

Part 2:

Wireless Communication

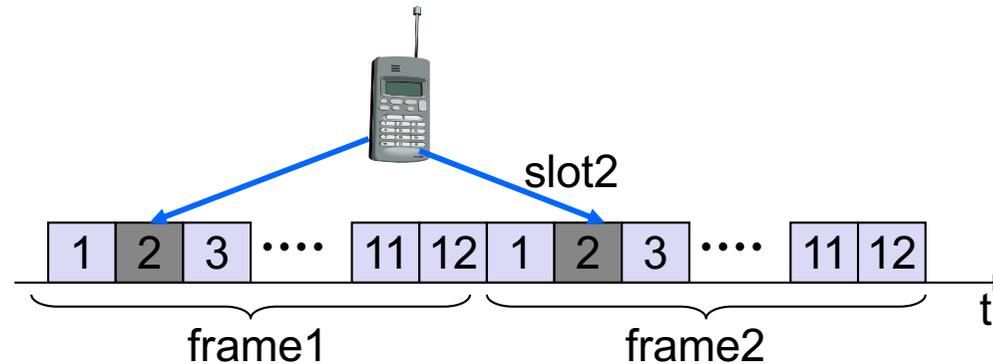
- Section 1: Wireless Transmission
- Section 2: Digital modulation
- *Section 3: Multiplexing/Medium Access Control*

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)

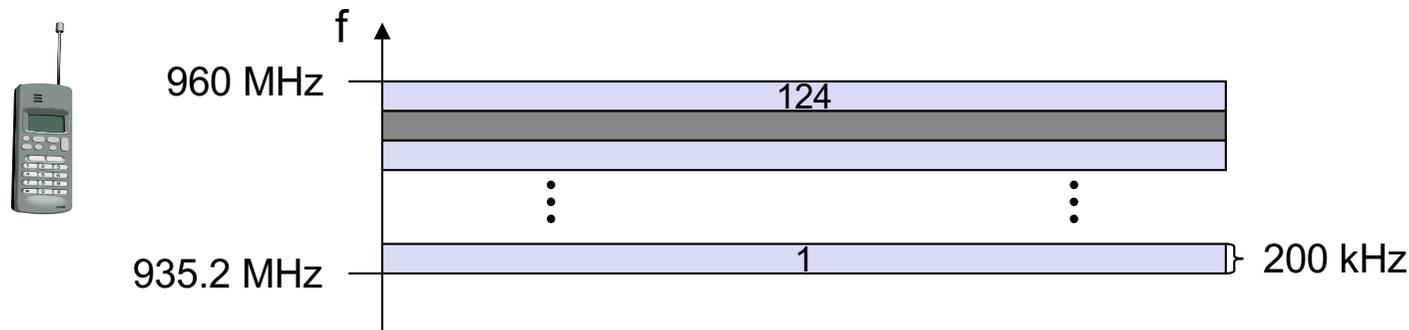
- divide time into **time frames**, further divided into **time slots**
- a single user is allowed to transmit or receive on a specific time slot



- 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*
- The initial application of spread-spectrum (SS) techniques was for military applications
 - achieve **jam-resistant communication** systems
- 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

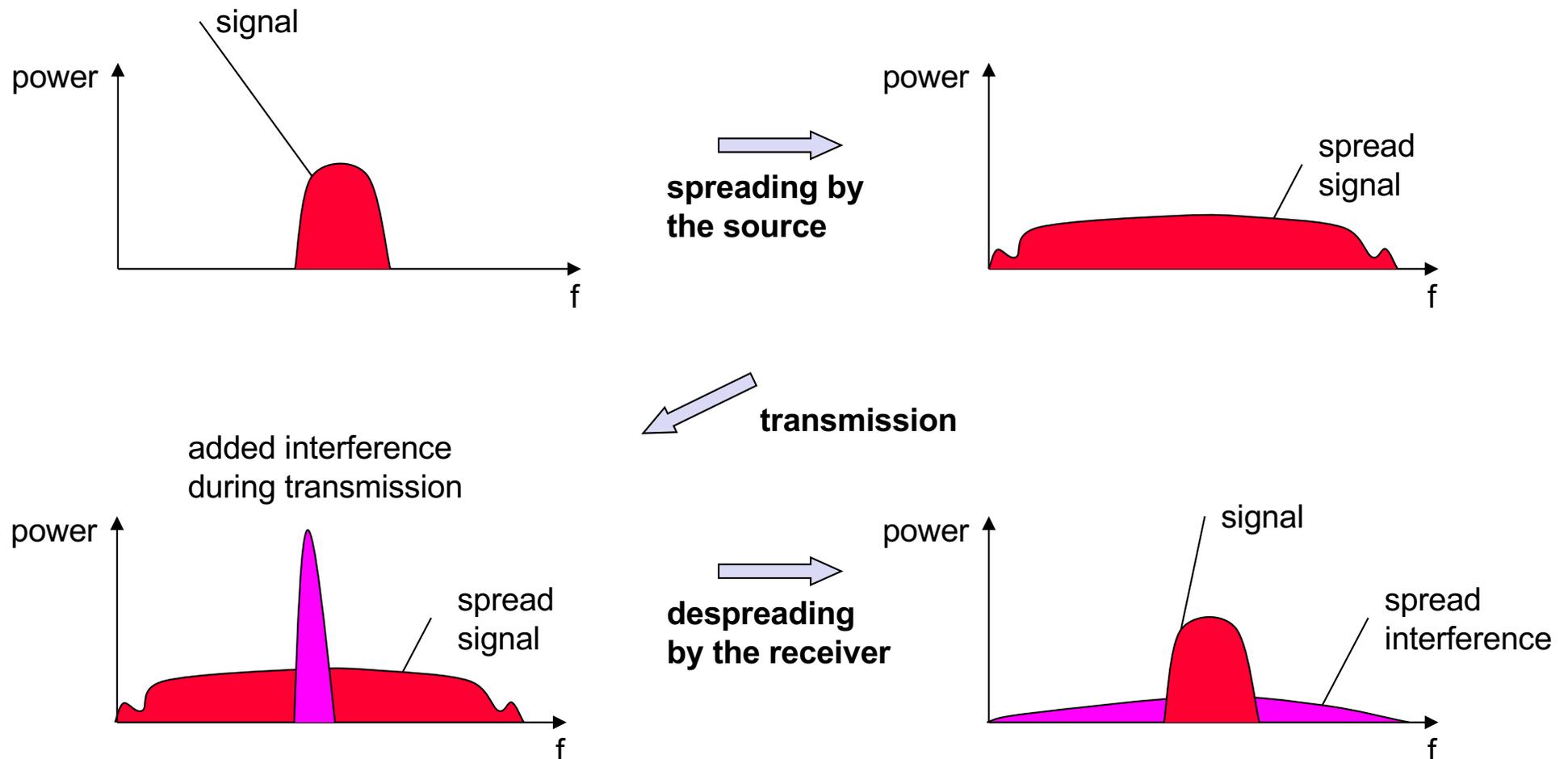
DSSS Technology

- 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...

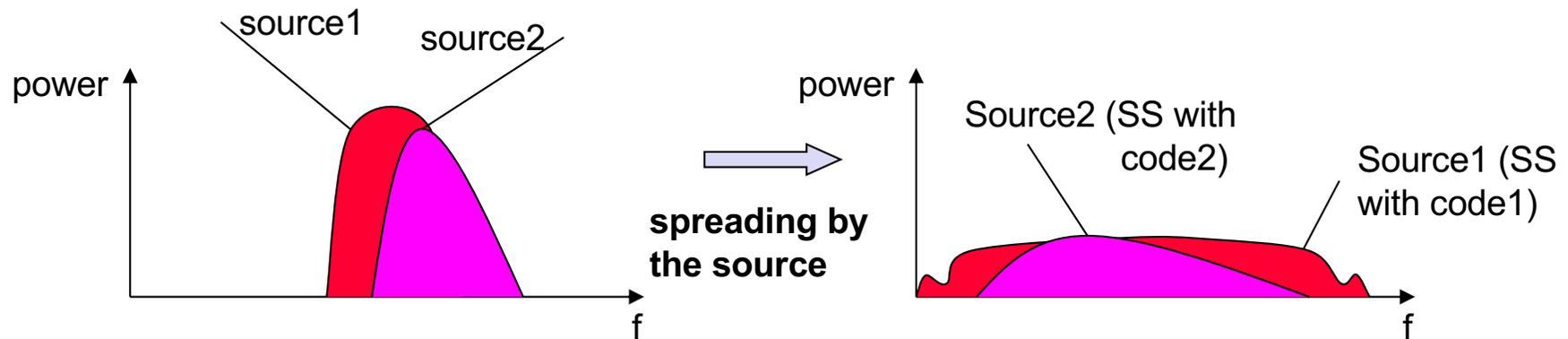
Spread spectrum Benefits (1)

interference suppression



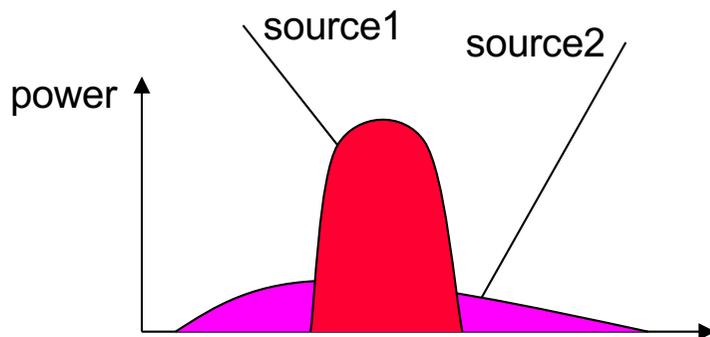
Spread spectrum Benefits (2)

multi access capability

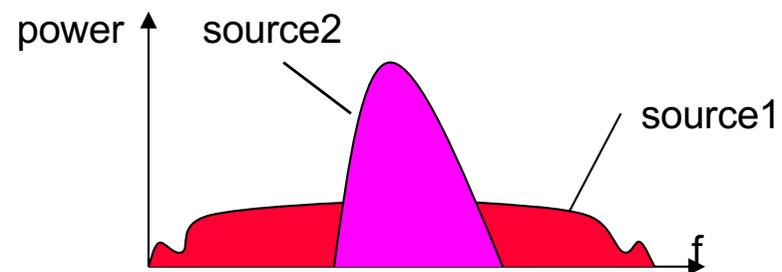


Signal *Despreading* at the receiver

– with code1



-with code2



Spread spectrum Benefits (3)

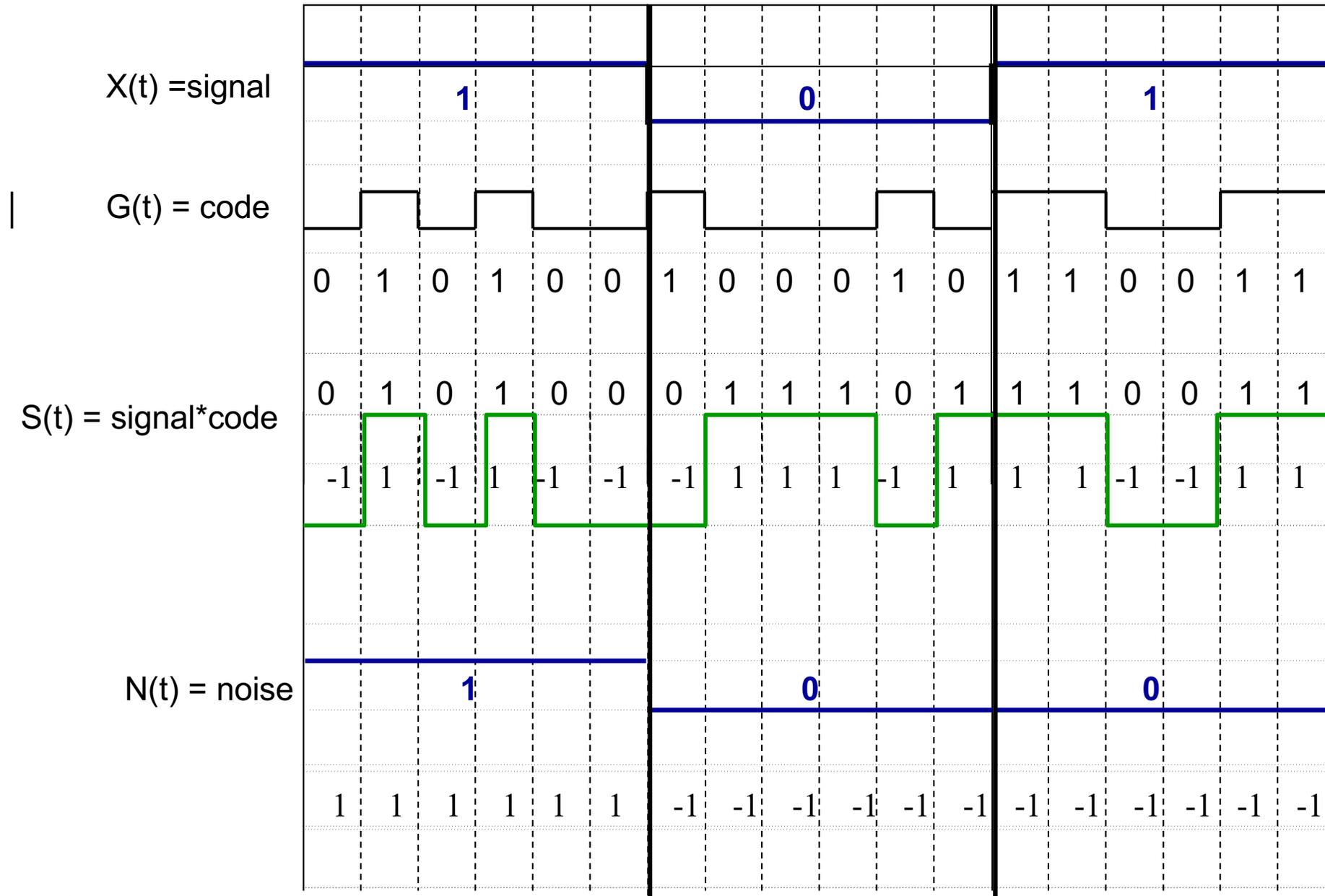
Other benefits

- 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
 - access control + robustness are key

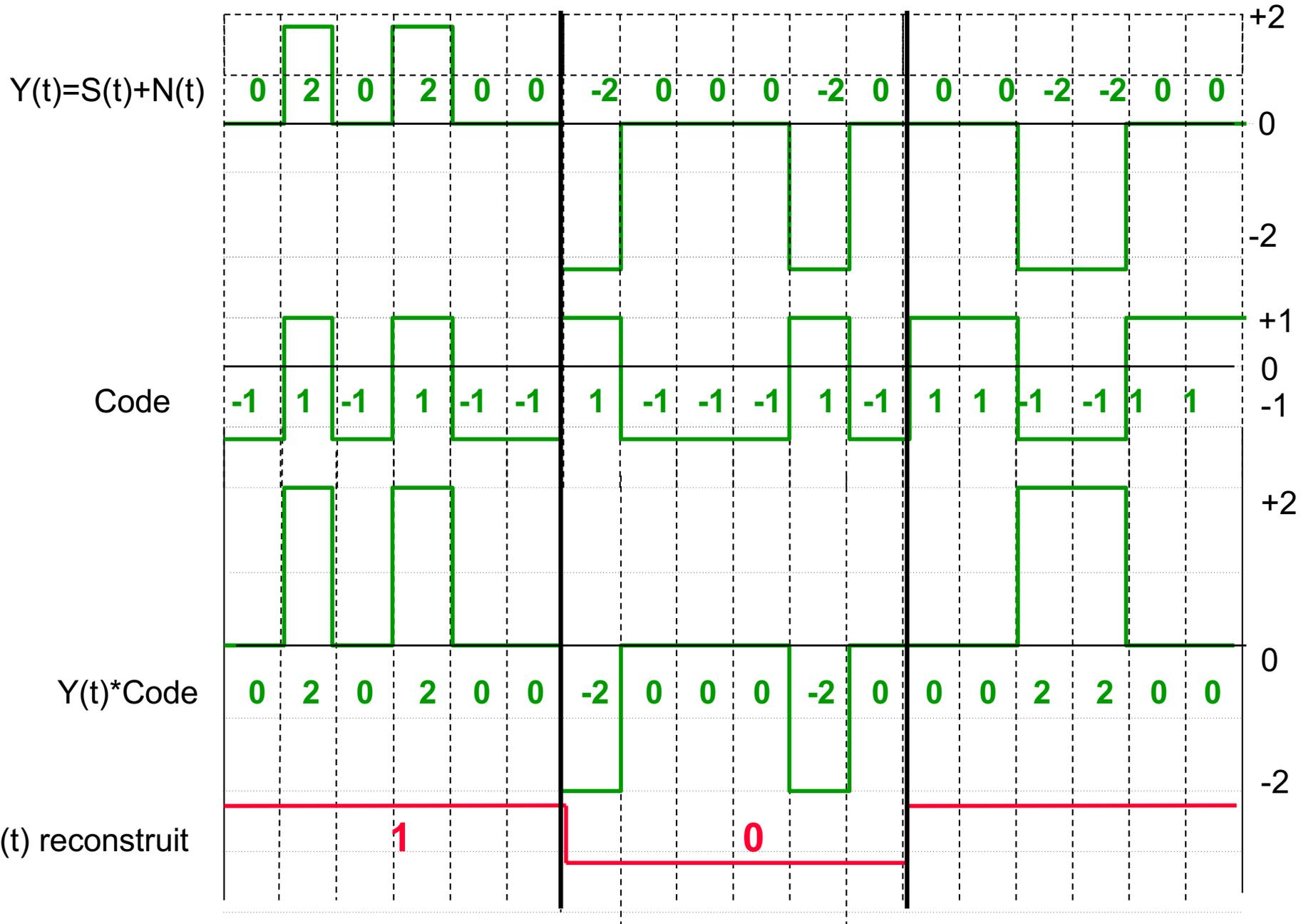
DSSS: interference filtering

- 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:
 - $s(t) = x(t).g(t) \leftrightarrow X(w)*G(w)$
 - 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

- 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

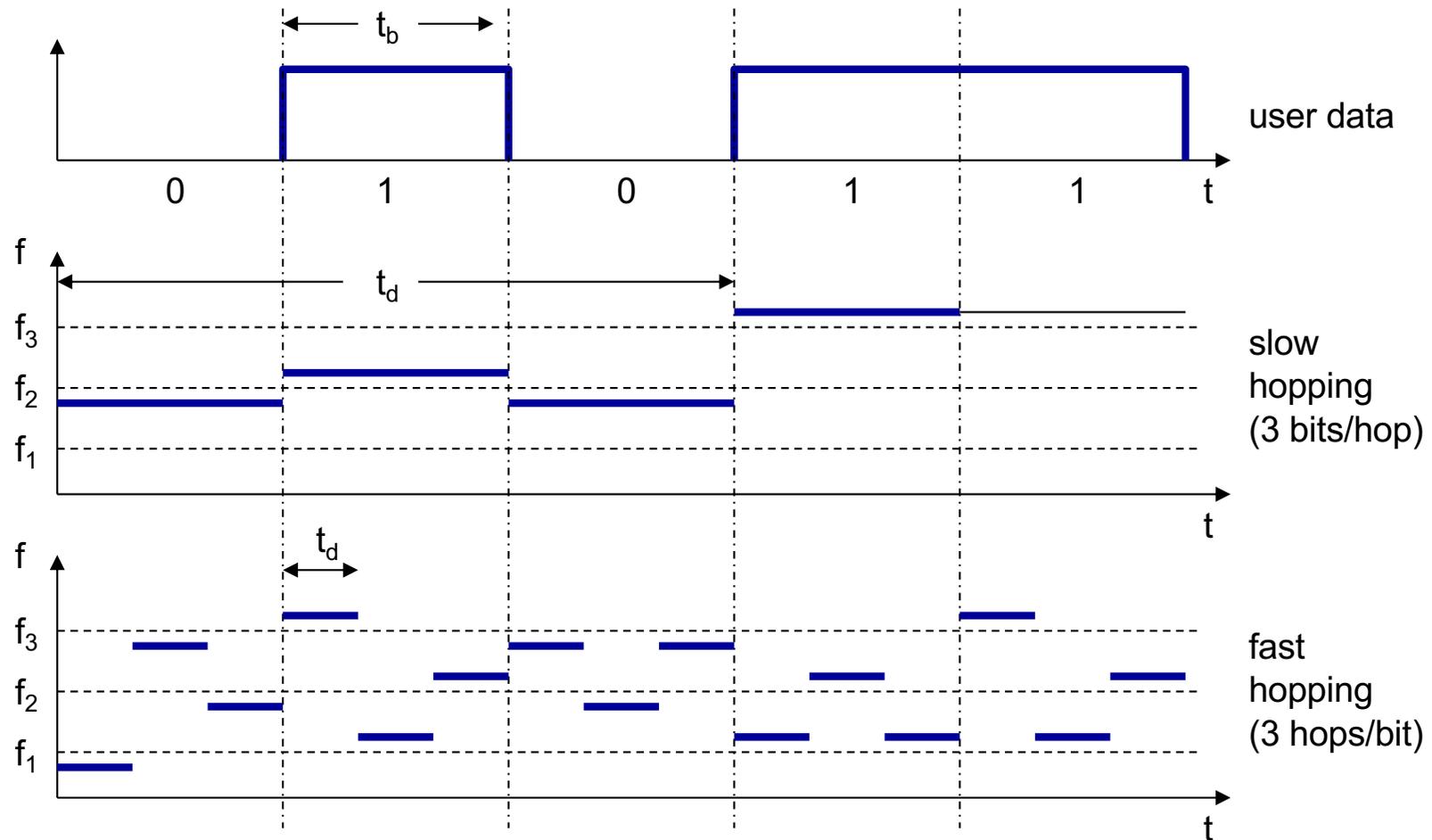
DSSS: multiplexing (2)

- **Signal spreading**
 - $s_1(t) = x_1(t) \cdot \text{code}_1$
 - $s_2(t) = x_2(t) \cdot \text{code}_2$
 - $s(t) = s_1(t) + s_2(t)$ = signal on the channel
- **Signal despreading at the receiver**
 - $y_1(t) = s(t) \cdot \text{code}_1 = s_1(t) \cdot \text{code}_1 + s_2(t) \cdot \text{code}_1$
 $= x_1(t) \cdot \text{code}_1 \cdot \text{code}_1 + x_2(t) \cdot \text{code}_2 \cdot \text{code}_1$
 - » since code_2 and code_1 are orthogonal:
 - » $\text{code}_1 \cdot \text{code}_2 = 0$
 - » $y_1(t) = x_1(t) \cdot \text{code}_1 \cdot \text{code}_1 = x_1(t)$
 - and the same with $y_2(t)$...

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)

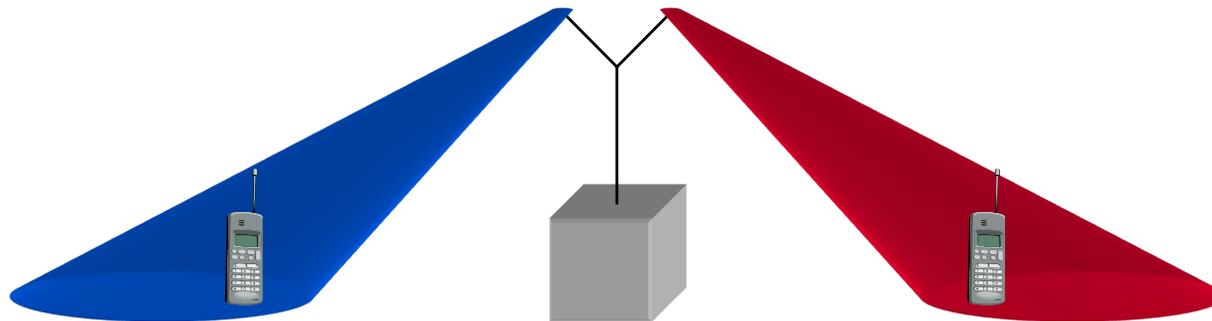


t_b : bit period

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)

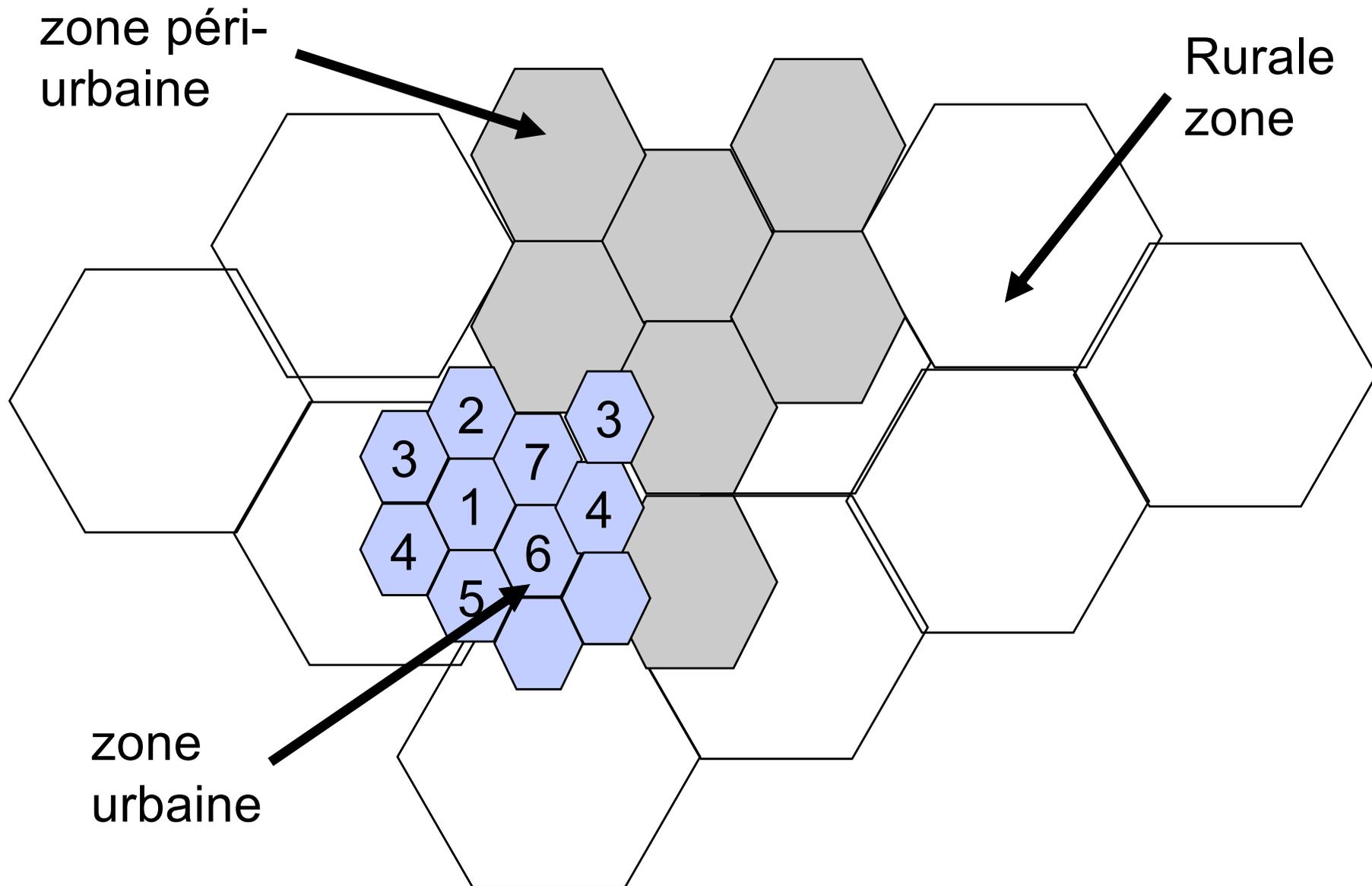
- Most commercial radio and television systems are designed to cover an as large as possible area
 - they operate at the maximum allowed power
- **Cellular systems** take the opposite approach: make an efficient use of available channels by using low-power transmitters to allow frequency reuse at smaller distances
 - **maximize the number of times each channel is reused in a given geographical area**
- Difficult tradeoff:
 - more channels \Rightarrow smaller cells
 - smaller cells \Rightarrow more interferences and more handovers ☹️

Cellular Systems (2)

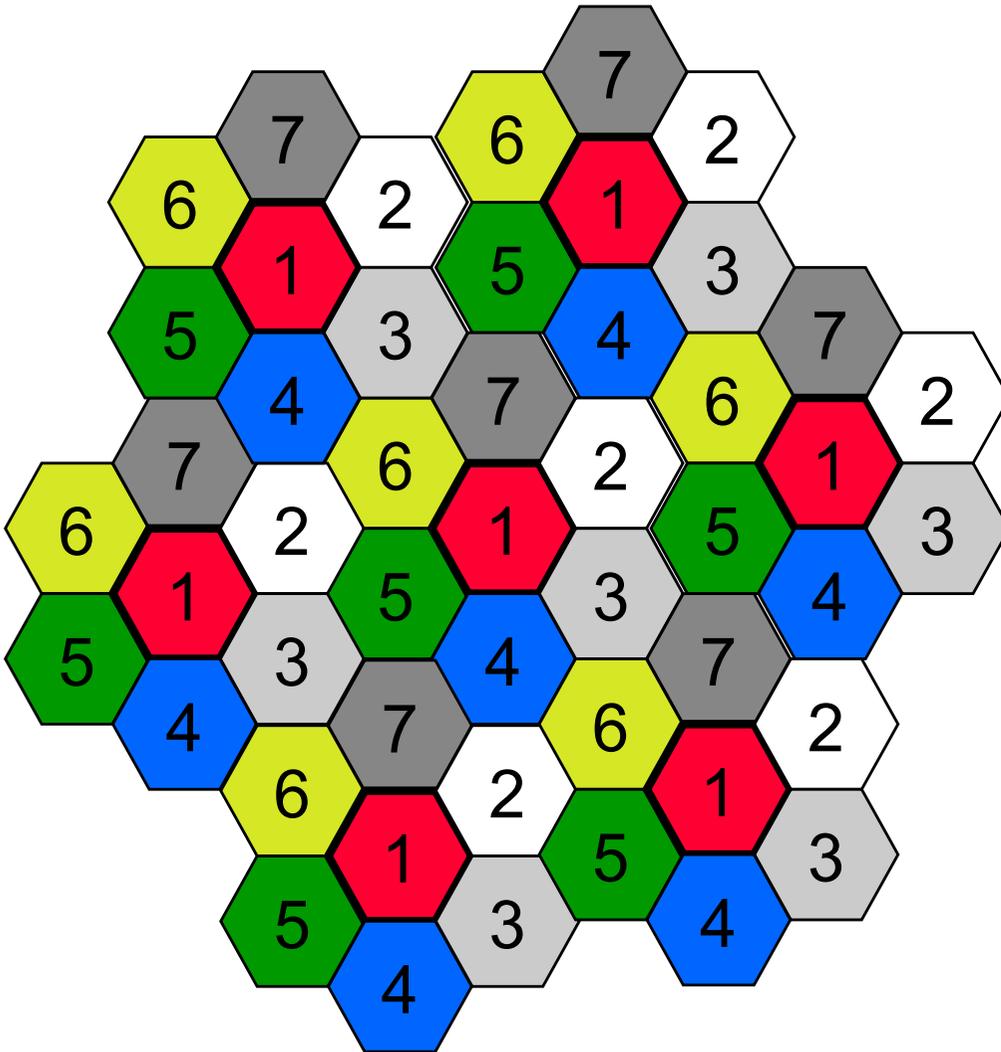
- **The size of the cells varies according to the user density**
- Over the years we saw an evolution towards **smaller cells**
 - better frequency reuse 😊
 - low power and less expensive base stations 😊
 - reduced battery drain on portable devices 😊

 - but also higher number of base stations 😞

Cellular Systems (3)



Cellular Systems (4)



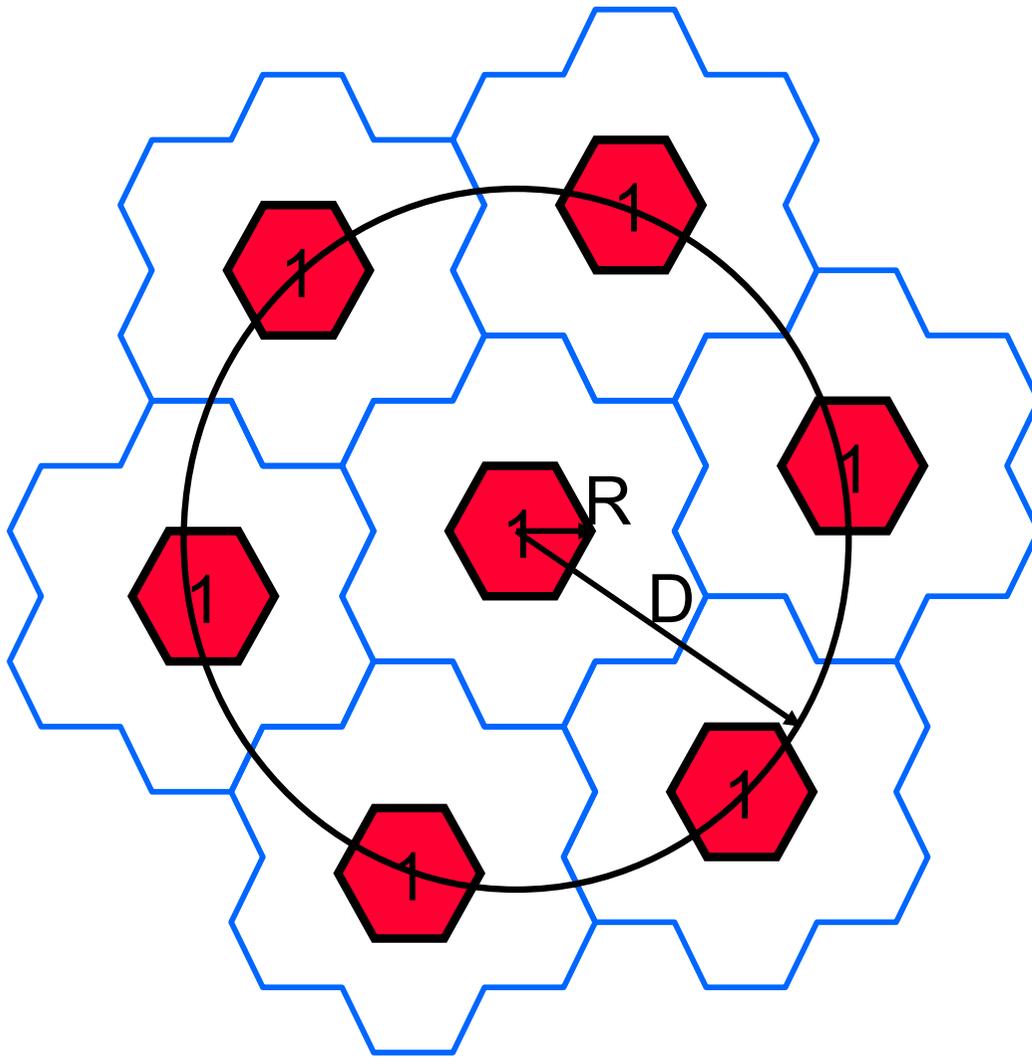
- In a cellular system, the space is divided into **clusters**.
- Each cluster uses the whole frequency spectrum of the system
- Each cluster is divided into **cells**
- Each cell of a cluster uses different frequency band
- Cells are laid out such as 2 cells of 2 clusters using the same frequency band 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:
 - $K = i^2 + j^2 + i \cdot j$ where i and j are positive integer
 - **$K = 1, 3, 4, 7, 9, 12, 13, 16, 19, 21, 25, 27, \dots$**

Cellular Systems (6)



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

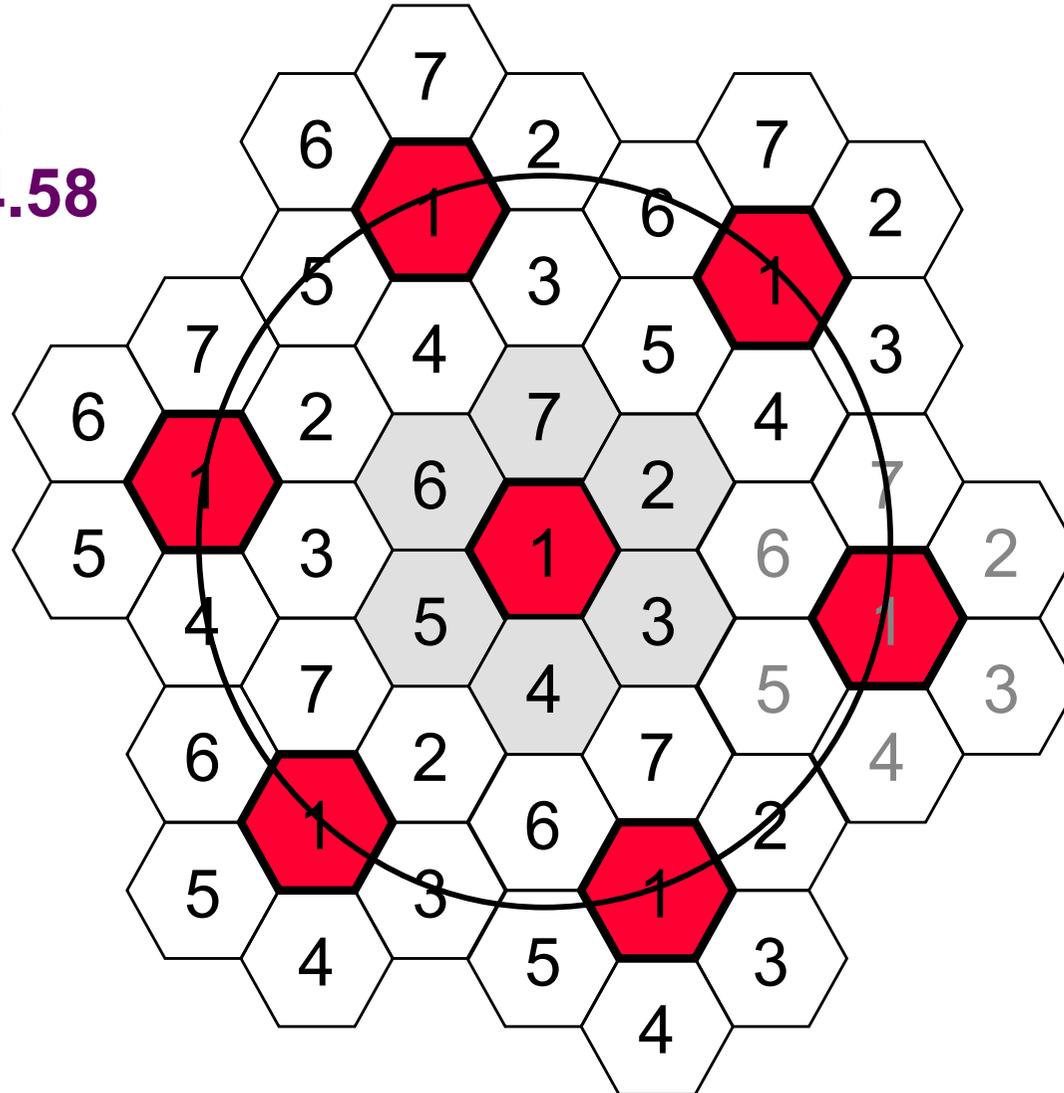
- the number of interfering cells is always equal to 6

- **$D/R = (3.K)^{1/2}$**

- where R is the center-to-vertex distance of a cell and D is the co-channel separation distance.

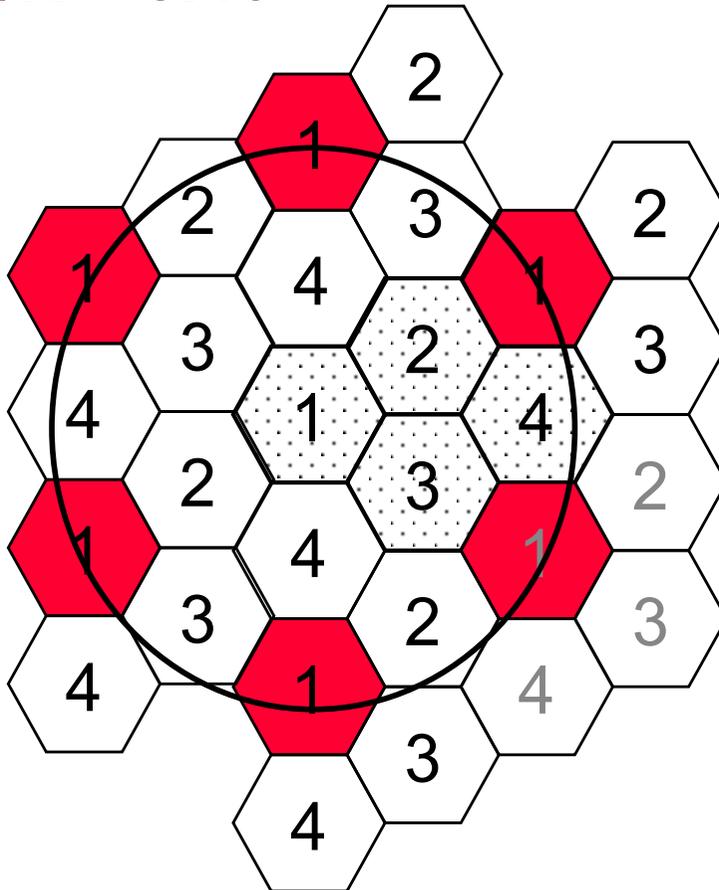
Examples (1)

$k=7$;
 $D/R = 4.58$

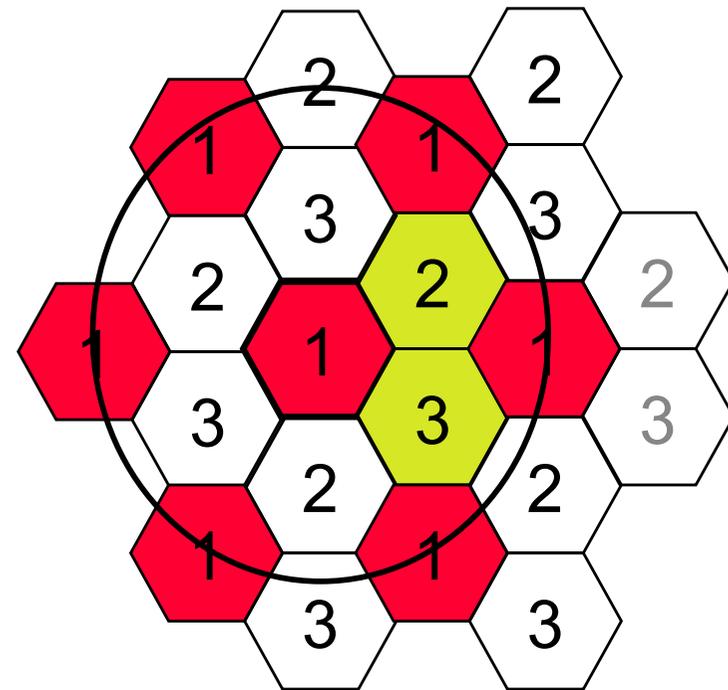


Examples (2)

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:
 - $S/I = S / (\sum_{i=1}^6 I_i) = \text{useful_signal/interferences}$
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 = $10 \cdot \log(63.1)$ 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

<i>K</i>	<i>Voice channels/cell</i>	<i>S/I (dB)</i>	<i>total channels</i>
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 size!**
 - for a given K, the capacity of a system can be increased by reducing the cluster size:

$$C \text{ (channels/m}^2\text{)} = \text{total nb of channels} / \text{cluster size}$$

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 (Contention 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...

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...

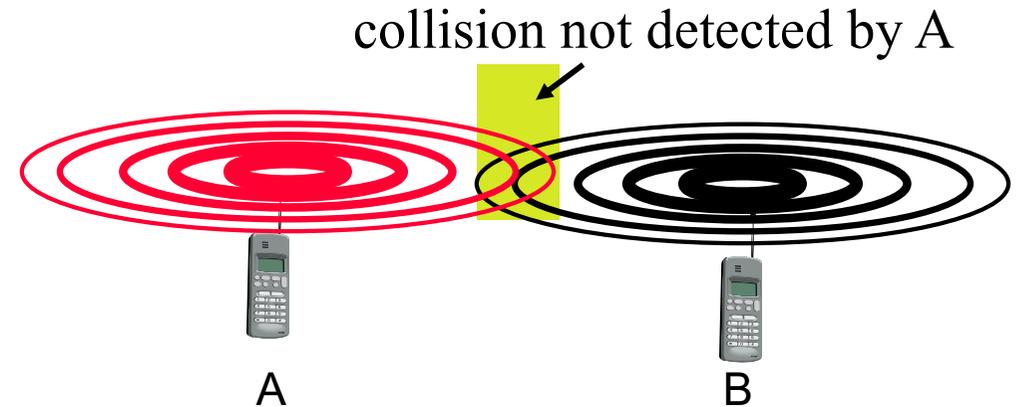
CSMA/CD

- 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!

CSMA/CD and Wireless networks

- CSMA/CD does not work with wireless networks
- CD does not work because:

- signal strength decreases rapidly with the distance, so a host does not always detect collisions

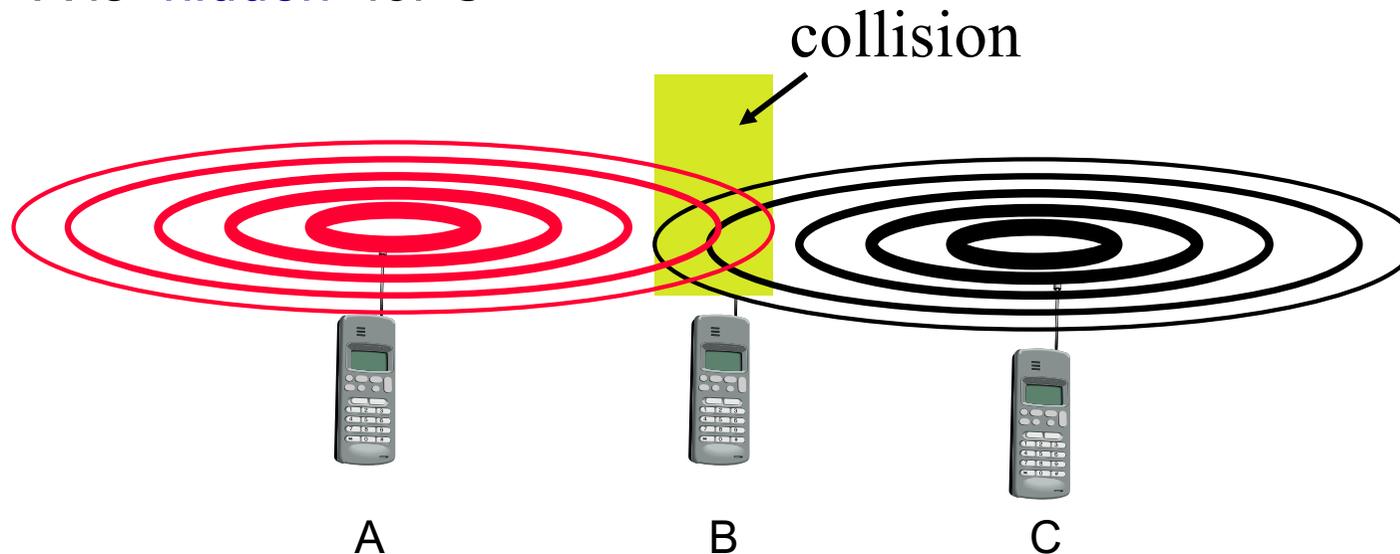


- a host is not necessarily able to detect a collision since the signal of the packet it is transmitting drowns out other packets' signals.

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

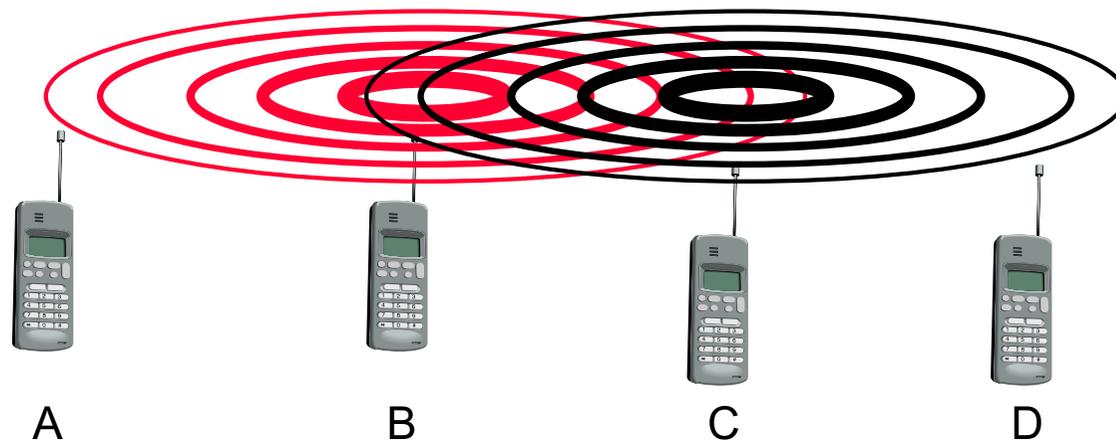
Hidden terminals

- 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

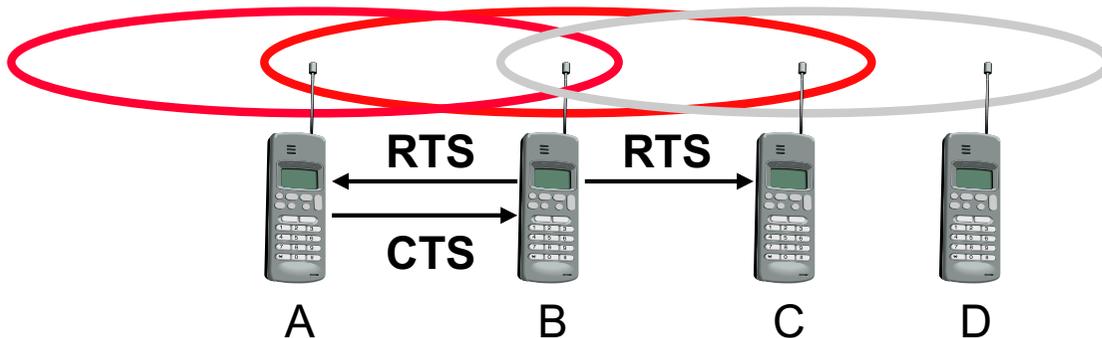
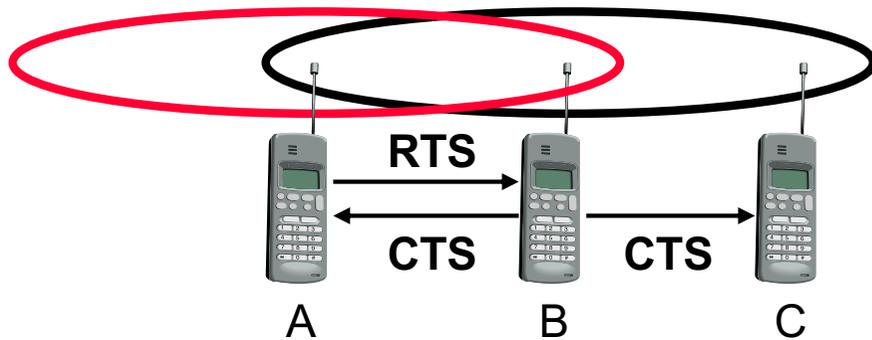
- **CA** (Collision Avoidance) uses short signaling packets for collision avoidance
 - **RTS (request to send)**: a sender first asks a receiver for the authorization to send with a short RTS packet
 - **CTS (clear to send)**: the receiver grants the right to send as soon as it is ready to receive
 - 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

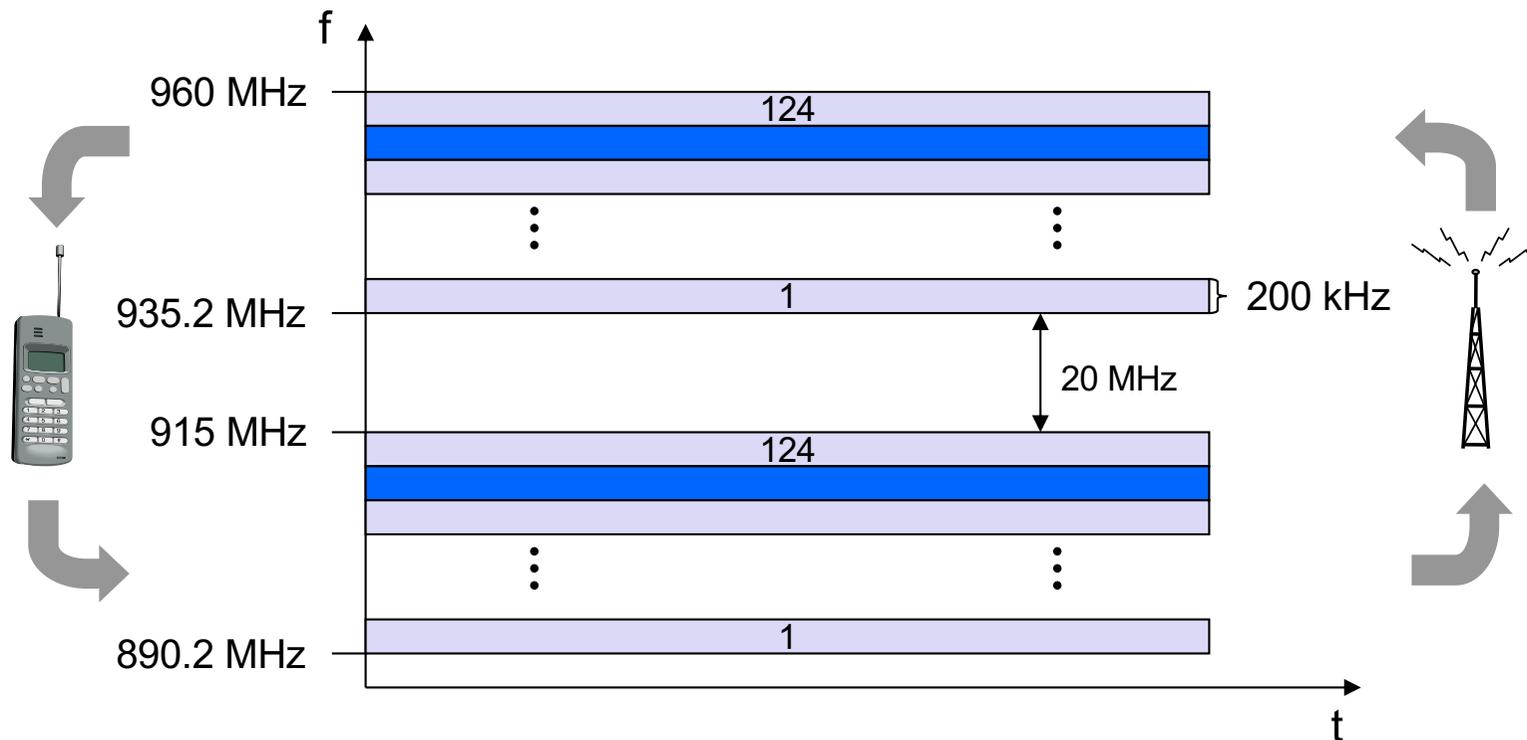
- It is desirable to allow a mobile to send to BS and receive from BS simultaneously: this is **Duplexing**

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.
- Example 1: SDMA/TDMA/FDMA/FDD - GSM



Duplexing vs Multiple Access (2)

- Example2: TDMA/TDD - DECT

