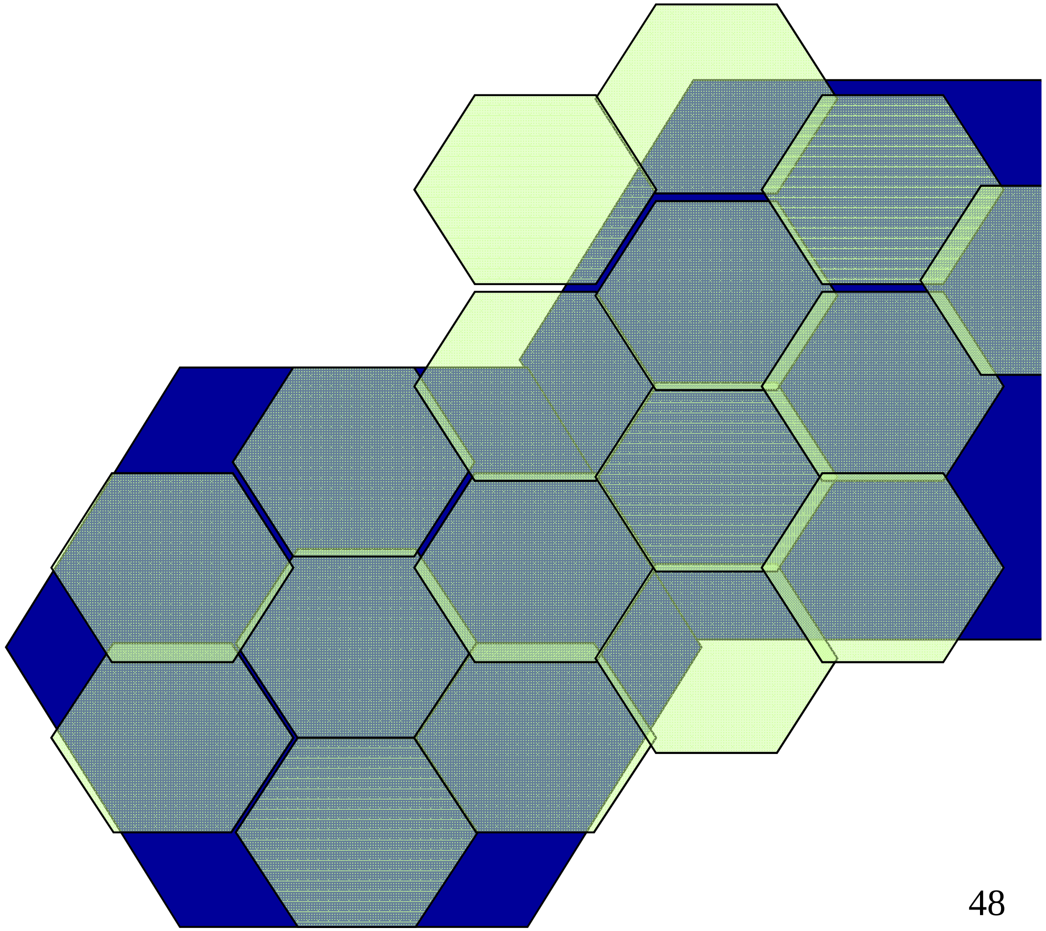
R= cell radius

Overlay

- Dual-mode or dual-frequency phones
  - Overlay different wireless access technologies
    - Different technologies
    - Same technology operating in different bands
- Increase system capacity
  - Reduce blocking
- Example:
  - GSM 900/1800
  - TDMA+CDMA

Overlaid cells





Handoff

- Handoff threshold: typically, -90~-100 dBm (1~10uW)
- Need to prevent from "ping-pong" effect