Part 2:
Wireless Communication

- Section 1: Wireless Transmission
- Section 2: Digital modulation

- *Section 3: Multiplexing/Medium Access Control*

Introduction to Multiple Access

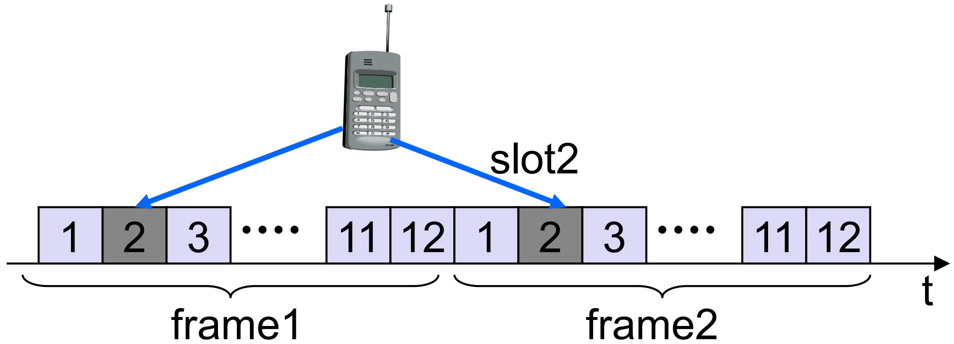
- Goal is to allow many mobile users to nicely share simultaneously a finite amount of radio spectrum

- 5 methods:
  - 3.1- TDMA Time Division Multiple Access
  - 3.2- FDMA Frequency Division Multiple Access
  - 3.3- SSMA Spread Spectrum Multiple Access
  - 3.4- SDMA Space Division Multiple Access
  - 3.5- PR Packet Radio

- These methods can be combined
  - eg: SDMA/FDMA/TDMA in GSM

3.1- TDMA (Time Division Multiple Access)

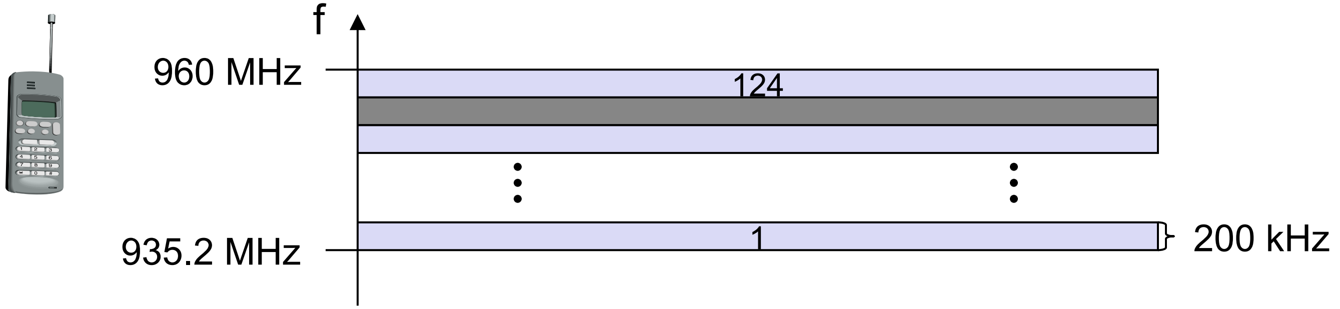
- divide time into **time frames**, further divided into **time slots**
- a single user is allowed to transmit or receive on a specific time slot



- TDMA transmits data in a buffer-and-burst method, thus transmissions to/from a given device is *non-continuous and predictable*
  - results in **low battery consumption** since the receiver's circuit can be turned off between slots of interest
  - **handoff process is much simpler** for a mobile, since it is able to listen for other base stations between slots of interest

3.2- FDMA (Frequency Division Multiple Access)

- radio spectrum is divided into narrowband (~30 kHz) channels
- each user is allocated a unique channel



- a channel carries only one connection at a time. If the mobile doesn’t have any data to send or receive, the capacity is lost
  – NB: it’s also the case with TDMA

3.3- SSMA
(Spread Spectrum Multiple Access)

- ***A system is defined to be a SS system if the signal occupies a bandwidth much in excess compared to the minimum bandwidth necessary to send the information***

- Initially used for military applications…
- …It is now used in civil applications
  - Multiple Access (ex: CDMA) / Modulation
  - coordinated systems coexistence (ex: SS UMTS)
  - uncoordinated systems coexistence (ISM bands)

Spread Spectrum Techniques

Two basic techniques

- Direct Sequence Spread Spectrum (**DSSS**):
  - the signal is multiplied by a spreading code in the time domain
  - the spreading code is a pseudo random sequence that looks like noise

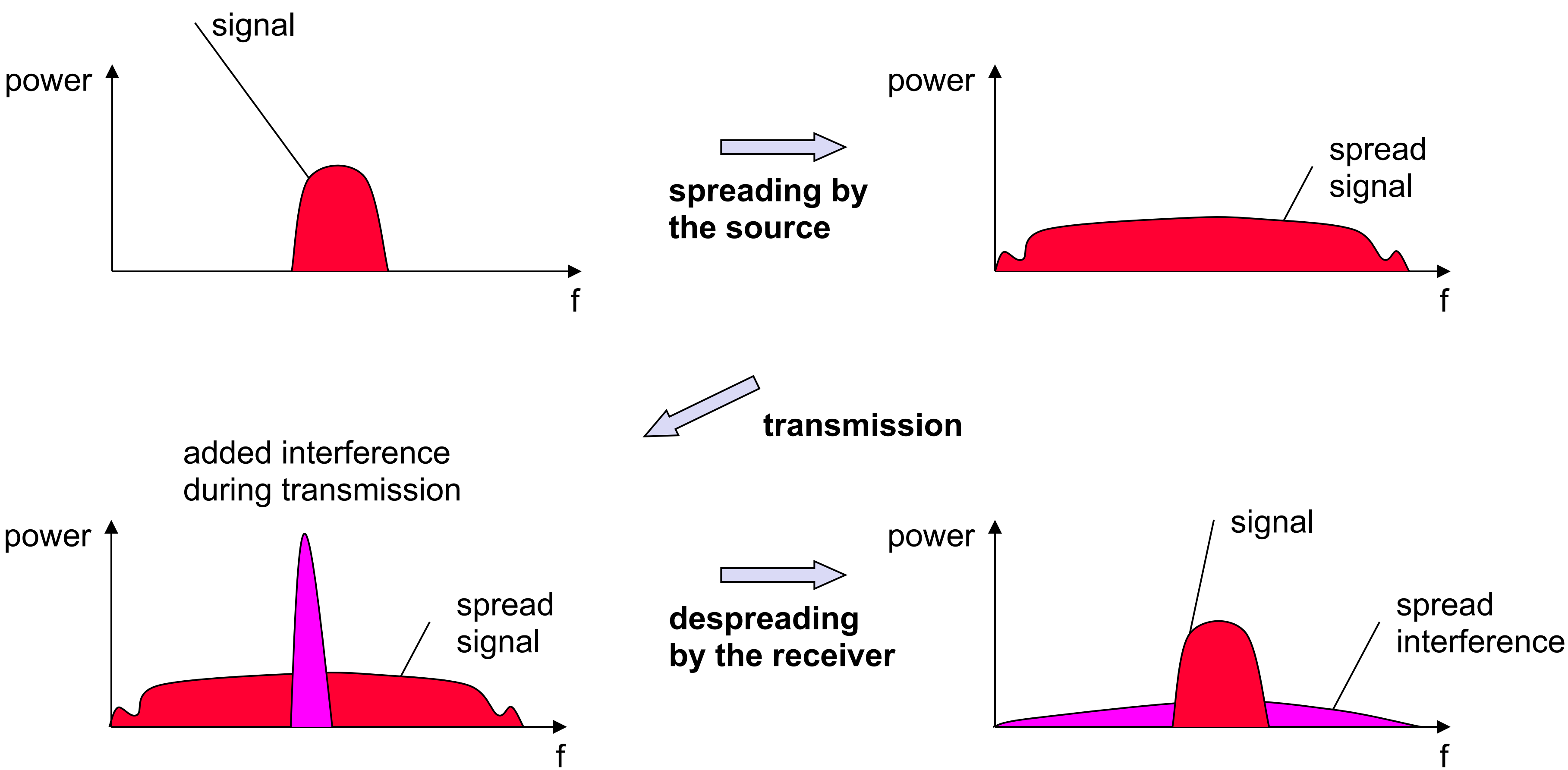
- Frequency Hopping Spread Spectrum (**FHSS**)
  - the signal changes of carrier frequency
  - sequence of frequency changes is determined via a pseudo random sequence

DSSS Technology

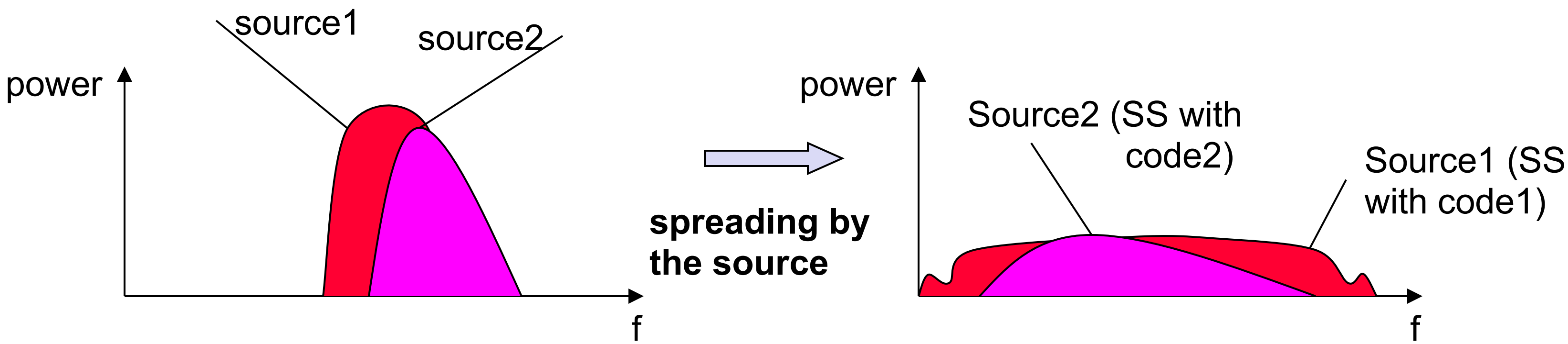
- Also known as CDMA (Code Division Multiple Access)
- The spreading signal is controlled by a pseudo-random sequence (called PN) or **pseudo-random code**
  - A PN sequence is a random binary sequence:
  - nearly equal number of 0s or 1s
  - very low correlation with shifted versions of the sequence
- Principle:
  - multiplication by the PN code *once* **spreads** the signal bandwidth
  - multiplication by the PN code *twice*, **recovers** the original signal
  - at a receiver, the desired signal gets multiplied *twice*, but the interference signal (if any) gets multiplied only *once*...

Once spread, a signal looks like noise…

Spread spectrum Benefits (1)
interference suppression



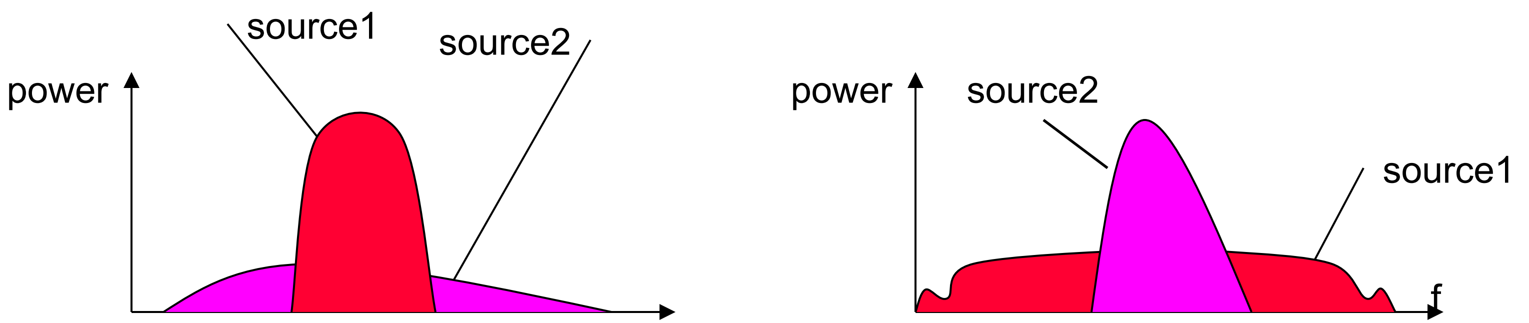
Spread spectrum Benefits (2)
multi access capability



Signal *Despreading at the receiver*

– with code1

-with code2



Spread spectrum Benefits (3)
Other benefits

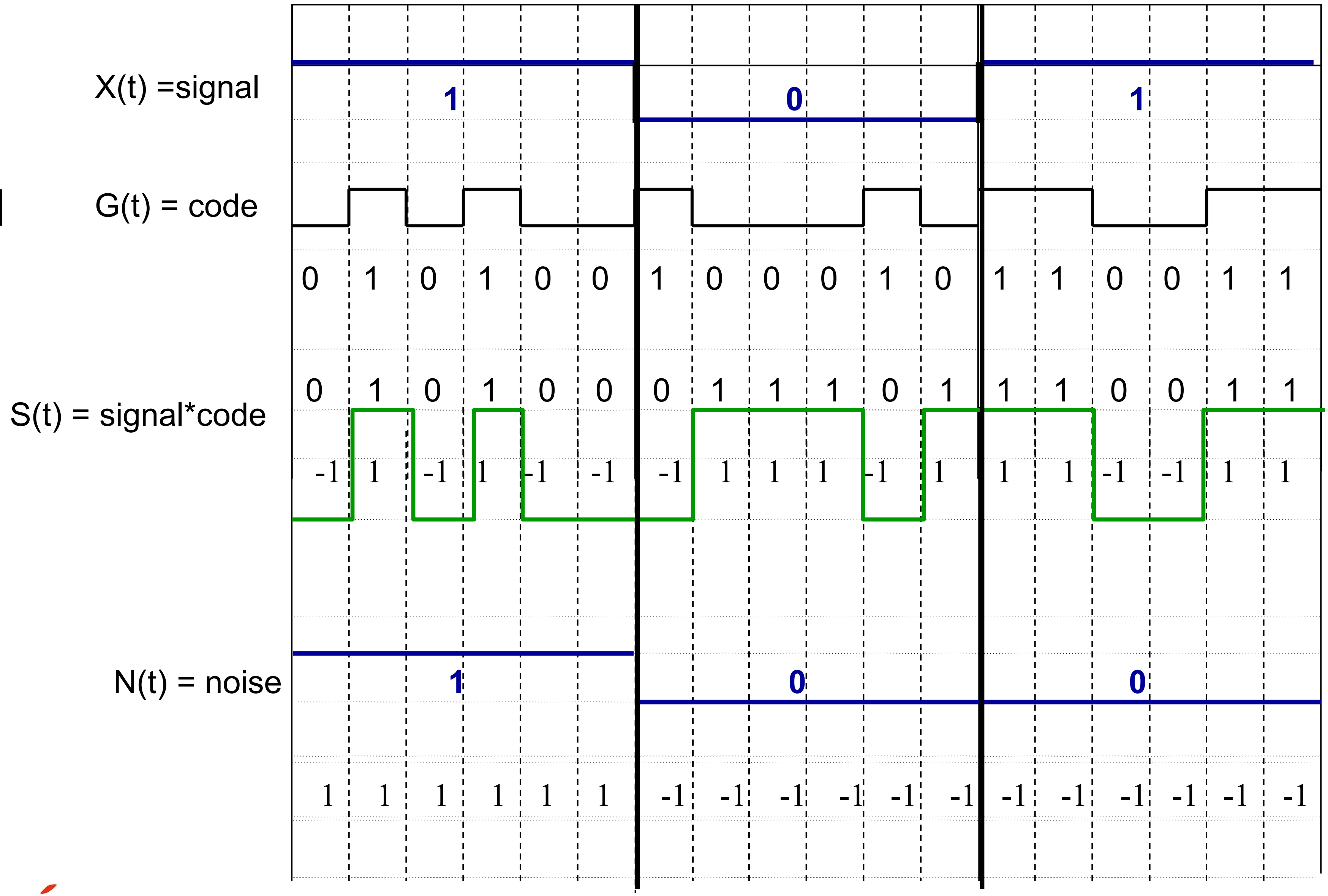
- initially motivated by military considerations:
  - improved confidentiality
    - » a receiver that doesn't know the code only sees white noise
  - anti-jamming capability
    - » jamming deliberately injected in the system is filtered just like interferences are
    - » especially true with narrow-band jamming
  - low probability of interception
    - » because of its low power density the signal is difficult to detect and intercept by a hostile listener

- no longer true of course
  - security requires cryptography
  - however, offers access control and robustness

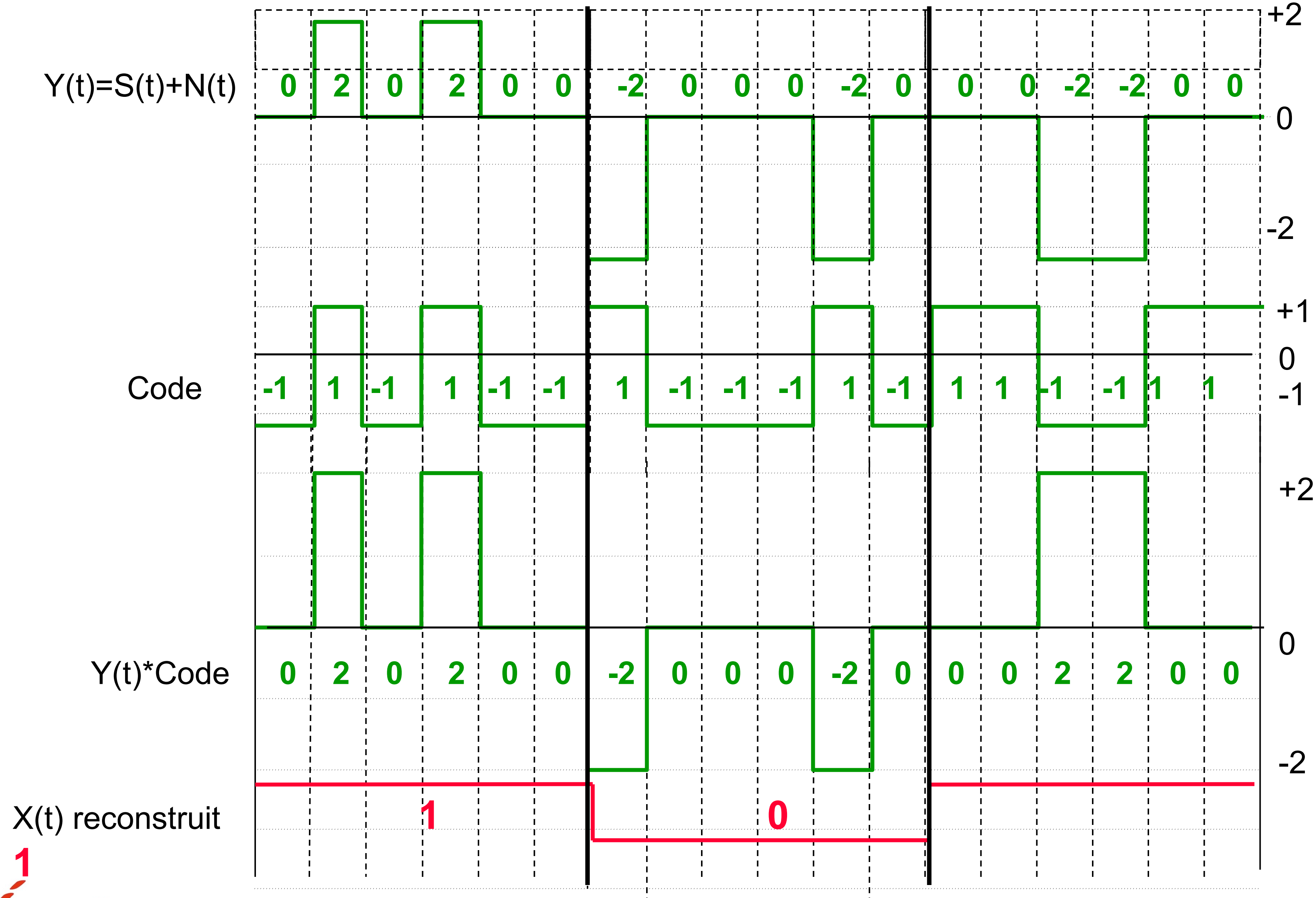
DSSS: interference filtering

- Assume a signal *x(t)* and a spreading code *g(t)*
- x(t) is narrowband compared to g(t)
- The spread signal is generated by:
  - s(t) = x(t).g(t) <-> X(w)*G(w)
  - if the x(t) is narrowband compared to g(t), s(t) will have approximately the bandwidth of the spreading signal.
- Y(t) = s(t) + n(t) is transmitted on the channel , where n(t) is the noise or interference
- At the receiver, y(t) is multiplied by the spreading code g(t):
  - y(t).g(t) = x(t).g(t).g(t) + n(t).g(t) = x(t) + n(t).g(t)
  - the signal x(t) is recovered, the noise is spread...

DSSS: interference filtering (2)



DSSS: interference filtering (3)



DSSS: multiplexing

- all terminals send on the same frequency, probably at the same time, and use the whole bandwidth of the channel
- each sender has a **unique pseudo random sequence**, that he multiplies (or XORs) with the signal
- the receiver can recover this signal if he knows the pseudo random sequence

- Disadvantages:
  - higher complexity of a receiver
  - occupies a larger bandwidth
- Advantages:
  - all terminals can use the same frequency, no planning needed
  - huge code space (e.g. 2^{32}) compared to frequency space
  - interferences (noise) are not coded
  - forward error correction and encryption can be easily integrated

DSSS: multiplexing (2)

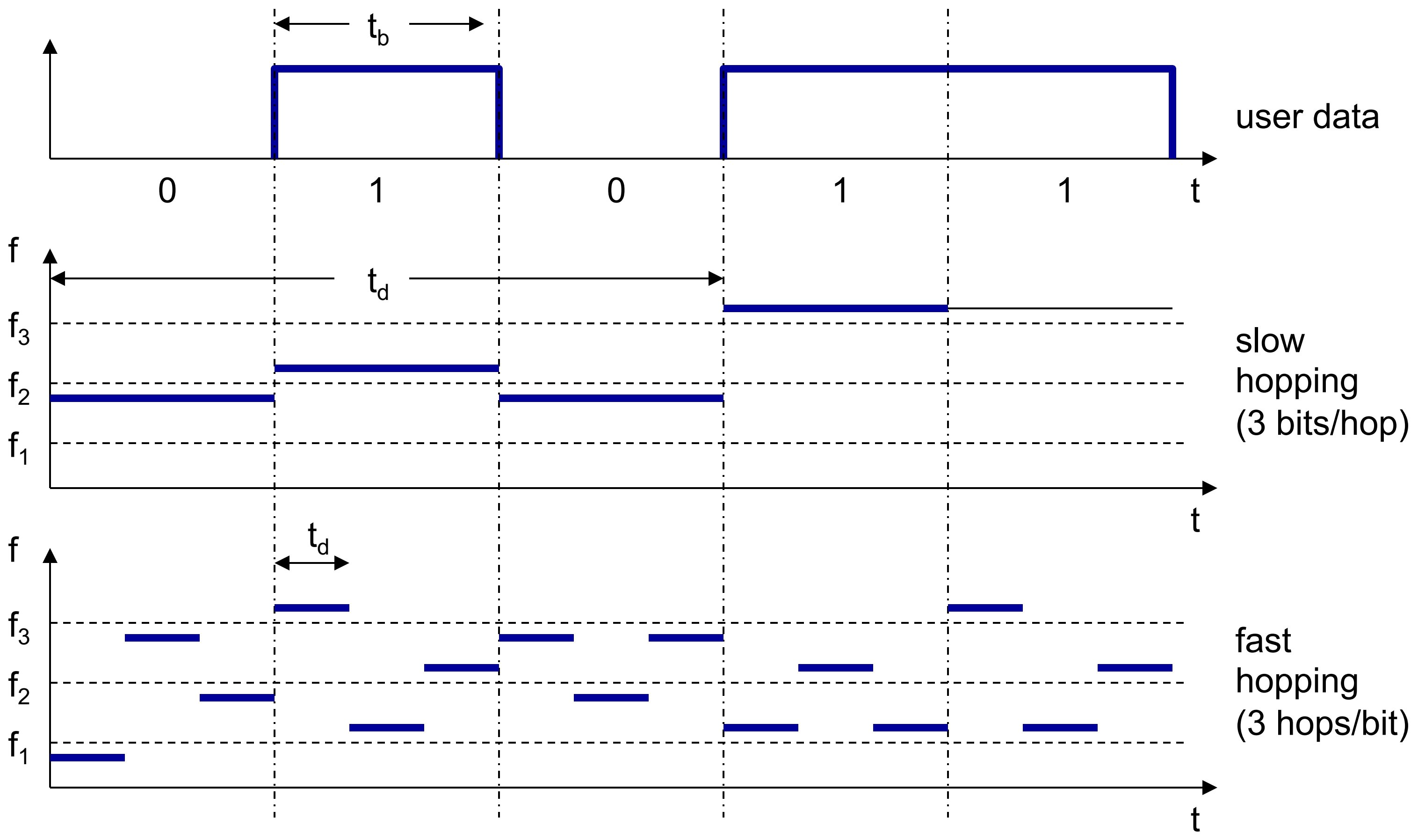
- Signal *spreading*
  - s1(t) = x1(t).code1
  - s2(t) = x2(t).code2
  - s(t) = s1(t) + s2(t) = signal on the channel
- Signal *despreading at the receiver*
  - y1(t) = s(t).code1 = s1(t).code1 + s2(t).code1
    = x1(t).code1.code1 + x2(t).code2.code1
    - » since code2 and code1 are orthogonal:
    - » code1.code2 =0
    - » y1(t) = x1(t).code1.code1 = x1(t)
  - and the same with y2(t)…

FHSS (Frequency Hopping Spread Spectrum)

- Discrete changes of carrier frequency
  - the freq. sequence is determined by a pseudo random sequence
- Two versions
  - **Fast Hopping:** several frequencies per user bit
  - **Slow Hopping:** several user bits per frequency

- Advantages
  - frequency interference limited to short periods
  - simple implementation
  - uses only small portion of spectrum at any time
- Disadvantages
  - not as robust as DSSS
  - simpler to detect than DSSS

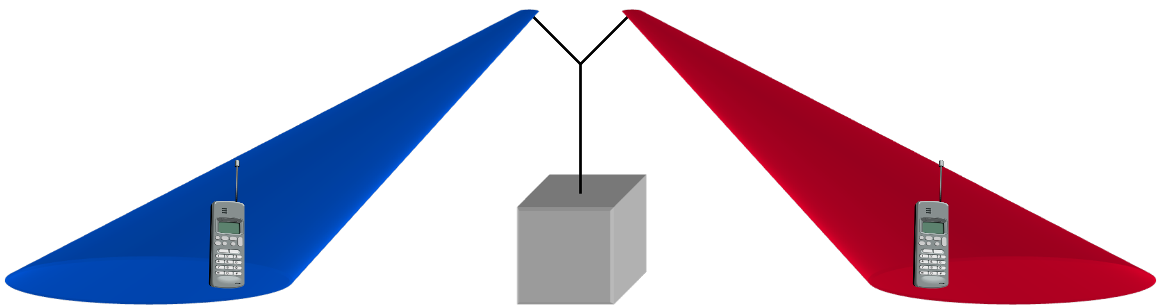
FHSS (2)



t_b: bit period t_d: dwell time

3.4- SDMA: Space Division Multiple Access

- SDMA controls the radiated energy for each user in space
- SDMA serves different users by using spot beams antennas



- These different areas covered by the antenna beam may be served by the same frequency

Cellular Systems (1)

- Most commercial radio and television systems are designed to cover an as large as possible area
  - they operate at the maximum allowed power

- **Cellular systems** take the opposite approach: make an efficient use of available channels by using low-power transmitters to allow frequency reuse at smaller distances
  - **maximize the number of times each channel is reused in a given geographical area**

- Difficult tradeoff:
  - more channels ⇒ smaller cells
  - smaller cells ⇒ more interferences and more handovers ☹

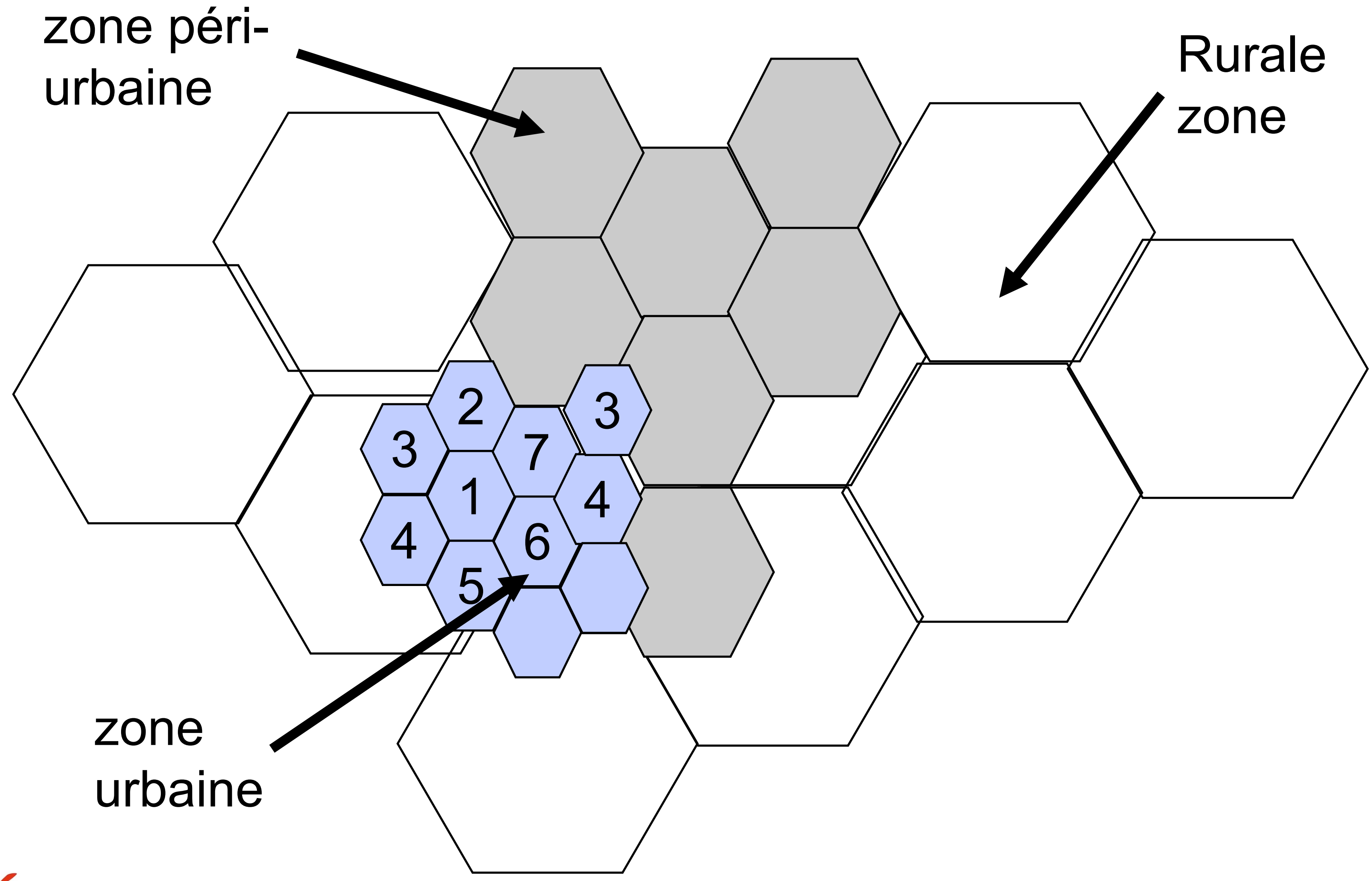
Cellular Systems (2)

- **The size of the cells varies according to the user density**

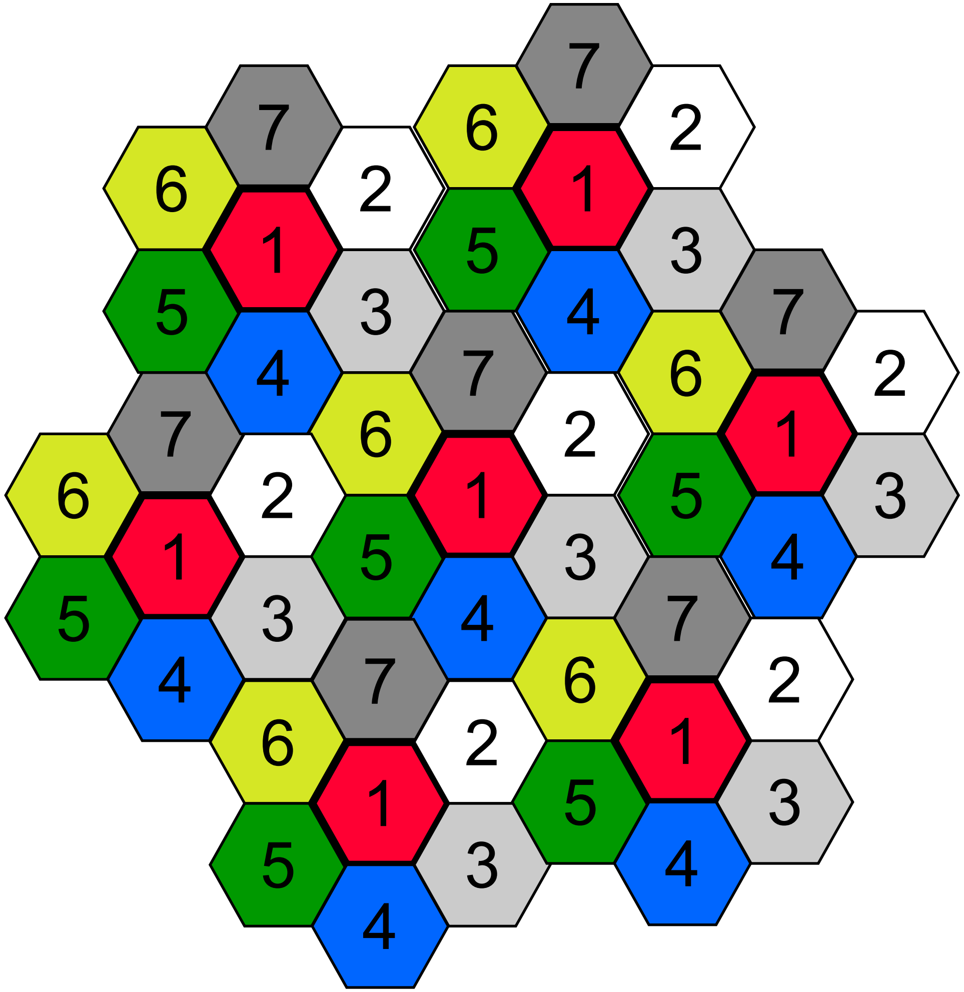
- Over the years we saw an evolution towards smaller cells
  - better frequency reuse ☺
  - low power and less expensive base stations ☺
  - reduced battery drain on portable devices ☺

  - but also higher number of base stations ☹

Cellular Systems (3)



Cellular Systems (4)



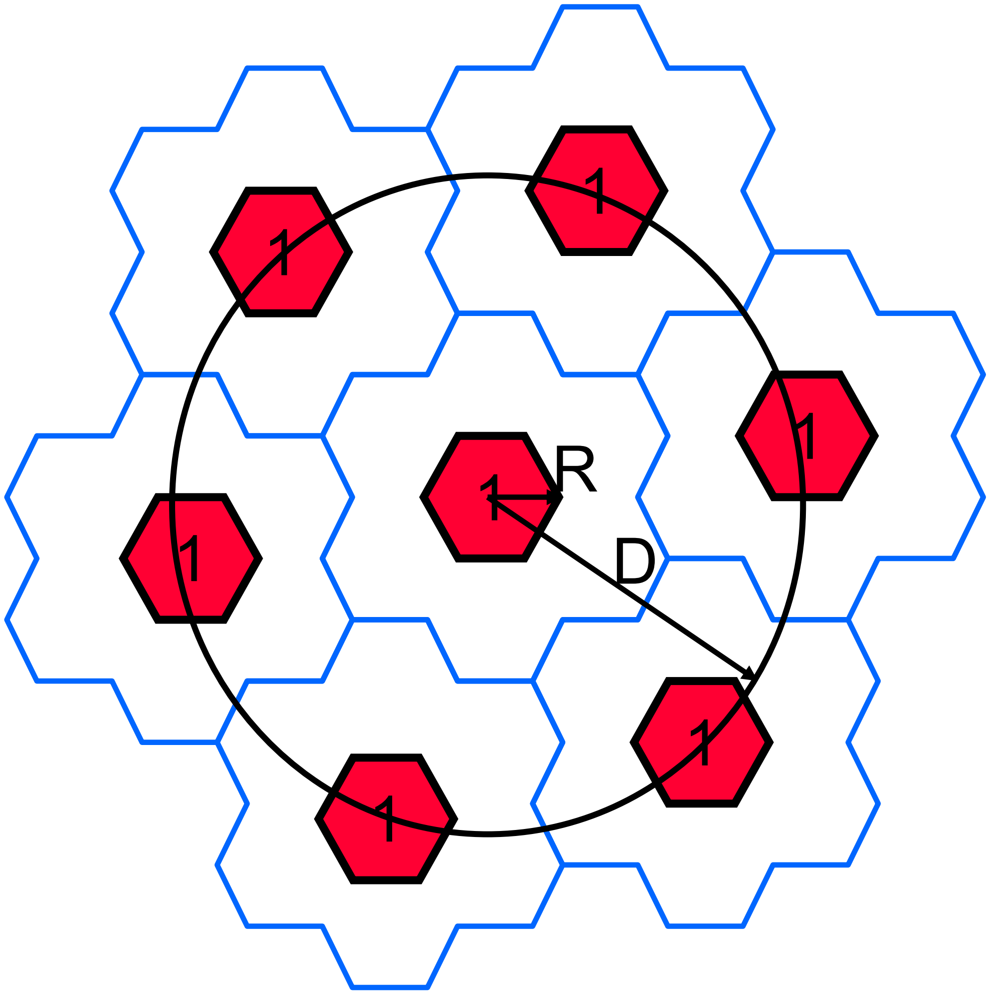
- In a cellular system, the space is divided into **clusters**.
- Each cluster uses the whole frequency spectrum of the system
- Each cluster is divided into **cells**
- Each cell of a cluster uses different frequency band
- Cells are laid out such as 2 cells of 2 clusters using the same frequency band do not interfere...

Cellular Systems (5)

In practice:

- A cell is covered by a base station
- A cell coverage is not hexagonal but irregular
- a cell size varies from few hundred meters to 50 kms
- Any number of cells by cluster could be used…
- …However geometry shows that **regular pattern** leads to more efficient use of the spectrum. A Pattern is regular if the number of cells, K, verifies:
  - $K = i^2 + j^2 + i.j$ where i and j are positive integer
  - **K = 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, 25, 27,…**

Cellular Systems (6)

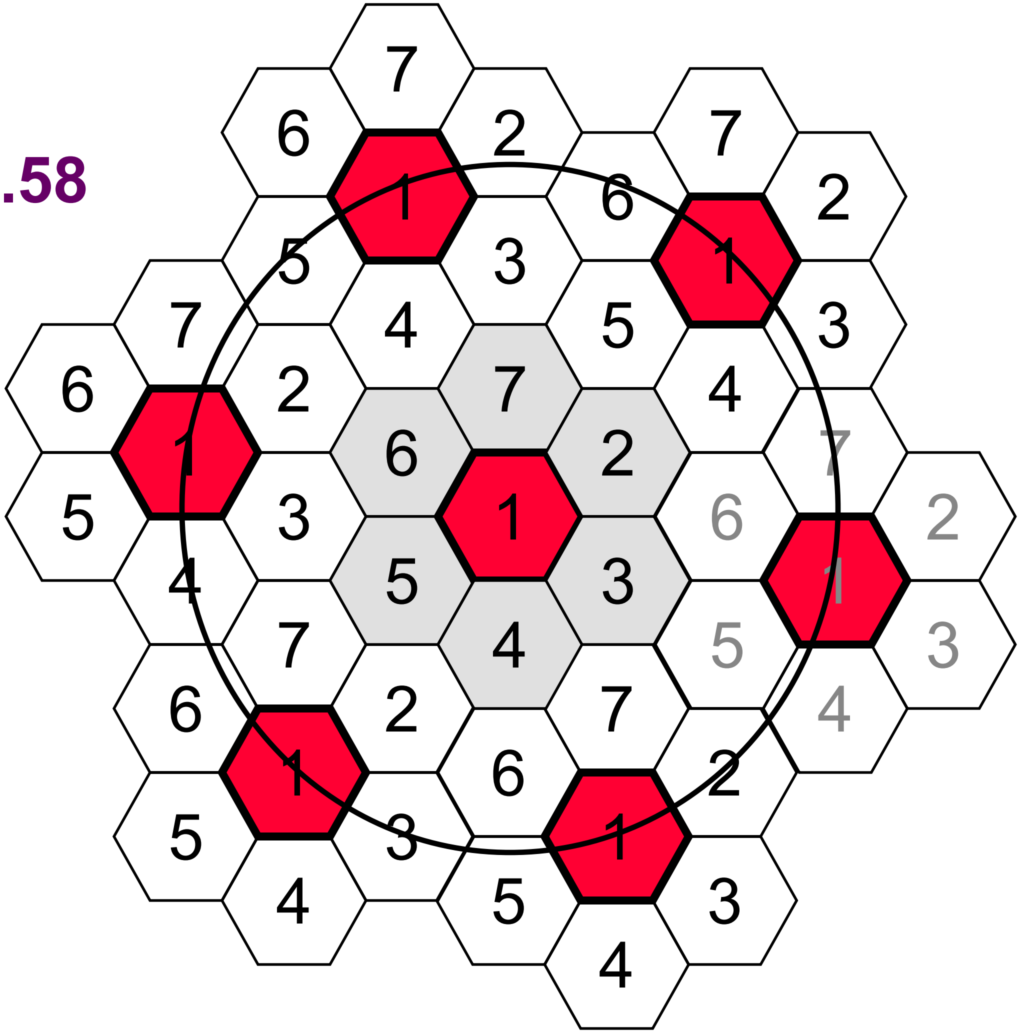


If a regular pattern is used, it can be shown that:

- the number of interfering cells is always equal to 6
- **D/R = (3.K)$^{1/2}$**
  – where R is the center-to-vertex distance of a cell and D is the co-channel separation distance.

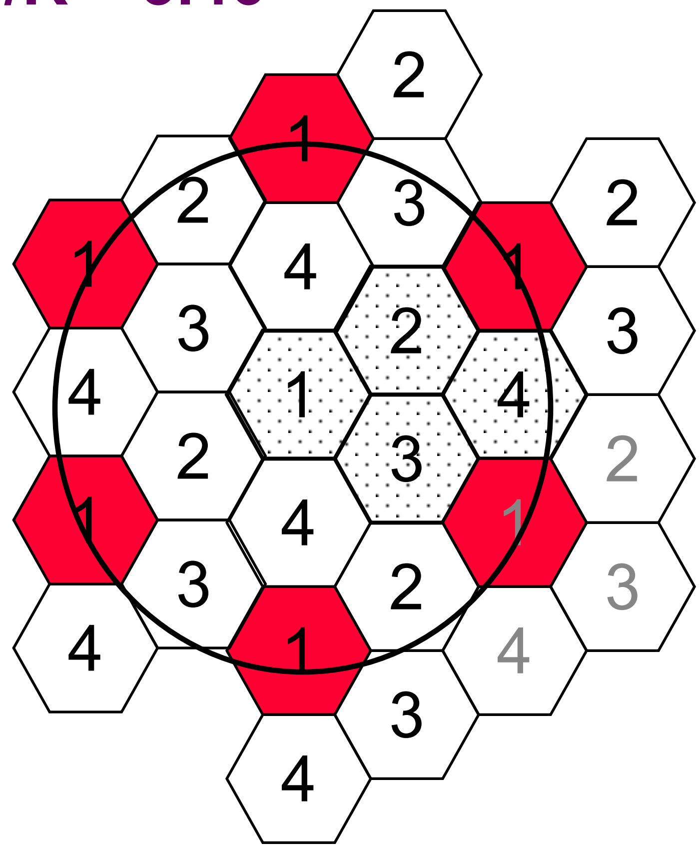
Examples (1)

k=7;
D/R = 4.58

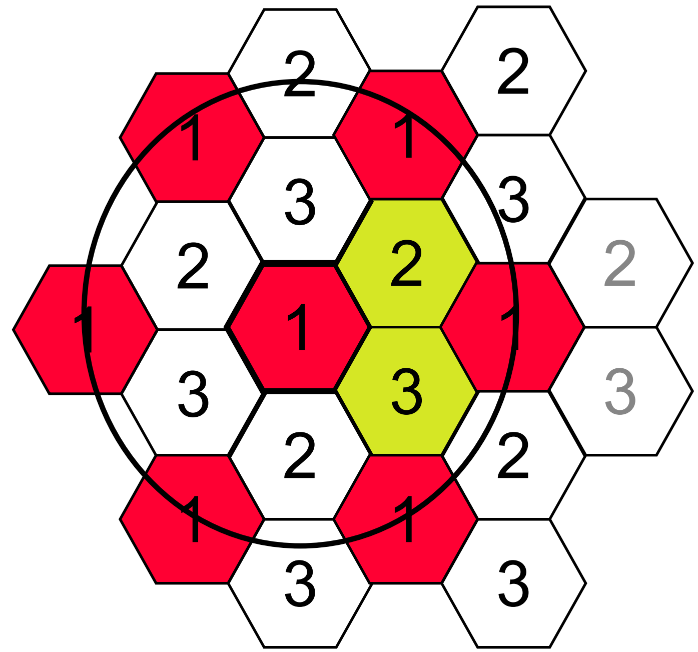


Examples (2)

k=4;
D/R = 3.46



k=3;
D/R = 3.0



Co-channel Interference Ratio

- The co-channel interference ratio at a receiver is:
  - $S/I = S/(\Sigma^{6}_{i=1} I_i)$ = useful_signal/interferences

    where:
    - » **$I_i = S/(D/R)^y$**
    - » **2 < y < 5 depending on the terrain environment**
- therefore:

  $S/I = (D/R)^y/6 = 1/6 * (3K)^{Y/2}$

- 18 dB = 10.log(63.1) is the agreed value for correct voice quality for current cellular systems
  - with y = 4, we find:
  - $(D/R) = (6 * S/I)^{1/y} = (6 * 63.1)^{0.25} = 4.41$
  - therefore $K = (D/R)^2/3 = 6.49 \sim 7$

  a seven-cell reuse pattern is needed!

Co-channel Interference Ratio (2)

Example:

- consider a cellular system with 396 total allocated voice channel frequencies.
- We have the following results for different K

K	*Voice channels/cell*	*S/I (dB)*	*total channels*
4	99	14.0	396
7	396 / 7 = 56	18.7	392
12	33	23.3	396

- By increasing the reuse factor (K):
  - the quality (S/I) is increased (better cell separation)
  - the capacity per cell is reduced (fewer frequencies per cell)
- **These results are independent of the cluster surface!**
  - for a given K, the capacity of a system can be increased by reducing the cluster surface:

C (channels/m^2) = total nb of channels / cluster surface

Inria

3.5- Packet Radio Access

- Here hosts attempt to access a single channel in an **uncoordinated** manner
- Transmission is done on a **per-packet basis**
- **Collisions** from simultaneous transmissions are detected at a receiver
- The receiver sends:
  - an ACK if the packet is successfully received
  - a NACK (Negative ACK) if the packet isn't correctly received
  - nothing if the packet has not been received at all

- **A wireless host uses the CSMA-CA (Collision Avoidance) technique**
  - derived from Ethernet's CSMA-CD

Carrier Sense Multiple Access Protocols (CSMA)

- In Carrier Sense protocols, a host listens the medium before transmitting...
- several protocols have been proposed
- Persistent CSMA:
  - when a station has to send a data, it listens to the channel
  - if the channel is idle, it transmits a frame, otherwise it waits until it becomes idle and then transmits immediately
  - if a collision occurs, the station waits a random amount of time and starts all over again
  - one problem is that if 2 stations get ready to send in the middle of a third station’s transmission, both will wait politely until the transmission ends, and both will begin transmitting at the same time resulting in a collision!
  - if they were not so impatient, there would be fewer collisions…

…reminder…

CSMA (2)

- Non-persistent CSMA:
  - before sending a station senses the channel
  - if the channel is idle, it transmits
  - if the channel is busy, instead of transmitting immediately after the current transmission ends, the station waits a random period of time and then repeats the algorithm...
  - Intuitively this algorithm reduces collisions...

... reminder ...

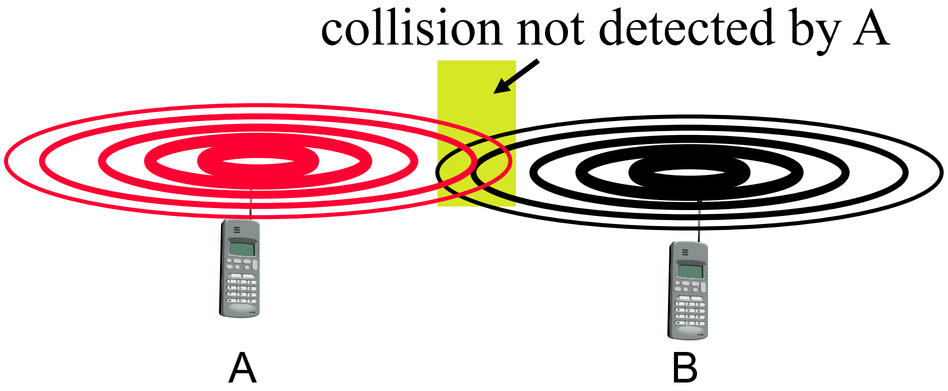
CSMA/CD

- With CSMA/CD, additionally a station aborts its transmission as soon as possible in case of collision
  - When 2 hosts begin transmitting simultaneously, they both detect the collision almost immediately and then stop transmitting
- Quickly terminating damaged frames saves:
  - time
  - bandwidth
  - energy
- Widely used in LANs (e.g. Ethernet)… but not in wireless networks!

…reminder…

CSMA/CD and Wireless networks

- CSMA/CD does not work with wireless networks
- CD does not work because:
  – signal strength decreases rapidely with the distance, so a host does not always detect collisions

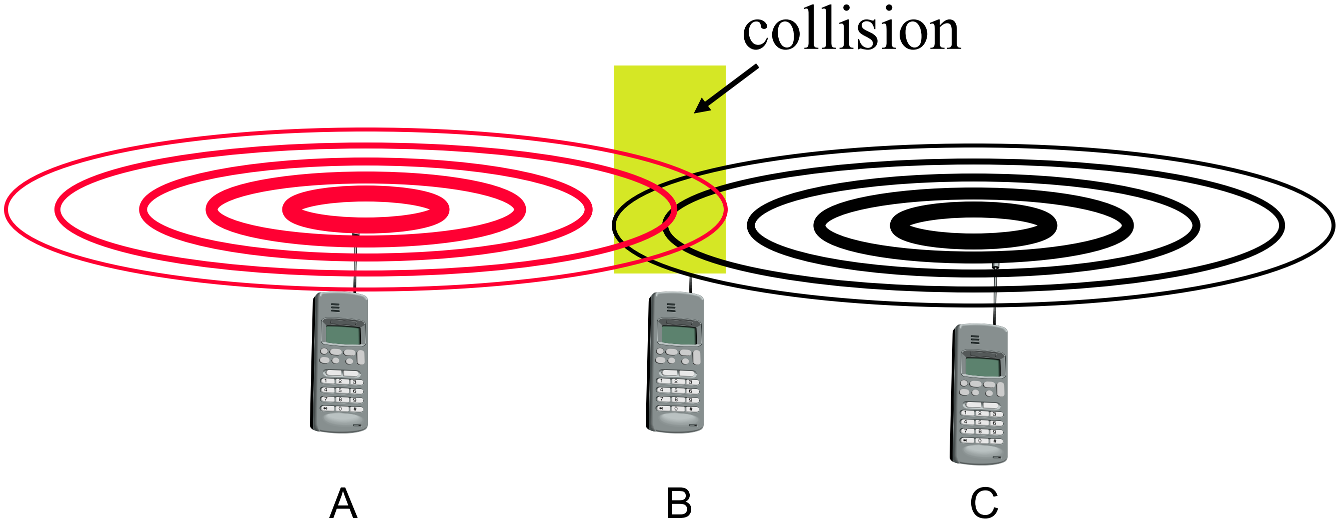


  – a host is not necessarily able to detect a collision since the signal of the packet it is transmitting drowns out other packets' signals.

- Other problems exist such as:
  – the hidden terminal problem
  – the exposed terminal problem

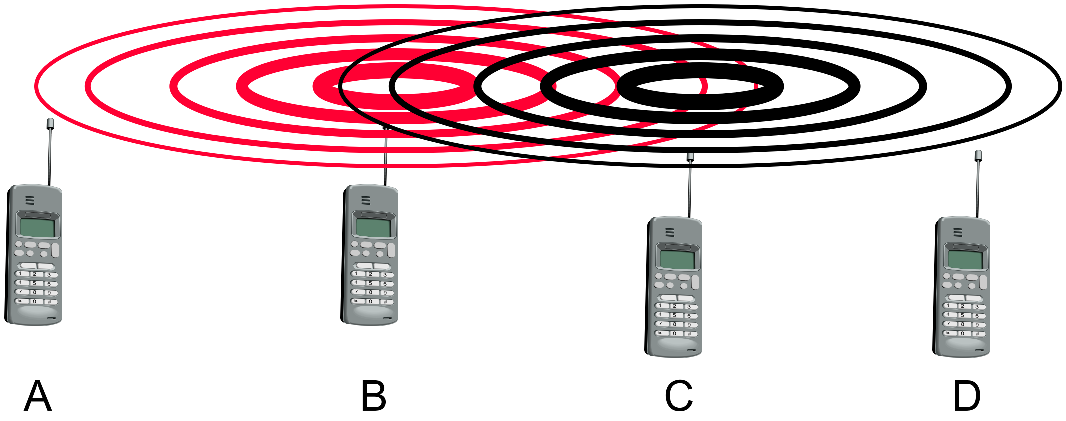
Hidden terminals

- Hidden terminals
  - A sends to B, C cannot receive A
  - C wants to send to B
    - » C senses a "free" medium (CS fails)
    - » sends packets to B
  - collision occurs at B
  - A and C cannot hear the collision (CD fails)
  - A is "hidden" for C



Exposed terminals

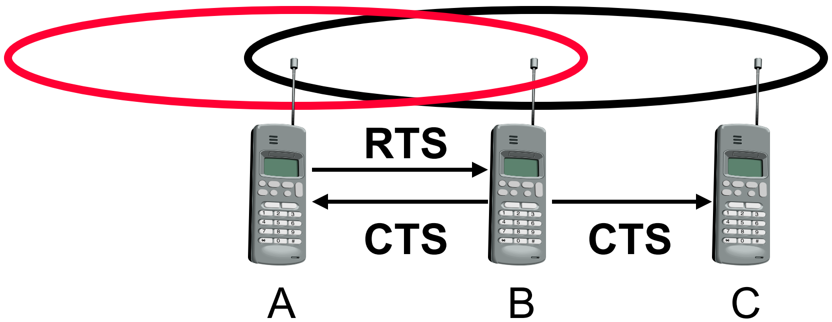
- Exposed terminals
  - B sends to A,
  - C wants to send to D
  - C has to wait, CS signals a medium in use
  - but A is outside the radio range of C, therefore waiting is not necessary and transmission from C to B would be possible
  - C is "exposed" to B



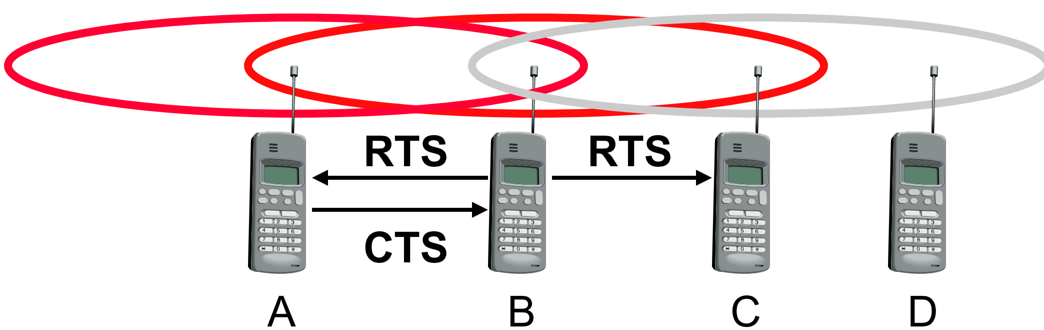
CSMA-CA for collision avoidance

- CA (Collision Avoidance) uses short signaling packets for collision avoidance
  - **RTS (request to send)**: a sender first asks a receiver for the authorization to send with a short RTS packet
  - **CTS (clear to send)**: the receiver grants the right to send as soon as it is ready to receive
  - when authorized, data transmission can take place...
- Signaling packets contain
  - sender address
  - receiver address
  - packet size
- Used in IEEE802.11 (Wifi)
- since RTS and CTS are small, collisions are rare

CSMA-CA for collision avoidance



- CA avoids the problem of hidden terminals
  - A and C want to send to B
  - A sends RTS first
  - B sends CTS
  - C waits ...



- CA avoids the problem of exposed terminals
  - B wants to send to A
    - » it sends a RTS
    - » A sends a CTS that C can not hear
  - C wants to send to D
    - » now C does not have to wait since it did not receive the CTS from A

3.6- Duplexing

- It is desirable to allow a mobile to send to BS and receive from BS simultaneously: this is Duplexing

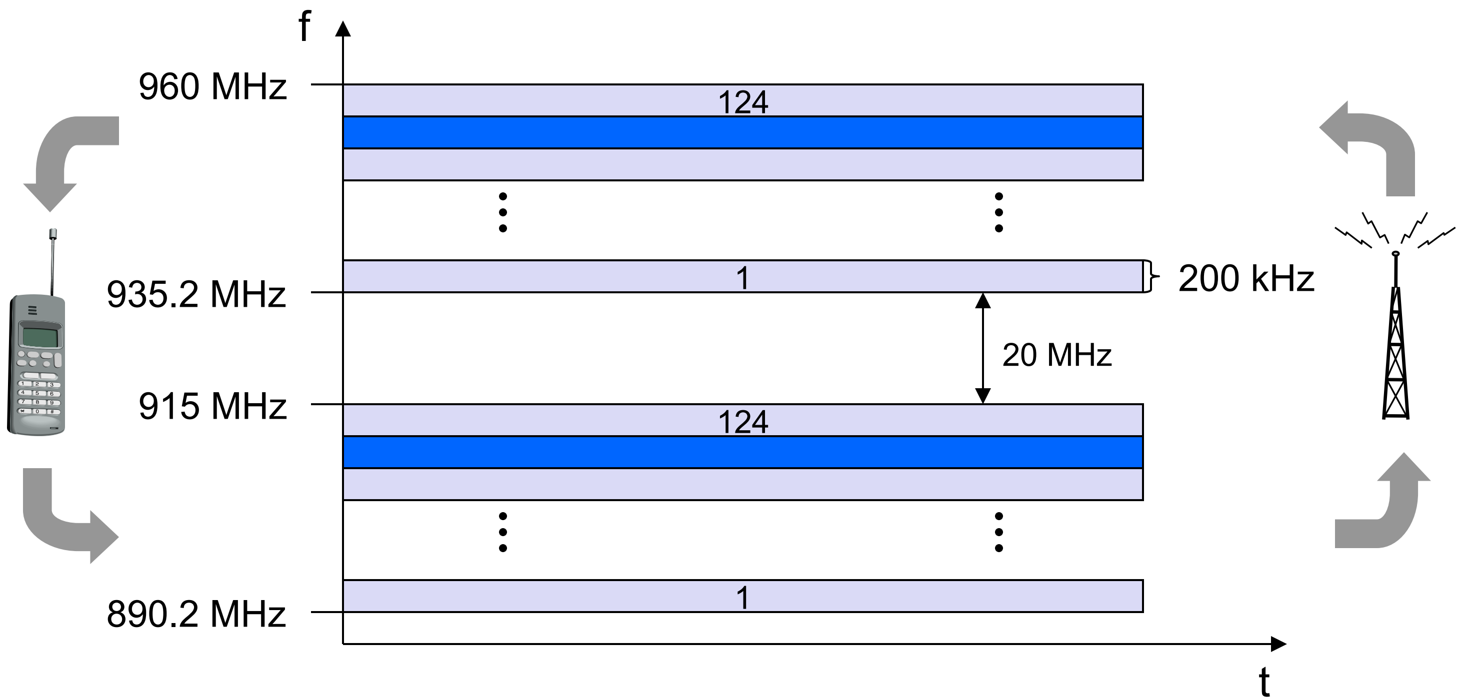
Two techniques:

- Frequency Division Duplexing (FDD): a user has 2 distinct frequency bands: one for emission, one for reception.
  - A duplex channel actually consists of two simplex channels and a duplexer is used to receive and send on 2 different frequency bands
  - The frequency split between the forward and reverse channel is constant for the whole system.

- Time Division Duplexing (TDD): uses time instead of frequency to provide both a forward and reverse link
  - Introduces some delay between emission and reception
  - simpler than FDD

Duplexing vs Multiple Access

- Any combinations of Duplexing and Multiple Access scheme can be used.
- Example1: SDMA/TDMA/FDMA/FDD - GSM



Duplexing vs Multiple Access (2)

- Example2: TDMA/TDD - DECT