ΕΠΛ 427:
ΚΙΝΗΤΑ ΔΙΚΤΥΑ ΥΠΟΛΟΓΙΣΤΩΝ
(MOBILE NETWORKS)

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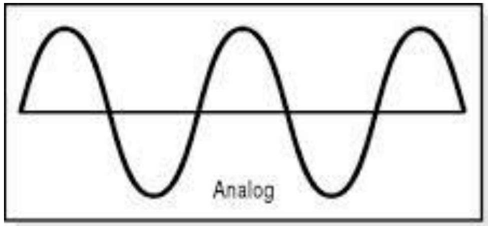
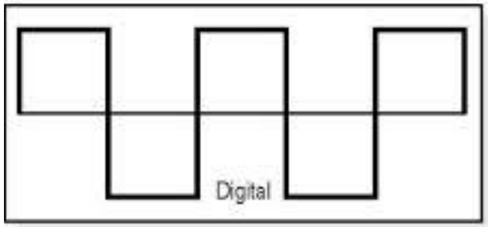
Επανάληψη για Τελική

Definitions
Analog and Digital Signals

- Means by which data are propagated (διαδίδονται) over a Communication Channel.
  - **Analog Signal:** is a continuously varying electromagnetic wave that may be propagated **over a variety of media. E.g.,**:
    - Wire, coaxial, **space (wireless), etc.**
    - There are **no breaks or discontinuities in the signal** (Continuous Signal)

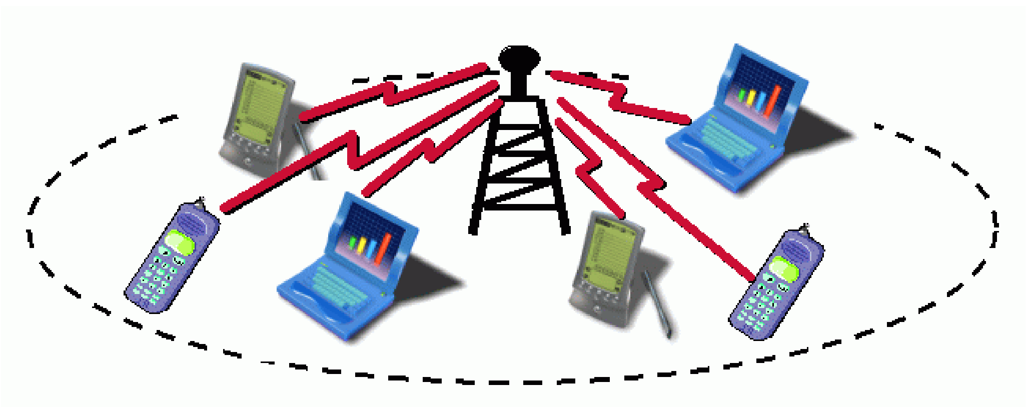


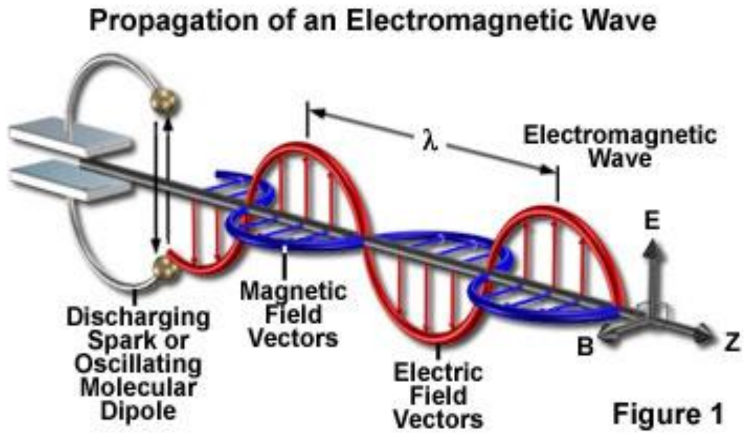


  - **Digital Signal:** is a sequence of discrete (διακριτές) voltage pulses that can be transmitted over a **wire medium (cannot be used to transfer data over the air)**.
    - For example, a constant **positive level of voltage is send** to represent binary 0 and a constant **negative level of voltage is send** to represent binary 1.

Definitions
Communication and Wireless Networks

- Wireless Networks **utilize Electromagnetic Waves** (radio waves) **of a certain frequency (Carrier Frequency)** to establish **Communication Channels and transmit data** between Wireless Communication Devices (e.g., Mobile Devices and the Base Station).





Challenges with Wireless/Mobile Networks

- **Two important challenges** with wireless/mobile networks (beyond those of traditional fixed networks):
  - **Wireless**: Communication over a **wireless link** - Transmitting voice and data using **electromagnetic (radio) waves in open space** (using a given frequency band).
    - The **Quality of a link connection** is **subjected to many (environmental) factors** and can vary substantially → Especially from the effects caused by the **Multipath propagation phenomenon**.
  - **Mobility**: Handling the mobile user who **changes point of attachment** (handover) to the network.

What is Mobility?

- **Two aspects of mobility**:
  - **Device Portability:** The device can **easily be carried** and can be connected (wireless) anytime and from anywhere to the network. **Changing point of attachment to the network offline** (connect from home, from work, from coffee shop, etc.)
  - **User Mobility (includes device portability):** Users communicates (wireless) with anyone, anytime and from anywhere. **Changing point of attachment (Handover) to the network online** (e.g., the user is driving from home to work and the call/connection is hand off from one cell to another during the call)

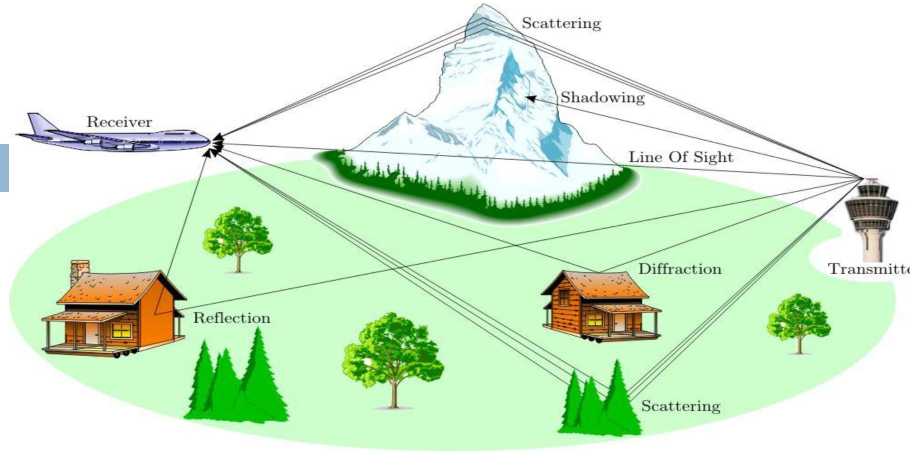
Benefits of Wireless Networking

- **Allows Mobility**
  - **Freedom to move** in the geographical area without being tethered by wires
  - Permits companies to shift toward an increasingly **mobile workforce**
- **Increased Reliability (no cables needed)**
  - **Network cable failures** is the most common source of network problems
- **Easier and Less Expensive Installation**
  - Installing network cabling can be a difficult, slow, and costly task!
  - Installation in Difficult-to-Wire Areas

Benefits of Wireless Networking

- **Expandability**
  - **Easy to add stations (Mobile/Portable Devices) on the network** since no cables or plugs are required to connect to the network
- **Long-Term Cost Savings**
  - **No need of Re-cabling** in case of re-organization of companies (i.e., new floor plans, office partitions, moving to a different building, renovations)

Wireless Networks in Comparison to Wired Networks



- **Higher loss-rates** due to (I):
  - **Noise and Interference. E.g.:**
    - **Self-interference**
      - **Inter-symbol interference** or **fast fading** due to **multipath propagation**
    - **Co-Channel** Interference (**Cross-Talk**):
      - **Interference with other channels** using the **same frequency band**
    - **Cross-system** Interference
      - Interference with other Radio sources in same frequency band, e.g., 2.4 GHz wireless phone interferes with 802.11b WLAN
    - **etc.**

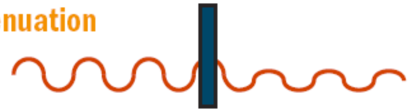
  - **Blocking of Radio Signals** by obstacles (**Shadowing**)

Wireless Networks in Comparison to Wired Networks

- **Higher loss-rates** due to (II):
  - **Decreasing signal strength during propagation making it difficult for the Receiver to decode the signal correctly.**
    - Signal Propagation in **wired Networks** has a wire to **determine the direction of signal propagation**
    - Signal Propagation in wireless networks has **an unpredictable behavior**
      - **Attenuates** as it travels greater distance (**Pathloss**)
      - **Attenuates** as it passes **through materials** (air, snow, rain, fog, walls, water, glass, etc.)

Attenuation Effects

Attenuation

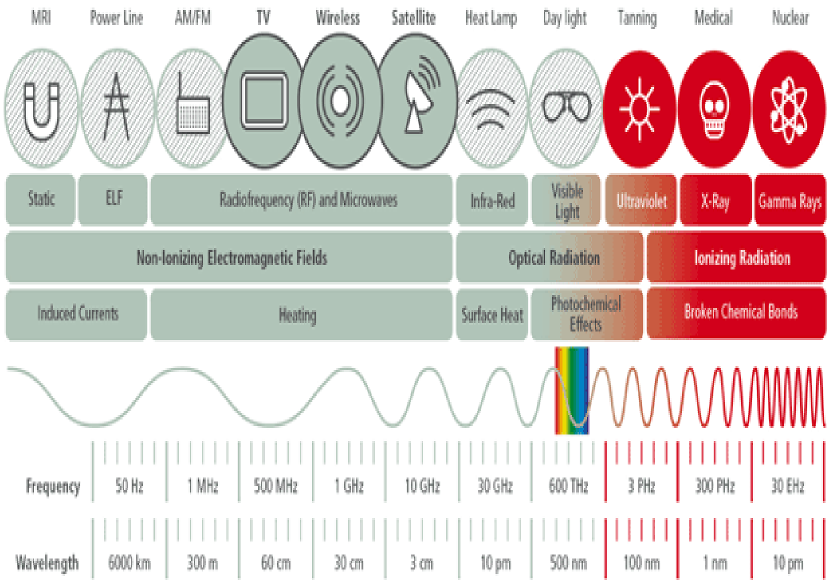


The signal strength is reduced as it passes through an object.

Material	Typical Attenuation (Loss) @ 5GHz
Cubical Wall	2dB
Drywall or Sheetrock	3dB
Brick Concrete or Block Wall	15dB
Elevator Shaft	10dB
Glass or Window	3dB
Concrete Floor	11dB

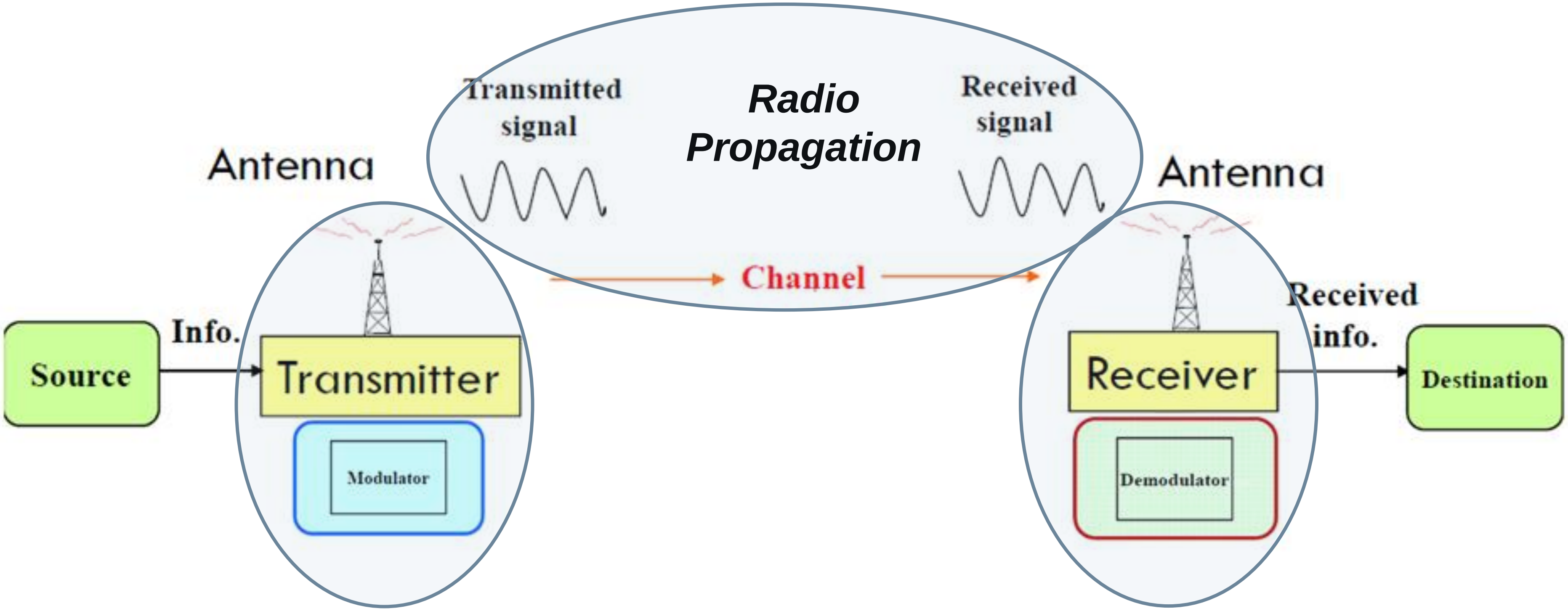
Wireless Networks in Comparison to Wired Networks

- **Limited availability of useful spectrum!!!**
  - **Radio Frequencies have to be coordinated**, all useful frequencies are "occupied".



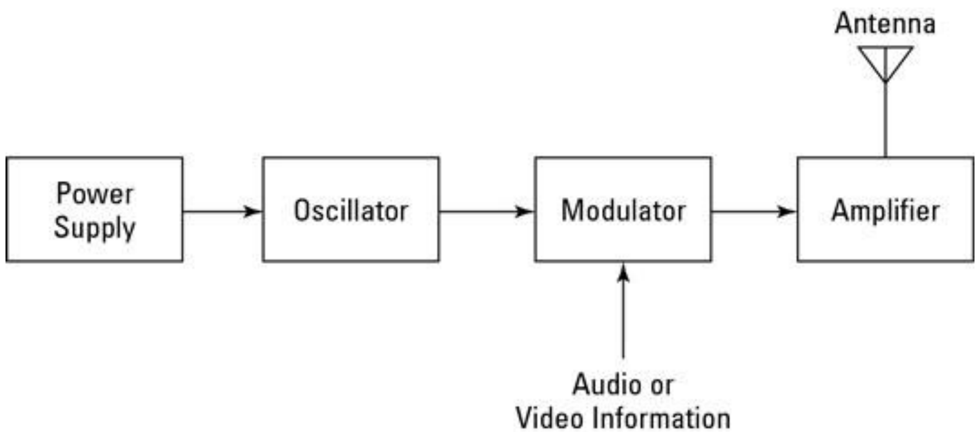
- **Lower security and easy to listen to/attack radio**
  - Radio interface accessible to everyone, e.g., a Base Station can be simulated, thus attracting calls from mobile phones
- **Always a shared medium**
  - Interference between several Senders/Receivers → **Multiple Access mechanisms (TDMA, FDMA, CDMA, OFDMA, etc.) are essential**

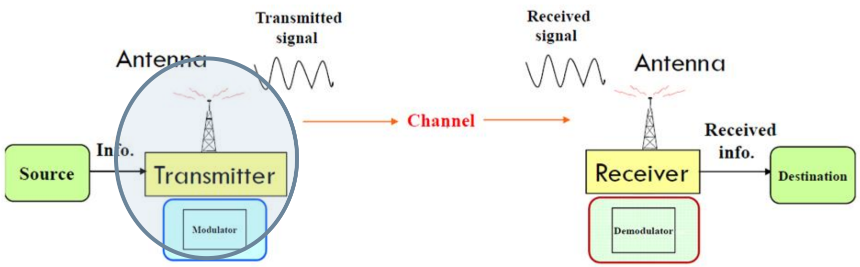
Process and Elements of Radio (Wireless) Transmission Διαδικασία και Στοιχεία Ασύρματης Διάδοσης



Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης

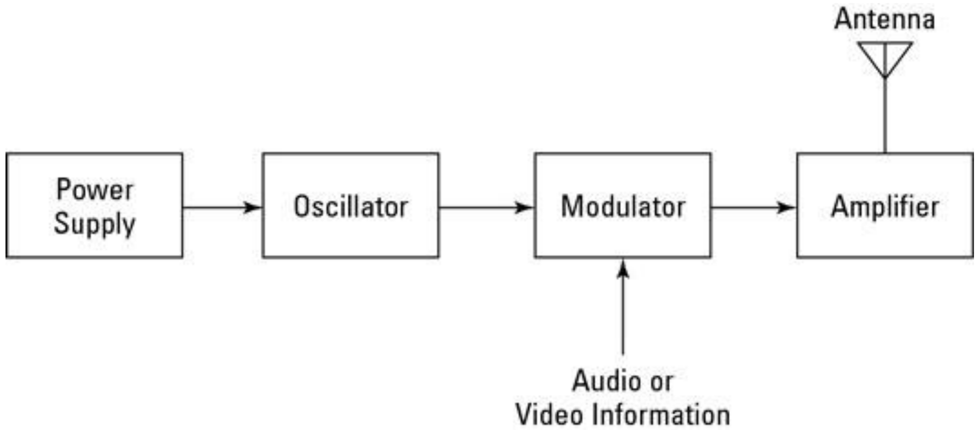
- **Radio Transmitter and Modulation (Πομπός και Διαμόρφωση)**
  - A **Transmitter (Πομπός)** or **Radio Transmitter** is an electronic device which, **with the aid of several components (Power Supply, Oscillator (Ταλαντωτής), Modulator (Διαμορφωτής), Amplifier, Antenna), produces radio waves that contain useful information** (10110111011111….) such as audio, video, or digital data.

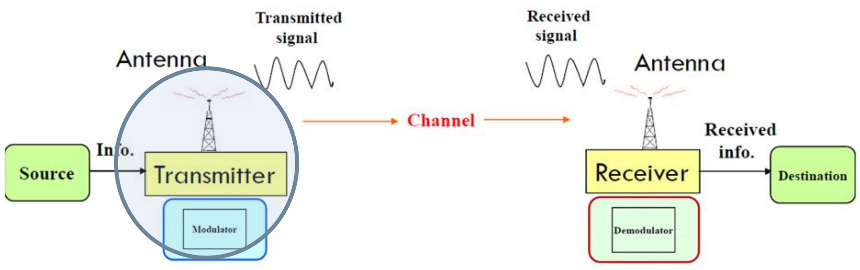




Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης

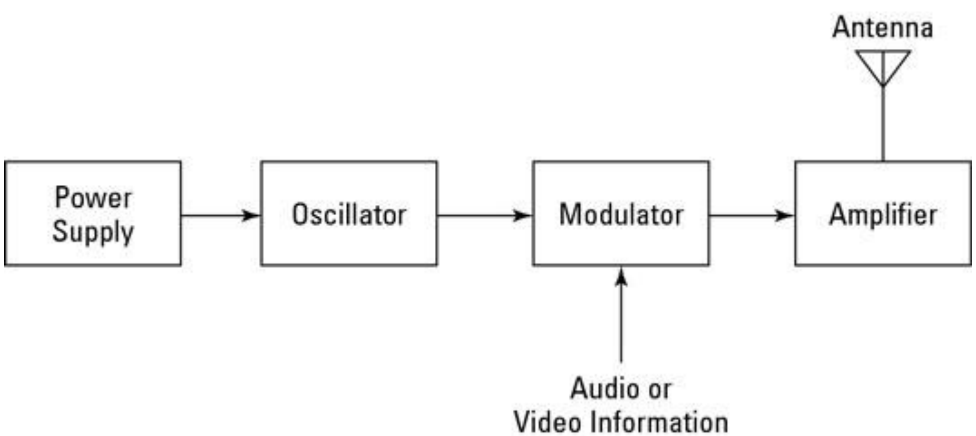
- **Radio Transmitter and Modulation (Πομπός και Διαμόρφωση)**
  - The **Power Supply** provides the necessary electrical power to operate the Transmitter.
  - The **Oscillator generates an alternating/oscillating (ταλαντευόμενο) electrical current** at the **specific frequency** on which the Transmitter will transmit (**carrier frequency**). The Oscillator usually generates a **sine wave**, which is referred to as a ***carrier wave (or carrier signal)***.

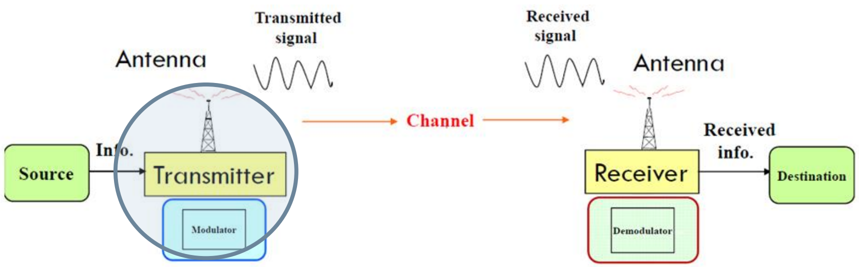




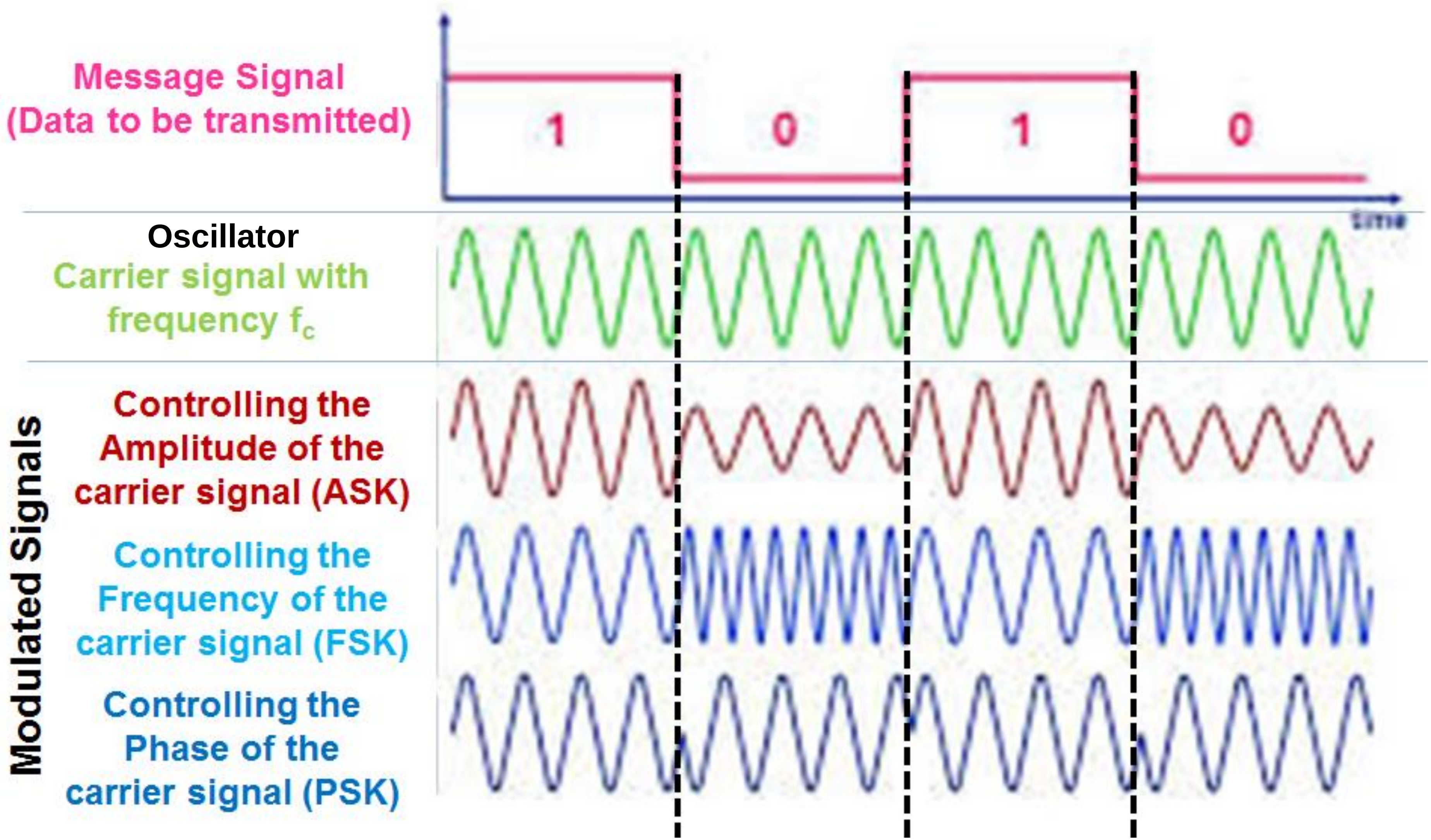
Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης

- **Radio Transmitter and Modulation (Πομπός και Διαμόρφωση)**
  - The **Modulator (Διαμορφωτής)** adds the **useful information** to the carrier wave by **modulating (changing)** **some properties of the oscillating electrical current (i.e., the carrier wave), before applied to the antenna.**
    - Such as its **Amplitude**, **Frequency**, **Phase**, or combinations of these properties. → ***Amplitude Shift Keying (ASK), Frequency Shift Keying (FSK), Phase Shift Keying (PSK), etc.***



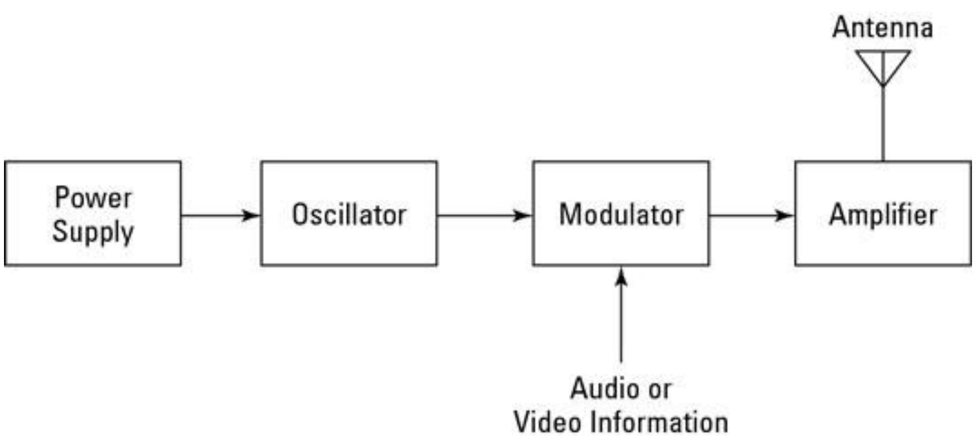


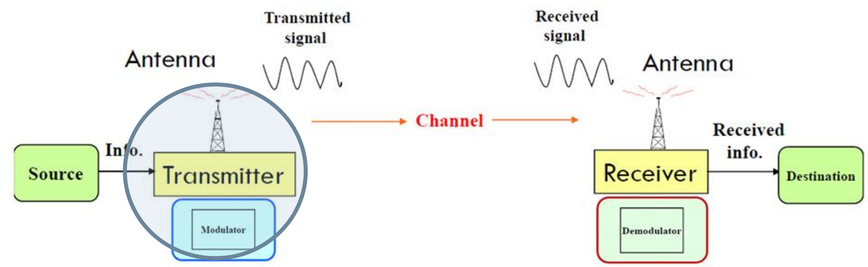
Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης



Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης

- **Radio Transmitter and Modulation**
  - The **Amplifier amplifies** the **modulated carrier wave** to **increase its power**. The more powerful the amplifier, the more powerful the broadcast.
  - The **amplifier** applies the **amplified modulated oscillating electrical current** to the **Antenna** which converts it into an **electromagnetic wave (or radio wave)** that can propagate through the air.





Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης

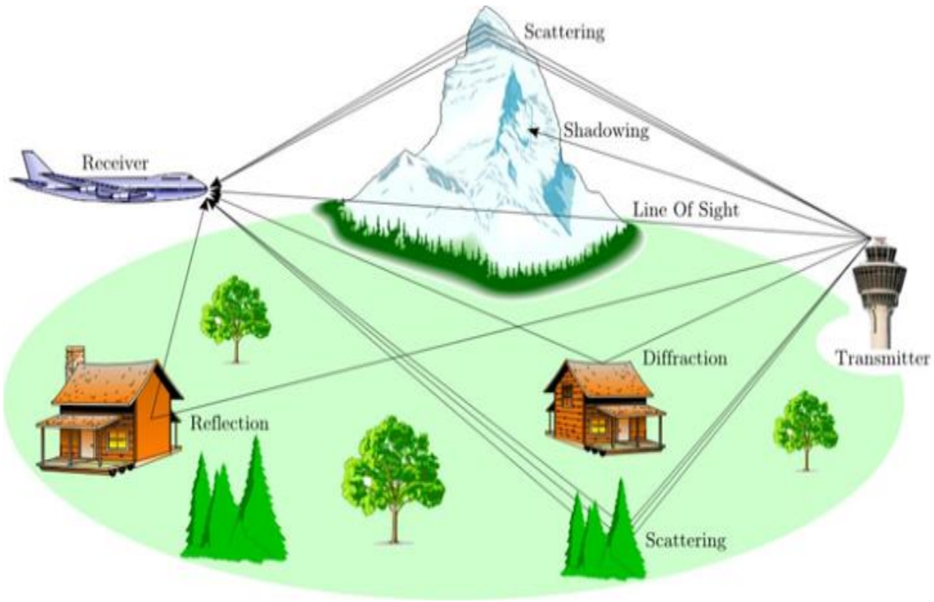
- **Radio Transmitter and Modulation**
  - In a **wireless environment**, a Base Station or an Access Point (i.e., the Antenna) needs a **radio connection between all the Mobile Stations in their transmission range**.
  - Thus, there is a need to address the issue of **simultaneous multiple access by numerous users** in the transmission range.
  - **Multiple Access techniques (Τεχνικές Πολύπλεξης)** are used to **allow a large number of mobile users to share the allocated spectrum** in the most efficient manner. E.g.:
    - Frequency Division Multiple Access (FDMA)
    - Time Division Multiple Access (TDMA)
    - Code Division Multiple Access (CDMA)
    - Orthogonal Frequency Division Multiple Access (OFDMA)

Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης

- **Radio Propagation (Ασύρματη Διάδοση Σήματος)**
  - Once generated, **electromagnetic waves travel through space either directly (line of sight)**, or have their **path altered** by Reflection (Ανταvάκλαση), Diffraction (Περίθλαση) or Scattering (Διασκόρπιση) → **Multipath Propagation - Πολυδιαδρομική Διάδοση**.

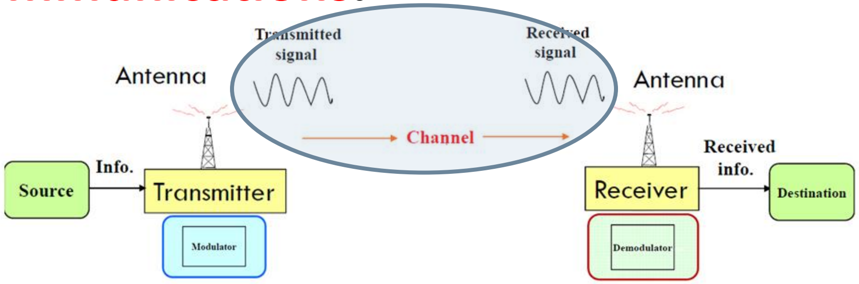
Multipath Propagation The phenomenon that results in **multiple copies of the same radio signal** reaching the receiving antenna by two or more paths.

Results in **Inter-symbol interference** and **fast fading**

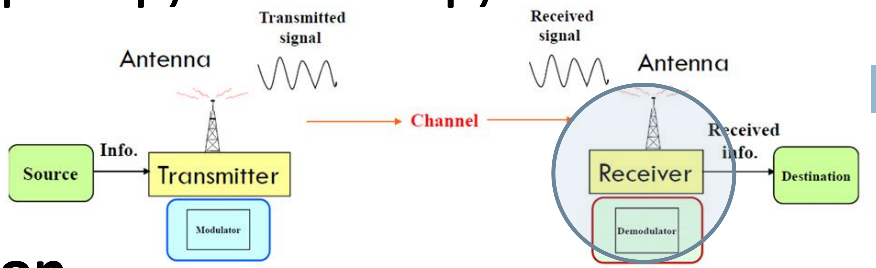


Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης

- **Radio Propagation (Ασύρματη Διάδοση Σήματος)**
  - The **intensity** of the radio waves **attenuates** during propagation (**Pathloss**); some energy may also be absorbed by the **intervening medium** in some cases.
  - **Also during propagation, Noise and Interference present in the air alter the desired signal.**
  - If the **magnitude** of the **Noise + Interference is large enough** compared to the **strength of the desired signal**, the desired/original signal **will be altered** is such a way that it will **no longer be discernible (διακριτό)**; **this is the fundamental limit to the range (εμβέλεια) of radio communications.**



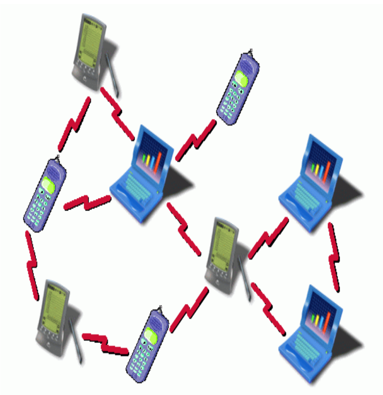
Process and Elements of Radio (Wireless) Transmission
Διαδικασία και Στοιχεία Ασύρματης Διάδοσης



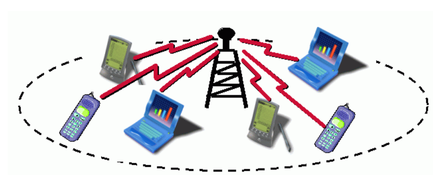
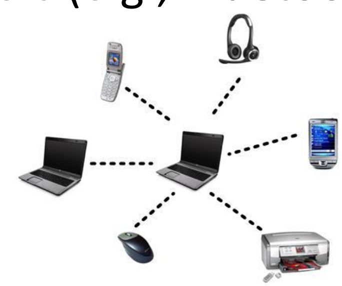
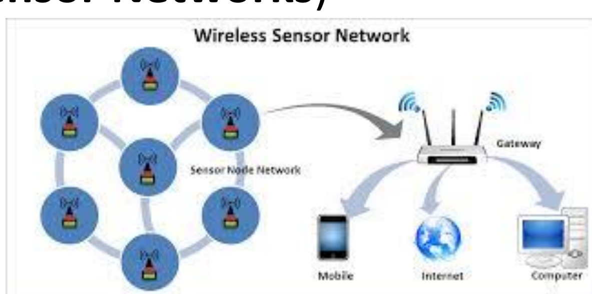
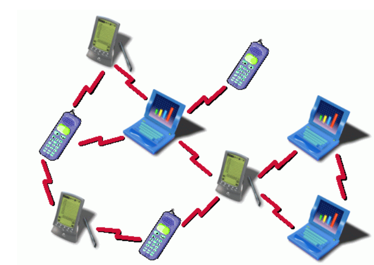
- **Radio Receiver and Demodulation**
  - The energy carried by the **modulated electromagnetic wave** is **captured** by the **receiving Antenna** and **returns it to the Radio Receiver** to the form of **oscillating/alternating electrical currents**.
  - The **Radio Receiver** uses **electronic filters (tuners)** to **separate the wanted radio signal** (transmitted in the **specific frequency** set for the **communication channel**) from all other signals picked up by its Antenna.
  - At the **Receiver**, these **oscillating electrical currents are amplified, demodulated** (recovers the useful information contained in the modulated radio wave) and converted into **to a usable signal form for interpreting the data.**

Infrastructure Vs Infrastructure-less (Ad Hoc) Based Networks

- **Infrastructure-based Networks**
  - **Wireless Hosts are associated with a Base Station** and **communication takes place only between the Wireless hosts and the Access Point** (Not directly between the Wireless Nodes) which is connected to the larger network infrastructure
  - **Traditional network services** (e.g., Resource Allocation, Routing, Transmissions Coordination, etc.) are **provided by the connected network infrastructure.**
- **Infrastructure-less (Ad hoc) based Networks**
  - Wireless hosts have **no infrastructure** to connect to (not associated with a Base Station or Access Point)
  - Hosts themselves **must provide network services** (hosts must organize themselves into a network)
  - Must **cooperate together** in a decentralized manner to **find a route** from one participant to another.

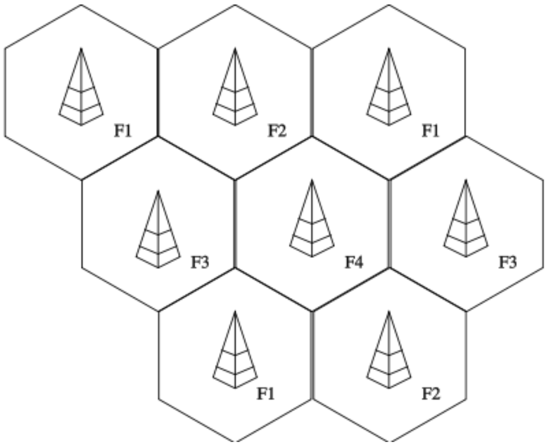


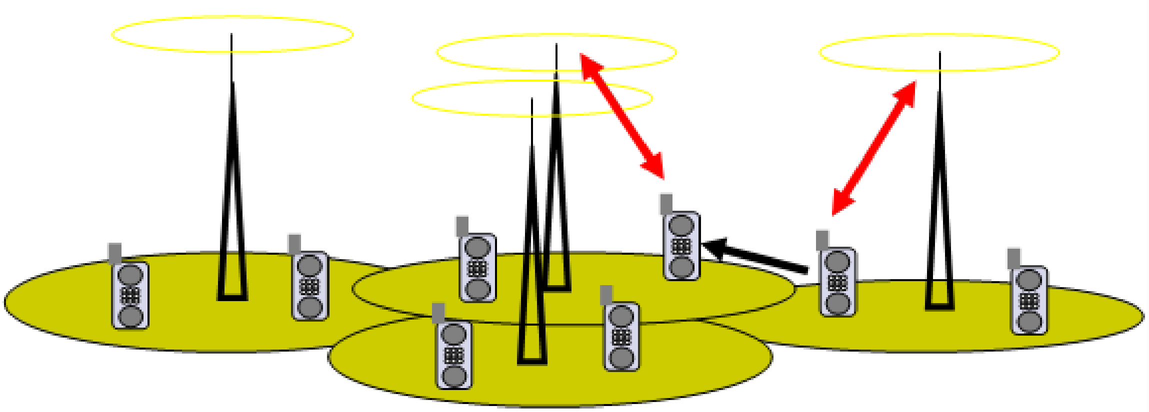
Different Types of Wireless Networks Διαφορετικοί Τύποι Δικτύου

	Infrastructure based	Infrastructure-less based
Single hop	Base Station exists and nodes communicate directly with the Base Station (e.g., **Wireless LAN, Cellular Networks**) 	No Base Station Exists; One node coordinates the transmissions of the others (e.g., **Bluetooth**) 
Multi-hop	Base Station exists, but some nodes must relay data through other nodes (e.g., **Wireless Sensor Networks**) 	No Base Station exists, and some nodes must relay data through other nodes (e.g., **Mobile Ad Hoc Networks**) 

Mobile Cellular Networks

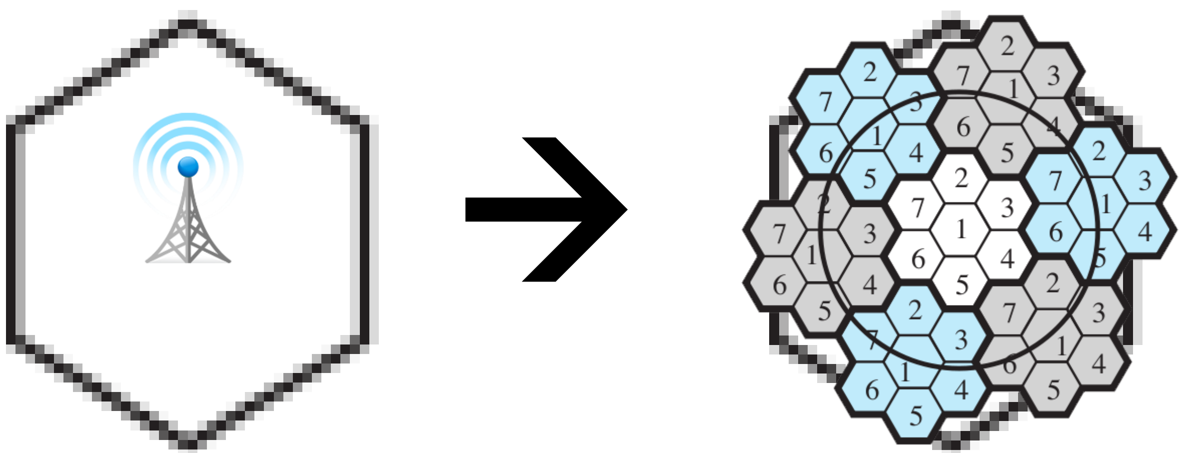
- **Mobile Cellular Networks concept:**
  - In a **Cellular** Network a geographical area is **split** into **several smaller land areas** called **Cells,** each served by a **fixed Base Station**.
  - **Service continuity** within this area is achieved by **handover**, which is the **seamless transfer of a call** from one Base Station to the other as the Mobile Station crosses Cell boundaries.





Cellular Network Advantages

Question: Why mobile network providers install several thousands of Base Stations throughout the country (**which is quite expensive**) and do not use powerful transmitters with huge cells?

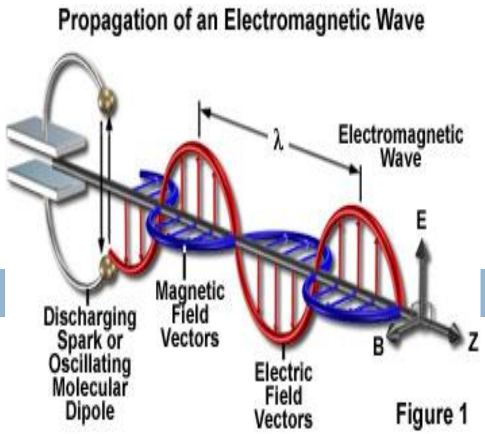


Cellular Network Advantages

Answer: Because Cellular Network provides:

- **Higher Capacity since smaller cells are used and the frequency reuse concept is applied**
- **Less Transmission Power is required by the MS to reach the BS, and vice versa, in shorter distances → Thus less the energy consumption (improves battery life for the MSs, lower power emissions thus positive health impacts, etc.)**
- **Interference is Reduced as less transmission power is required for the signal to cover shorter distances, thus less intra- and inter- cell interference.**
- **More Robustness to the network as if one BS fails, only one small part of the network will be affected.**

Electromagnetic Waves
Ηλεκτρομαγνητικά Κύματα



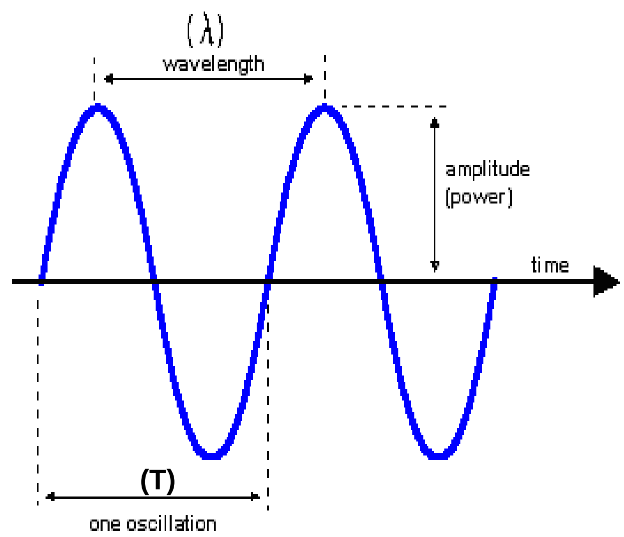
- The **electromagnetic waves** are **created** by the **vibration (ταλάντωση) of an electric charge**. This vibration creates a wave which has both an **electric** and a **magnetic field** and have the ability to **propagate through space**.
- The **speed of the electron vibration (η ταχύτητα ταλάντωσης των ηλεκτρονίων)** determines the **wave's frequency (measured in hertz).**
- Parameters that describe electromagnetic waves include **Frequency (f), Period (T), Amplitude (A) and Wavelength (λ)**.

Electromagnetic Waves Ηλεκτρομαγνητικά Κύματα

- **Frequency (f) (Συχνότητα),** is the number of complete oscillations (or cycles) which take place in a second.
  - Measured in **hertz** .

$$f = \frac{1}{T} \quad \text{and} \quad T = \frac{1}{f}$$

- **Period (T) (Περίοδος)** is the **amount of time** required for **one oscillation** (cycle) and is measured in **seconds**.
- **Amplitude (A) (Πλάτος)** is the value or **strength (power)** of the signal over time. It is measured from the middle point until the peak point of the oscillation. The higher the amplitude the more the energy the radio ware is carrying. It is typically measured in **watts** or **volts**.
- **Wavelength (λ) (Μήκος Κύματος)** is the **distance occupied** by a **single oscillation** of the signal, and is usually **measured in meters**
  - Or, the distance between two points of **corresponding phase** of two **consecutive cycles (δύο αντίστοιχων φάσεων δυο διαδοχικών ταλαντώσεων).**



Electromagnetic Waves Ηλεκτρομαγνητικά Κύματα

- **All electromagnetic (radio) waves travel** at the **speed of light**
  - C : Speed of Light (m/s) = (3x10^8 m/s or 300,000,000 m/s)
- In vacuum (e.g., the air), **all electromagnetic waves travel at this speed** .
- In copper or fiber the speed slows down to about 2/3 of this value.

- **Relationship** between the **Speed**, the **Frequency** and the **Wavelength** of the radio wave:
  - **Speed (C)= Frequency (f) x Wavelength (λ)**
    - **Speed** (**meters/sec**)
    - **Frequency** (oscillations per second; in Hz/second)
    - **Wavelength** (in meters)

Electromagnetic Waves
Ηλεκτρομαγνητικά Κύματα

- **Speed (C)= Frequency (f) x Wavelength (λ)**

  → Wavelength (λ) = Speed (C) / Frequency (f)

  → Frequency (f) = Speed (C) / Wavelength (λ)

Frequency	Wavelength
60 Hz	5,000 km
100 MHz	3 m
800 MHz	37.5 cm
20 GHz	15 mm

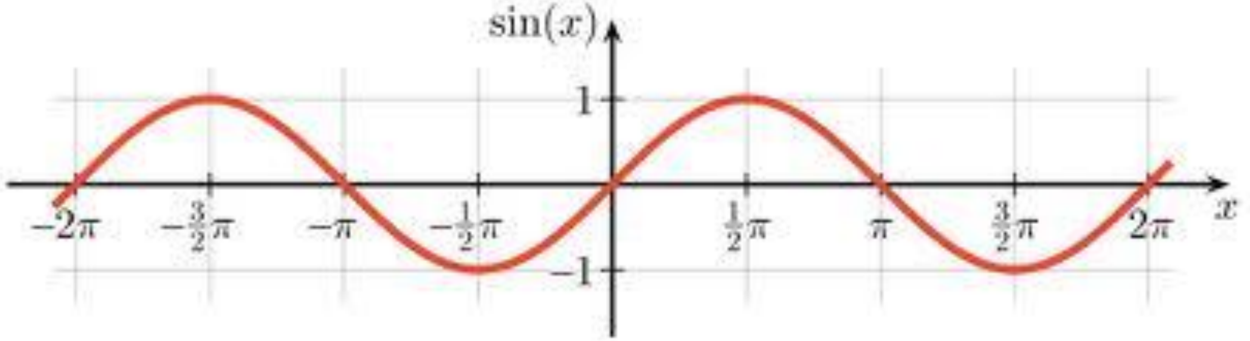
Electromagnetic Waves
Ηλεκτρομαγνητικά Κύματα

- **Relationship** between the **Frequency (f)** and the **Period (T)** of the wave:
  - **Frequency** (total number of oscillations performed in one second)
  - **Period** (time required for one complete oscillation)
  - **Period (T)= 1/Frequency (f)**

  - **Examples:**
    - **Frequency** = 60 Hz → **Period** = 0.0166 seconds
    - **Frequency** = 100 MHz → **Period** = 1×10^{-8} seconds
    - **Frequency** = 800 MHz → **Period** = 1.25×10^{-9} seconds
    - **Frequency** = 20 GHz → **Period** = 5×10^{-11} seconds

Electromagnetic Waves – Sine Wave

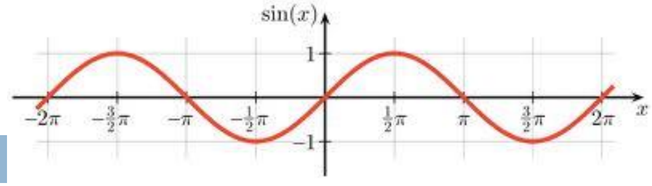
- **General** **Sine Wave**:
  - **s(t) = A sin(2πft + ϕ)** → **A:** Amplitude**, f:** Frequency**, ϕ:** Phase
  - Note: 2π radians = 360° = 1 Period

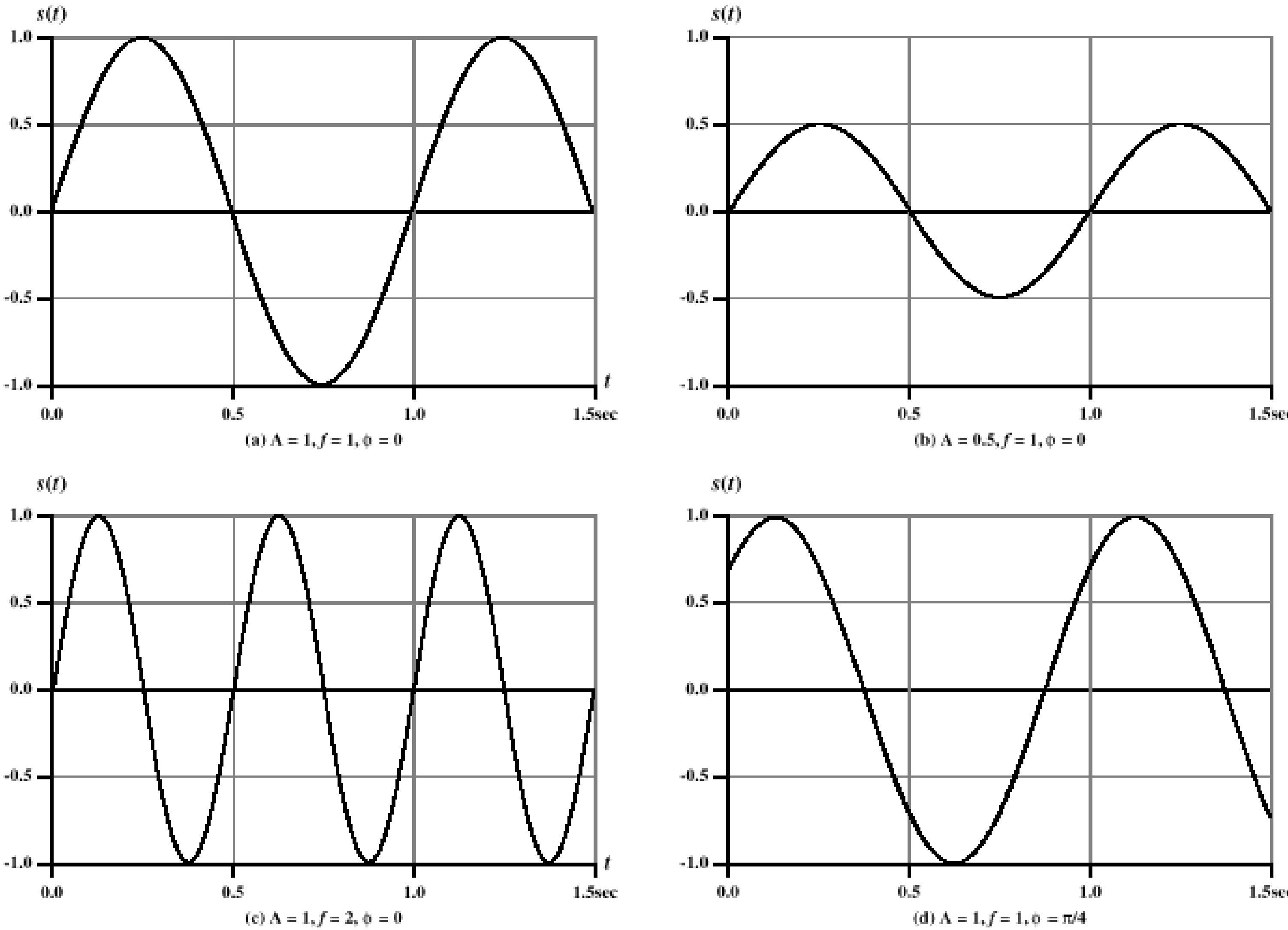


- The picture in the next slide shows the **effect of varying each of the three parameters** (**A, f** and **ϕ**)
  - (a) A = 1, f = 1 Hz, ϕ = 0; thus T = 1s
  - (b) Reduced peak amplitude; A=0.5, f = 1 Hz, ϕ = 0
  - (c) Increased frequency; A = 1, f = 2 Hz, ϕ = 0; thus T = 0.5s
  - (d) Phase shift; A = 1, f = 1 Hz, ϕ = π/4 radians (45 degrees)

Electromagnetic Waves – Sine Wave

$s(t) = A \sin(2\pi f t + \phi)$





Low Frequencies Vs High Frequencies
Χαμηλές Συχνότητες Vs Ψηλές Συχνότητες

Low frequency = long wavelengths
High frequency = short wavelengths

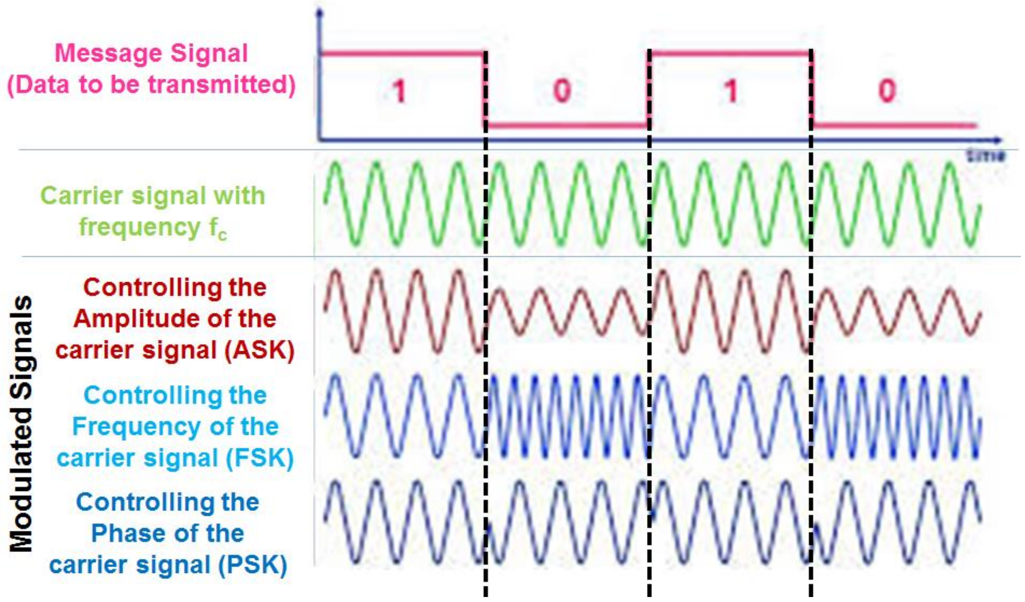
- **Lower frequency waves** have **better penetration (Καλύτερη Διαπέραση)**, meaning they pass through objects such as walls with **less attenuation (λιγότερη εξασθένιση),** and also can **propagate longer distances (διαδίδονται σε μεγαλύτερες αποστάσεις)**.
- However**, higher frequency waves** are **easier to radiate (ευκολότερο να τα εκπέμψουμε) as** they **require smaller antennas (the antenna size is proportional to the ¼ of the signal wavelength)** to transmit and receive, and can **support higher bandwidths (and thus higher data rates)** than lower frequency waves.

Low Frequencies Vs High Frequencies
Χαμηλές Συχνότητες Vs Ψηλές Συχνότητες

- **Frequency Vs Coverage (Συχνότητα Vs Ραδιοκάλυψη)**
  - Καθώς η **συχνότητα αυξάνεται**, οι **απώλειες που προκαλούνται λόγω απορρόφησης της ενέργεια του σήματος από την ατμόσφαιρα ή από άλλα μέσα τα οποία διαπερνά το σήμα αυξάνονται**, οι οποίες με τη σειρά τους **μειώνουν γρηγορότερα την ενέργεια που μεταφέρεται**.
  - Το τελικό **αποτέλεσμα** είναι **πιο μικρή ραδιοκάλυψη**.
  - Αυτός είναι ο κύριος λόγος που ένα σήμα WLAN **5 GHz**, που χρησιμοποιεί την **ίδια ισχύ εκπομπής** και κέρδος κεραίας με ένα WLAN σήμα των 2.4 GHz, έχει **μικρότερο εύρος**.

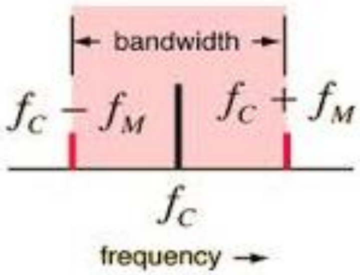
Carrier Signal, Modulation, Carrier Frequency and Bandwidth

- **Carrier Signal (or Carrier Wave)** is a waveform (κυματομορφή) oscillated in a **certain frequency (f_c)** **(Carrier wave frequency)** that will be used to **carry the data (i.e., 1 or 0)**.
- However, to **carry data**, the **carrier wave** have to be **modulated in some way** in order to produce **the signal** that will **carry the data**. This process is called **Modulation**.



Carrier Signal, Modulation, Carrier Frequency and Bandwidth

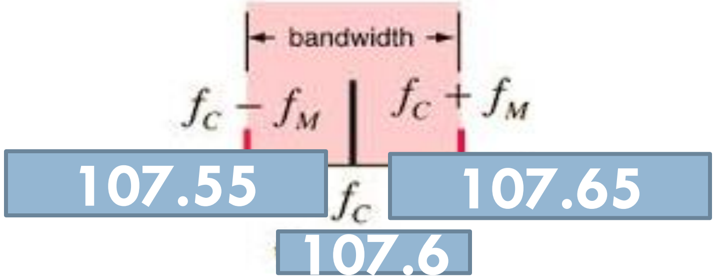
- The **Bandwidth (i.e., the frequency band) that needs to be allocated to send the data** it **strongly relates to the data rate that needs to be achieved** (**measured in bits per second (bit/s)**)
- Usually if the **Data Rate = R bps**, then the **Bandwidth** that should be allocated for the transmission should be **equal to 2 x R** (two times greater) so as to be able to carry the data with the specific data rate.
  - **However this also strongly depends on the Modulation Technique that will be used.**
- The **frequency band (Bandwidth)** that will be allocated will be in the range from **($f_C - f_M$) to ($f_C + f_M$) having t**he carrier frequency (f_C) in the middle.



$$Bandwidth = f_{MAX} - f_{MIN}$$

Carrier Signal, Modulation, Carrier Frequency and Bandwidth

- For example, if a radio station that radiates at 107.6 MHz (Carrier Frequency), if it transmits a 50 Kbps audio, it will require **100 KHz bandwidth**!
  - Thus it will use the **frequency band** from **107.55 MHz** to **107.65 MHz** to transmit the audio.
- **The larger the bandwidth**, **the more data** that can be **conveyed** (να μεταφερθούν) **through the channel**.



Carrier Signal, Modulation, Carrier Frequency and Bandwidth

- Metaphorically speaking, imagine a **Train** that carries mail **letters**:
  - The **Carrier Signal (or Carrier Wave)** can be described as a **"Train".**
  - **The Carrier frequency** can be described as **"The rail that the Train will follow"** to reach its destination.
  - **Modulation** can be described as the **Person Responsible for putting the** "letters" in the **"Train Wagon".**
  - The **Bandwidth** can be described as the **"number of Wagons allowed to be carried by the Train".**
    - The greater the "number of wagons allowed" to be carried by the train, the more the letters that can be carried at a given point in time.

Decibel (dB)

- **Decibel (dB)** is a logarithmic unit that is used to **describe a ratio (περιγραφή μιας αναλογίας)**.
  - Let say we have two values P1 and P2. The ratio between them **can be expressed in dB** and is computed as follows:
    - $10 \times \log_{10} (P1/P2)$ dB
  - **Example**: Transmit power **P1 = 100W**, Received power **P2 = 1 W**
    - The ratio is $\mathbf{10 \times \log_{10}(100/1)}$ = **20dB**. → P1 is **20 dB** stronger than P2
- **dB** unit can describe **very big ratios** with **numbers of modest size**.
  - Example: Transmit power = 100W, Received power = 1mW
    - Transmit power is **100,000 times** of received power
    - The **ratio** here is $10 \times \log_{10}(100/0.001)$ = **50dB** → Transmit power is **50 dB** stronger than Received power

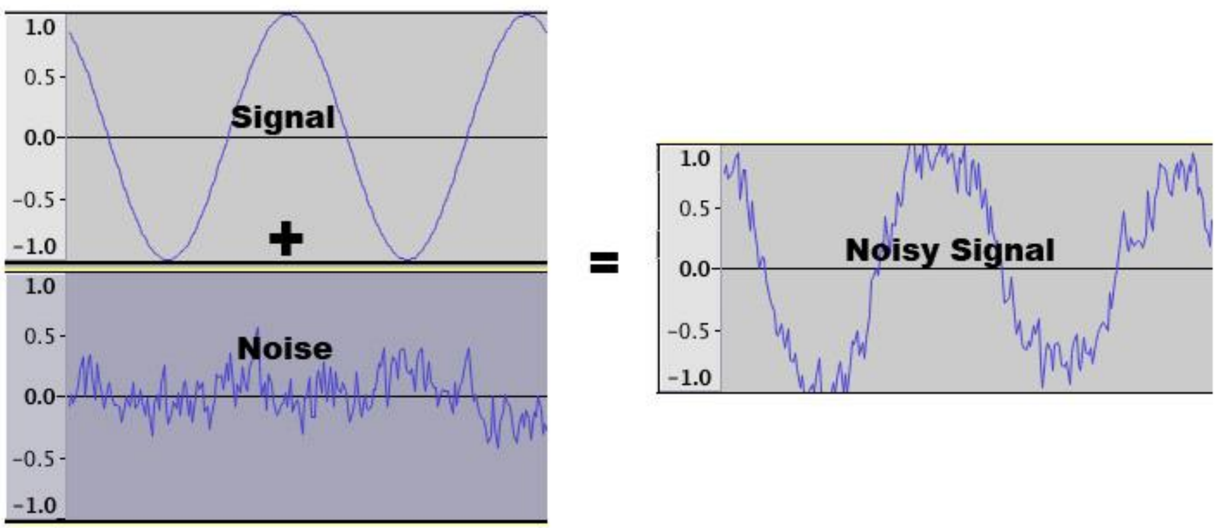
dBm and dBW

- **dBm** is used to denote a **power level (ένταση ισχύς) with respect to 1mW** (**milliwatt**) as the **reference power level**.
  - **Question:** Let say transmit power of a system is 100W. What is the transmit power in unit of dBm?
  - **Answer**: Transmit_Power(dBm) = $10\log_{10}(100W/1mW) = 10\log_{10}(100W/0.001W) = 10\log_{10}(100{,}000) =$ **50dBm**

- **dBW** is used to denote a **power level** with **respect to 1W** as the reference power level.
  - **Question:** Let say that the transmit power of a system is 100W. What is the transmit power in unit of dBW?
  - **Answer**: Transmit_Power(dBW) = $10\log_{10}(100W/1W) = 10\log_{10}(100) =$ **20dBW.**

Noise

- **Noise** is an error or **undesired random disturbance (ανεπιθύμητη τυχαία αναταραχή)** of a useful **information signal** in a communication channel.
- Is a **summation of unwanted or disturbing energy** from natural (i.e., thermal noise; generated by random motion of free electrons in the atmosphere, light, pressure, sounds, etc.) and sometimes man-made sources (i.e., microwave ovens).



Signal to Noise Ratio (SNR)

- **Compares the power** of a **desired signal** to the **power** of **background noise**. It is defined as the ratio of signal power to the noise power, often expressed **in decibels**.
- A **ratio higher than 1:1** (greater than 0 dB) indicates **more signal than noise**.
- This value is typically **measured at the Receiver**

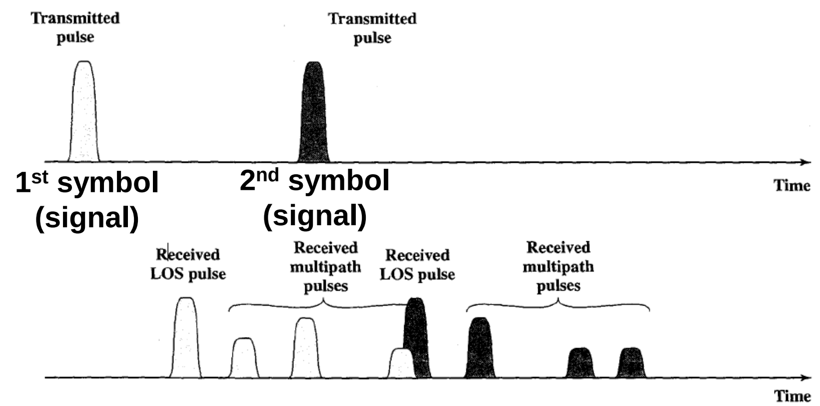
$$SNR_{dB} = 10\log_{10}\left(\frac{P_{Signal}}{P_{Noise}}\right)$$

- A **high SNR** means **a high-quality signal**.
- If the **SNR is low the Receiver** may not be able to decode the signal correctly (resulting in data losses).

Signal to Interference Plus Noise Ratio (SINR)

$$SINR_{dB} = 10\log_{10}\left(\frac{P_{Signal}}{P_{Noise} + P_{Interference}}\right)$$

- **SINR** is defined as **the power of a certain signal of interest** divided by **the sum of the interference power** (**from all the other interfering signals**) and **the power of the background Noise**.
- **Interference** typically refers to the **addition of unwanted signals to a useful signal** that **modifies**, or **disrupts** a signal as it travels along a channel between a source and a receiver.
  - **Co-Channel Interference** (i.e., interference caused from other channels that uses the same frequency band)
  - **Adjacent Channel Interference** (i.e., interference caused from other channels that uses the adjacent frequencies)
  - **Self-Interference: Inter-symbol Interference** and **Multipath (Fast) Fading** (i.e., interference caused by Multipath Propagation – due to **Delay Spread**)

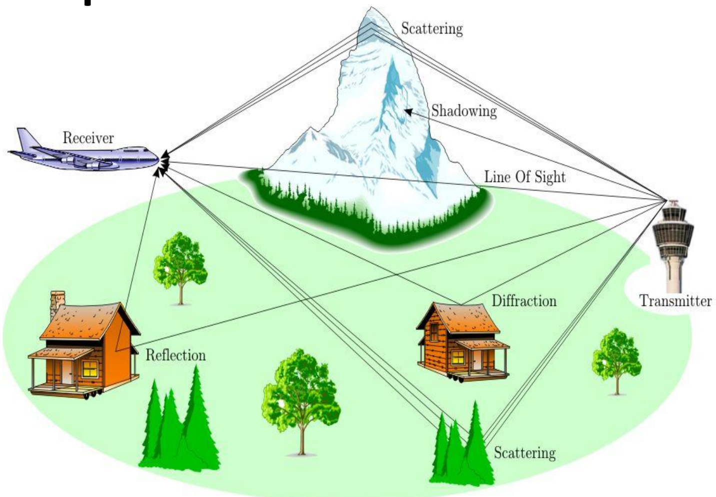


Radio Propagation
Ασύρματη Διάδοση Σήματος

- **Radio propagation** is the **behavior of radio waves** when they are transmitted, or **propagated from one point on the Earth to another**, into the atmosphere **(Ασύρματη Διάδοση** είναι η συμπεριφορά των σημάτων (ραδιοκυμάτων) καθώς διαδίδονται **ασύρματα** στην ατμόσφαιρα από ένα σημείο της γης σε ένα άλλο).
  - We will focus on how radio signals travel (propagate) from one **transmitting antenna** to **another receiving** antenna.

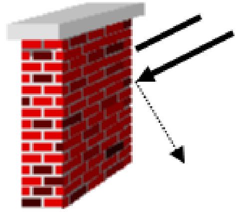
Radio Propagation
Ασύρματη Διάδοση Σήματος

- **Radio Propagation includes:**
  - **Line of Sight (LOS) Transmissions (**Υπάρχει γραμμή ορατότητας μεταξύ Transmitter και Receiver**):** There is a **direct path (**Υπάρχει απευθείας μονοπάτι**) between Transmitter** and **Receiver** (no obstacles in the way).
  - **Non-Line of Sight (NLOS) Transmissions (Δεν υπάρχει γραμμή ορατότητας μεταξύ Transmitter και Receiver)**: **Not a direct path (Δεν υπάρχει απευθείας μονοπάτι) between Transmitter** and **Receiver** (obstacles in the way). When the radio waves reach close to an obstacle (όταν τα ραδιοκύματα βρουν ένα εμπόδιο), the following **propagation phenomena** do occur to the waves:
    - **Shadowing (or blocking, Επισκίαση)**
    - **Refraction (Διάθλαση)**
    - **Reflection (Αντανάκλαση),**
    - **Diffraction (Περίθλαση),**
    - **Scattering (Διασκόρπιση)**

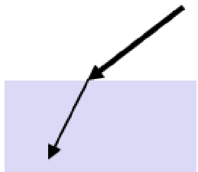


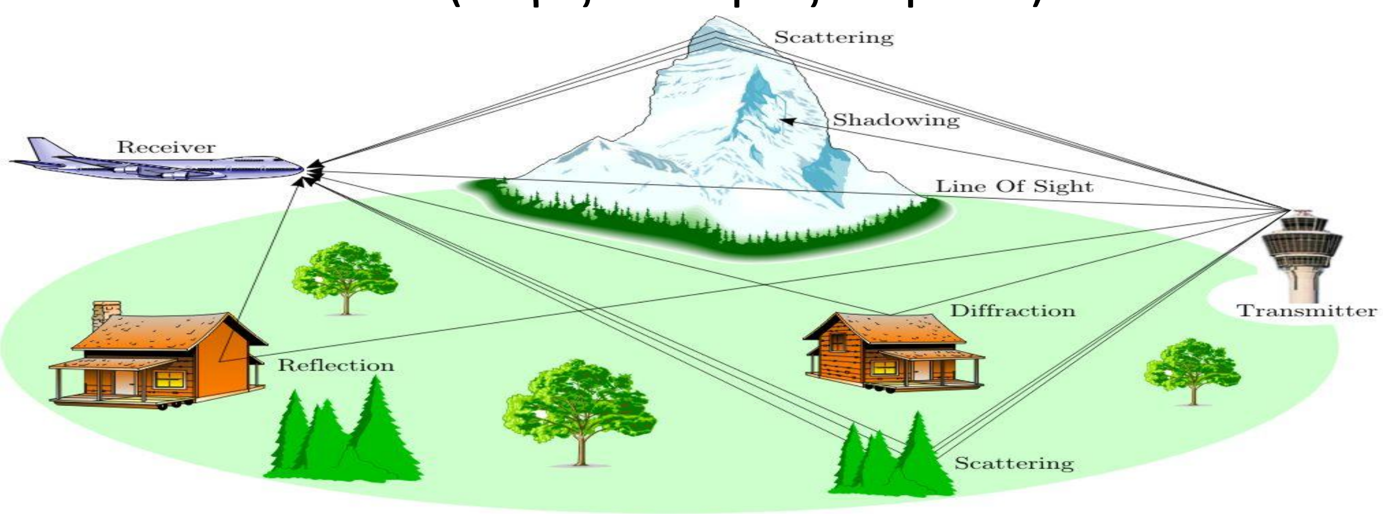
Radio Propagation Phenomena
Φαινόμενα Ασύρματης Διάδοσης

- **Radio Propagation Phenomena (I):**
  - **Shadowing (or blocking, επισκίαση):** The signal can be **blocked due to large obstacles**. The signal may not reach the Receiver.



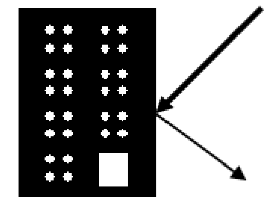
  - **Refraction (Διάθλαση):** Signals that travel **into a denser medium** (σε πιο πυκνό μέσο) not only become weaker (εξασθενούν) but also bents towards the medium (λυγίζουν προς το μέσο)



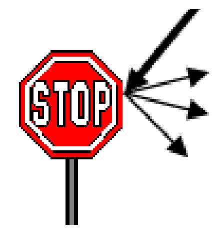


Radio Propagation Phenomena
Φαινόμενα Ασύρματης Διάδοσης

- **Radio Propagation Phenomena (II):**
  - **Reflection (Αντανάκλαση):** The signal can be reflected on buildings. The **reflected signal** is **not as strong as the original** as **objects can absorb some of the signal's energy** (Το ανακλώμενο σήμα δεν θα είναι τόσο δυνατό όσο το αρχικό επειδή κατά την ανάκλαση απορροφάται μερική από την ενέργεια του σήματος).

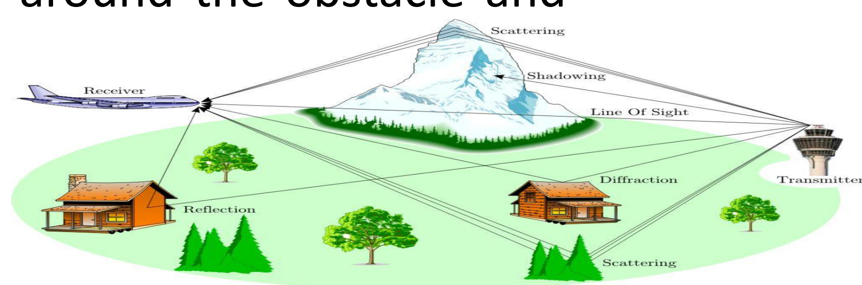


  - **Scattering (Διασκόρπιση)**: The incoming signal is **scattered into several weaker** outgoing signals**.**



  - **Diffraction (Περίθλαση):** Signals can be deflected (αποστρακίζονται) at the edge of a mountain (or other **surfaces with** sharp irregular edges) and **propagate in different directions** (Waves bend around the obstacle and move in different directions).

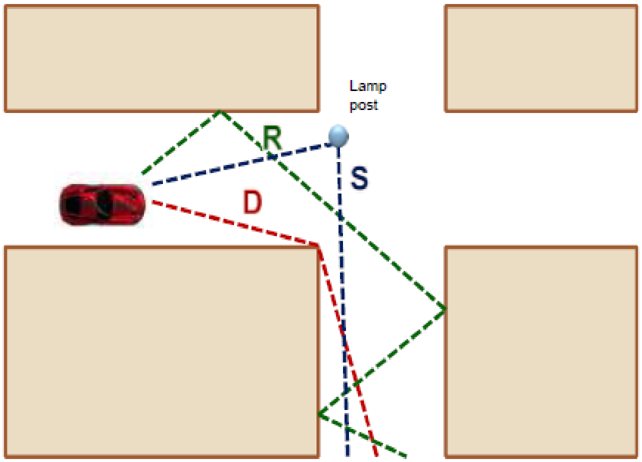
Reflection, Scattering and Diffraction helps transmitting a signal to the receiver if NLOS exists!



Radio Propagation Phenomena
Φαινόμενα Ασύρματης Διάδοσης

- **Reflection (Ανάκλαση)**: Occurs when a propagating electromagnetic wave meets **an object** that is **much larger than its wavelength** (συμβαίνει όταν το εμπόδιο έχει μέγεθος μεγαλύτερο από το μήκος του κύματος). - e.g., the surface of the Earth, buildings, walls, etc.

- **Scattering (Διασκόρπιση)**: Occurs when a propagating electromagnetic wave meets **an object that is smaller than its wavelength** (συμβαίνει όταν το εμπόδιο έχει μέγεθος μικρότερο από το μήκος του κύματος) - e.g., foliage, street signs, lamp posts.



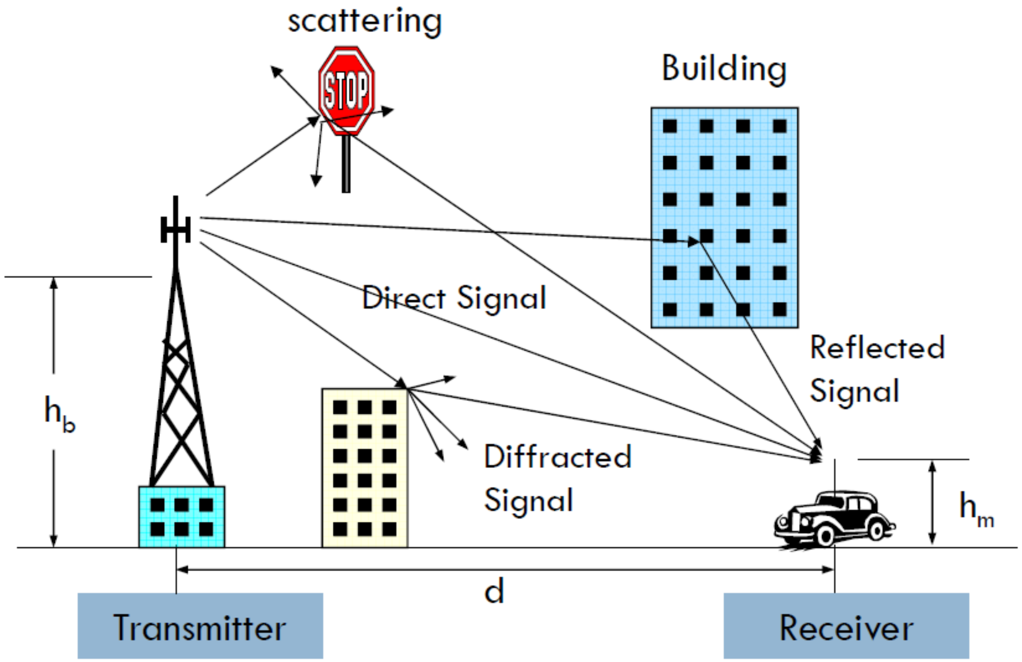
Reflection, Scattering and Diffraction leads to Multipath Propagation!!!

Οδηγούν στην Πολυδιαδρομική Μετάδοση!

Many copies of the same signal will reach the Receiver from many paths of different lengths!

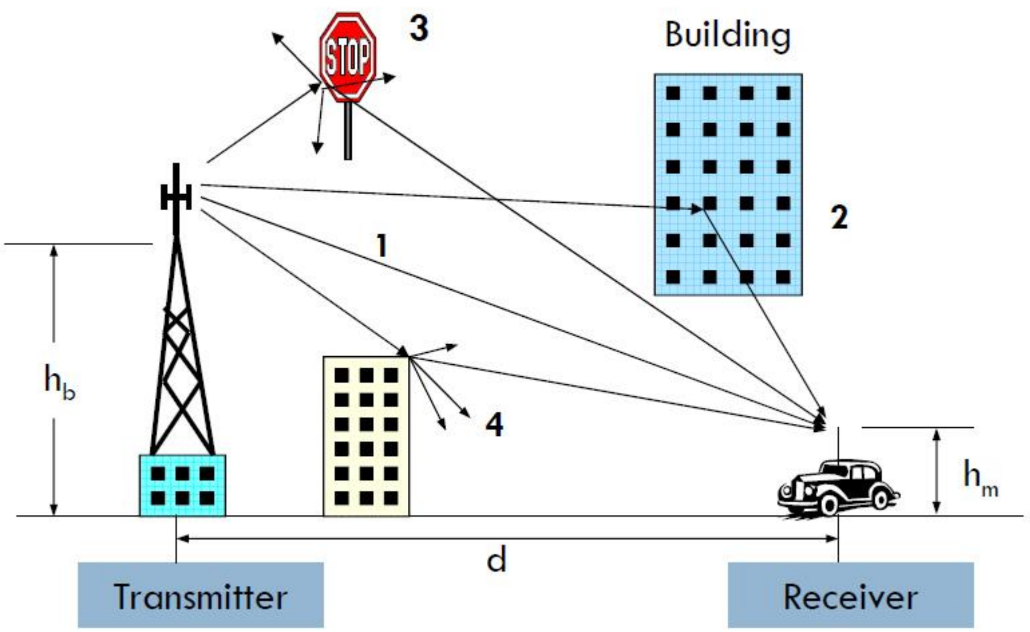
Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

- **Transmission paths** between **Sender** and **Receiver** could be:
  - **Direct Paths (Απευθείας Μονοπάτια)** → **LOS** between Transmitter and Receiver.
  - **Indirect Paths (Έμμεσα Μονοπάτια)** → Resulted by Scattering, Diffraction and Reflection by buildings, mountains, street signs, foliage, etc.



Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

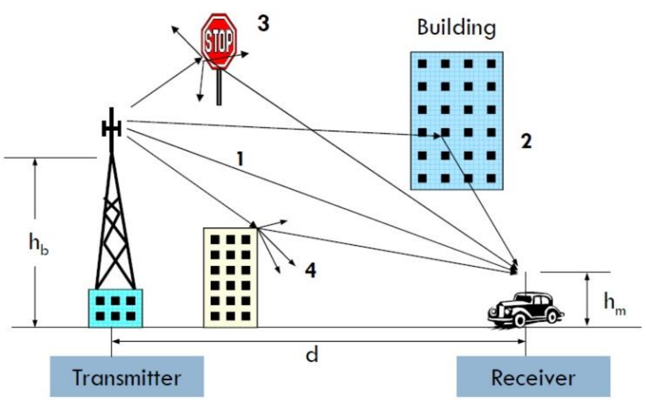
- **Thus, the Received signal** is **made up of several paths** which can be classified as:
  1. **Direct Path**
  2. **Reflected Path**
  3. **Scattered Path**
  4. **Diffracted Path**



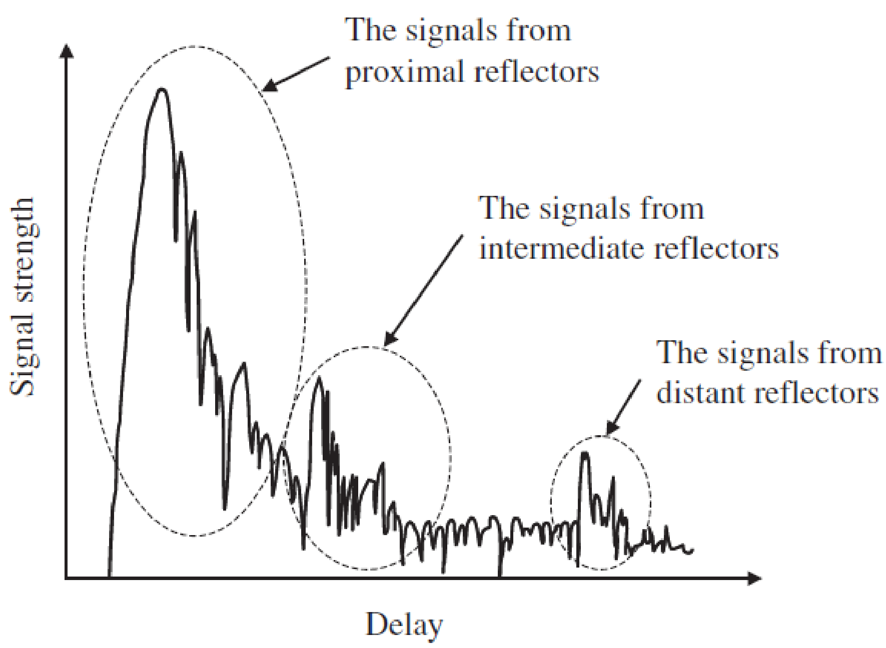
- In this case, **the Receiver** will receive **four different copies** of the **same signal (due to Multipath Propagation).**

Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

- **Since each path has a different path length, the time of arrival of each copied signal at the Receiver is different causing the Delay Spread phenomenon.**



Receiver



Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

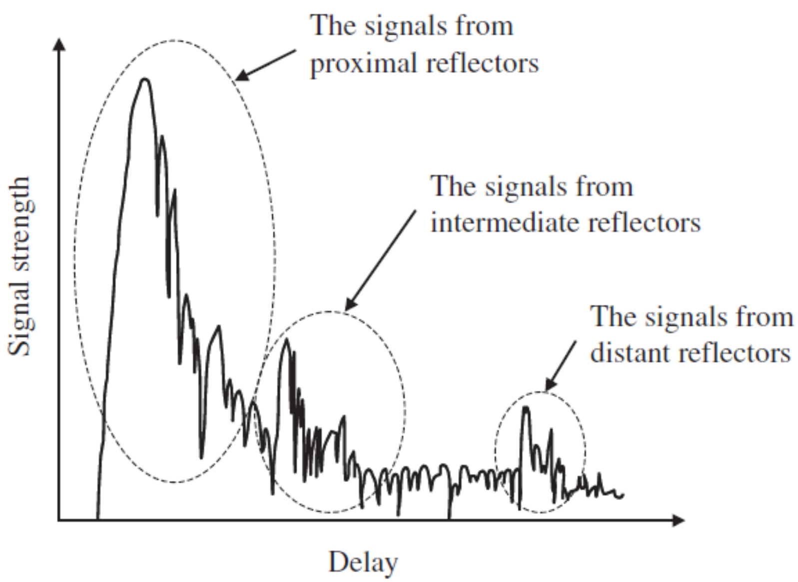
- **Multipath Propagation** results in:
  - **Delay Spread (**Διασκόρπιση σήματος λόγω καθυστερημένων μονοπατιών**)**
  - **Multipath Fading** (referred also as **Fast Fading**) (Ξεθώριασμα σήματος λόγω **constructive (εποικοδομητική)** or **distractive (καταστροφική) interference που προκαλείται από** τα πολλαπλά (καθυστερημένα) μονοπάτια που ακολουθεί το σήμα από τον Transmitter για να φτάσει στον Receiver)
  - **Inter-Symbol Interference (ISI) (**Παρεμβολές μεταξύ δύο διαφορετικών σημάτων/συμβόλων τα οποία στέλνονται στο ίδιο κανάλι (από τον Transmitter στον Receiver), με μια μικρή διαφορά χρόνου.

Although the effects caused, Multipath Propagation is what makes reception of the signal in Non Light Of Sight Conditions possible!!!

Παρά τις επιπτώσεις της, είναι η Πολυδιαδρομική Διάδοση που κάνει δυνατή τη διάδοση του σήματος σε περιπτώσεις που δεν υπάρχει γραμμή ορατότητας μεταξύ του Transmitter και του Receiver!!!

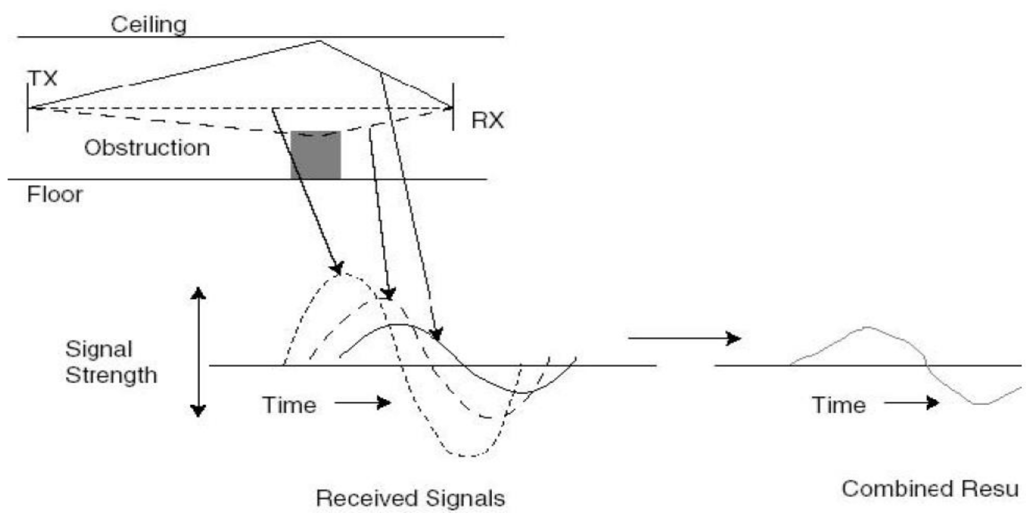
Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

- **Delay Spread**
  - When a signal propagates from a transmitter to a receiver, **the signal suffers one or more reflections (το σήμα ανταναλάται αρκετές φορές)**.
    - This forces radio signals to **follow different paths** (Multipath Propagation).
  - Since each path has a **different path length**, **the time of arrival** for **each path** is **different**.
  - The spreading out effect of the signal (Το αποτέλεσμα αυτό της διασποράς του σήματος) is called "**Delay Spread**."
  - The **Delay Spread** is what it **causes** **the** **Multipath Fading** and **InterSymbol Interference**.



Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

- **Multipath Fading (Known also as Fast Fading)**
  - Each signal copy will experience **differences in attenuation (εξασθένιση)**, **delay**, and **phase shift** while traveling from the source to the receiver.
  - At **the receiver**, these signals **will be combined** (θα προστεθούν), resulting in either **constructive (εποικοδομητική)** or **distractive (καταστροφική) interference**, **amplifying** or **attenuating** (ενισχύοντας είτε εξασθενώντας) the signal power **seen at the receiver**.



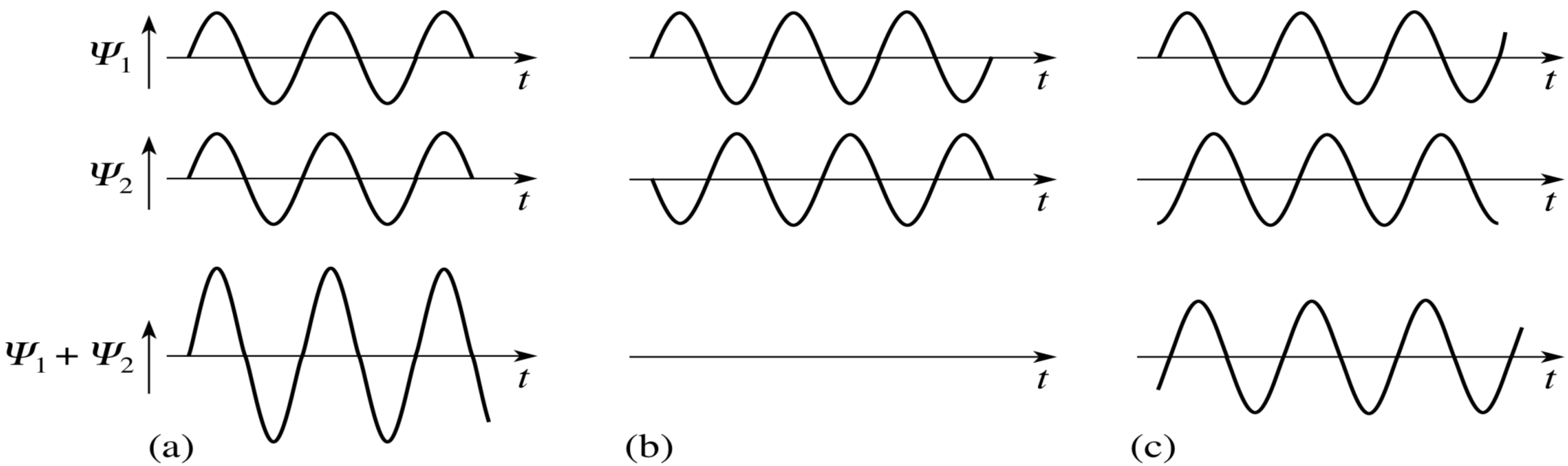
Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

- ***Multipath Fading - Signal Properties, the phenomenon of interference***
  - When two or more waves propagates at the same space using the same frequency band, the **net amplitude at each point** is **the sum of the amplitudes** of the **individual waves (i.e., these two waves are combined)**.

Constructive Interference
Signals are in phase

Destructive Interference
Signals are completely out of phase

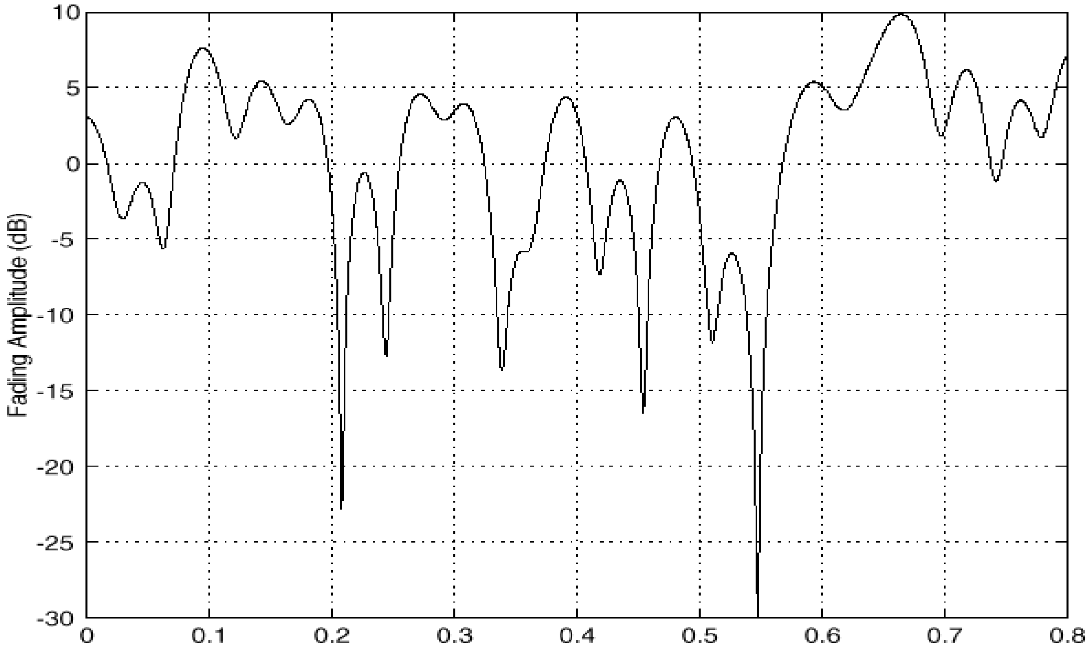
Signals are slightly out of phase



Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

- **Multipath Fading (Known also as Fast Fading)**
  - **Strong destructive interference** (Δραστικά καταστροφικές παρεμβολές) is frequently referred to as a **deep fade** (προκαλούν μεγάλη εξασθένιση στο σήμα) and may result in **temporary failure of communication** (προσωρινή αποτυχία της επικοινωνίας) due to a **severe drop** in the channel **Signal to Interference plus Noise (SNIR) ratio**.

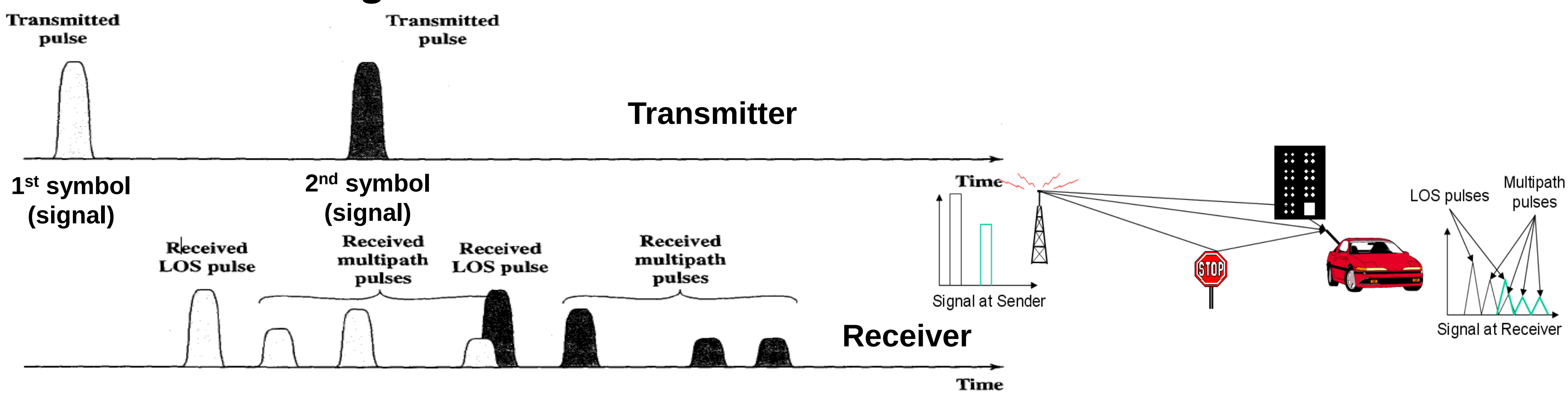
SINR



Multipath Propagation Effects
Επιπτώσεις Πολύδιαδρομικής Διάδοσης

Inter-Symbol Interference (ISI)

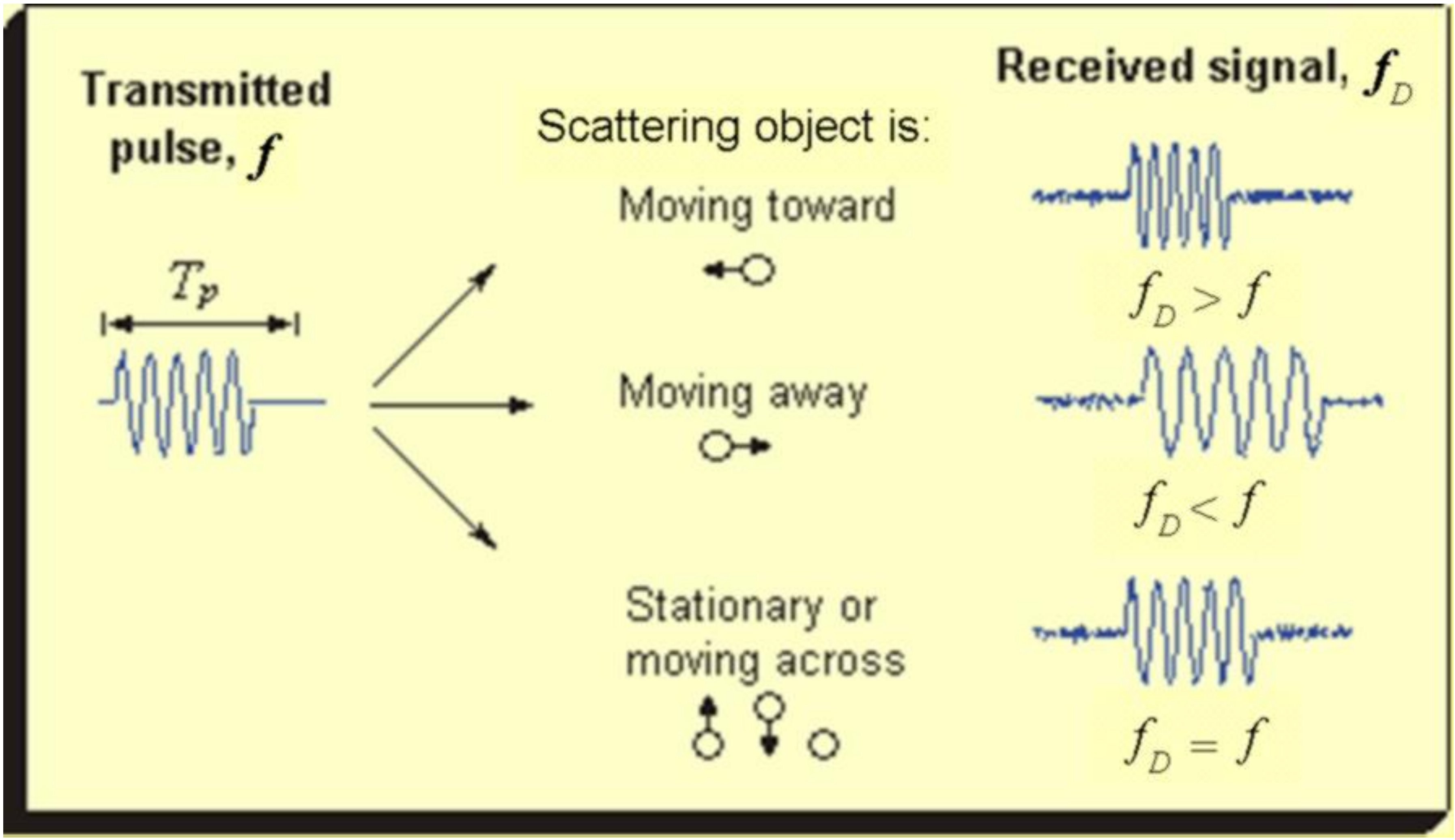
- Due to **Delay spread**, the **energy indented for one symbol splits over to an adjacent symbol (**Η ενέργεια που προοριζόταν για ένα σήμα, διασκορπίζεται και ένα μέρος της συμπίπτει με την ενέργεια ενός άλλου σήματος**)** (appeared as Noise).
- Due to this interference, the **signals of different symbols can cancel each other out** (σήματα διαφορετικών συμβόλων μπορούν να εξουδετερωθούν μεταξύ τους), leading to **misinterpretation (παρερμήνευση)** at the **receivers** and **causing errors during decoding.**



Doppler Effect

- The **Doppler effect** (or **Doppler shift**) is the **change in the frequency** (and thus the wavelength) of a wave for an observer (i.e., Mobile Station (MS)) moving relative to its source (i.e., Base Station (BS)) **(**Είναι η **αλλαγή στη συχνότητα του σήματος** που διακρίνει ένας **κινούμενος παρατηρητής κινούμενος** σε **σχέση με την πηγή** του σήματος)**.**
- In a wireless and mobile system, the location of the **BS is fixed** while the **MSs are mobile**.
  - Therefore, **as the receiver (i.e., the MS) is moving** with respect to the wave source (i.e., the BS), **the frequency of the received signal** will **not be the same as the one transmitted by the source** (ο receiver θα αντιλαμβάνεται διαφορετική συχνότητα από εκείνη που εκπέμπεται από τον Transmitter).
  - Compared to the **emitted frequency** (Συγκριτικά με την εκπεμπόμενη συχνότητα), the **received frequency** is **higher during the approach (προσέγγιση)** and **lower during the recession** (απομάκρυνση) from the source.
  - Also, the **speed (v)** of the receiver and its **direction (θ)** relative to the source, matters.

Doppler Effect



Doppler Effect

- The **frequency (f_r) that the moving user (the Receiver) will** experience is $f_r = f_c + f_d$

Where: f_c is the **emitted (from the source) radio wave carrier frequency** and
f_d is the Doppler frequency or **Doppler shift**

- **Doppler frequency** or **Doppler shift** is $$f_d = \frac{v}{\lambda}\cos\theta$$

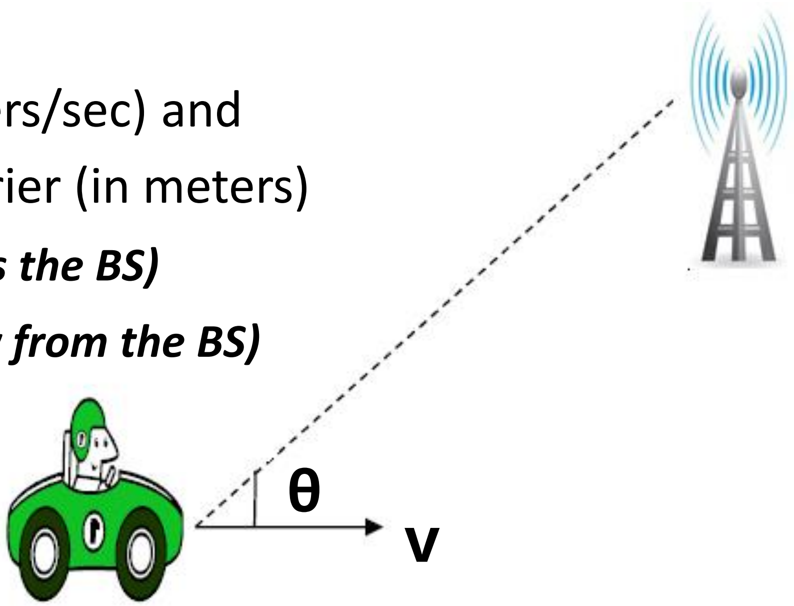
Where: f_d *is measured in Hertz*

v is the moving speed (in meters/sec) and

λ is the wavelength of the carrier (in meters)

When θ = 0º (MS moving towards the BS)

When θ = 180º (MS moving away from the BS)



Doppler Effect

$$f_d = \frac{v}{\lambda}\cos\theta$$

An example:

***Radio wave Carrier Frequency (f_c)** = 100 MHz (100,000,000 Hz)*

→ ***Wavelength (λ)** = C / f = 300,000,000 / 100,000,000*

→ ***λ = 3 meters***

***Speed of the User (v) 60 Km/h** → **v =** 16.6666666 meters/second*

*We assume that **the MS is moving towards the source** (θ = 0^o)*

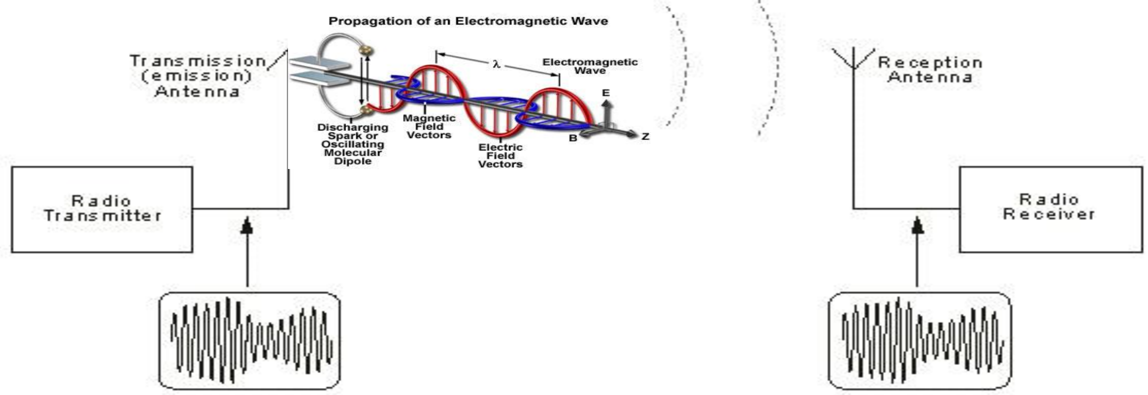
f_d ***= (16.66666666/3) cos 0^o →*** f_d ***= 5.5544Hz***

$f_r = f_c + f_d$ ***=100,000,000 Hz + (5.5544Hz) →*** f_r ***= 100,000,005.55 Hz***

Antennas

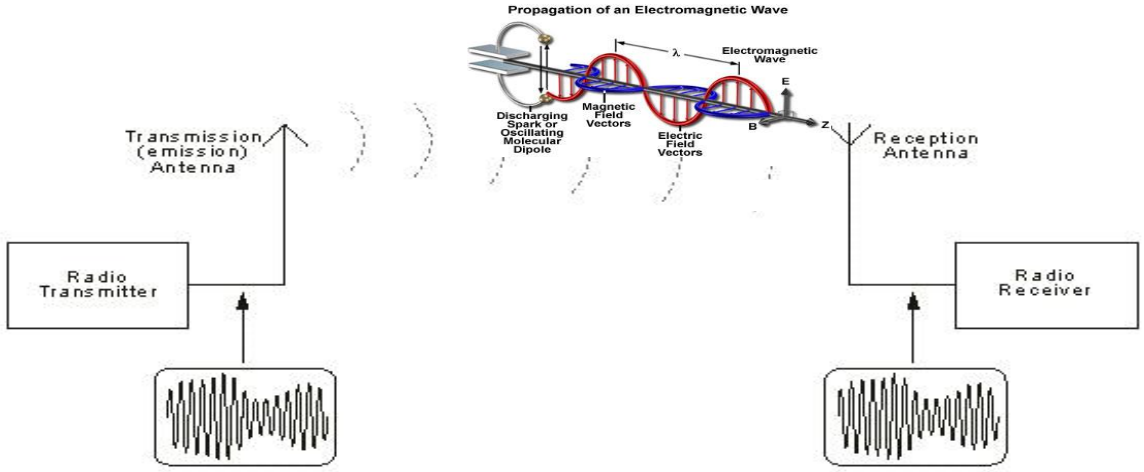
- The **first antennas** were built in 1888 by German physicist **Heinrich Hertz** in his pioneering experiments to **prove the existence of electromagnetic waves**.
- An antenna is an electrical device which converts **oscillating electric currents** into **radio waves** (μετατρέπει ταλαντευόμενα ηλεκτρικά φορτία σε ραδιοκύματα), and vice versa.
  - **Transmission**: Radiates (εκπέμπει) electromagnetic energy into space.
  - **Reception**: Collects electromagnetic energy from space.
- In two-way communication, the same antenna can be used both for Transmission and Reception.

Antennas



- Typically an antenna consists of an arrangement of **metallic conductors** (**"antenna elements"**) (**μια διάταξη μεταλλικών αγωγών**), **electrically connected (using a cable)** to the Receiver or the Transmitter.
- In **Transmission:**
  - The **Radio Transmitter applies** a **modulated oscillating electric current** to the antenna.
  - This **oscillating electric current** will create an **oscillating magnetic field** around the **antenna elements**, while **the charge of the electrons (το φορτίο των ηλεκτρονίων)** also creates an oscillating **electric field** along the elements.
  - These time-varying fields (μεταβαλλόμενα στο χρόνο πεδία) **radiate away from the antenna** into space **as a moving electromagnetic wave** (radio waves).

Antennas



- In **Reception:**
  - **During Reception**, the **oscillating electric** and **magnetic fields** of an incoming radio wave **exert force on the electrons (ασκούν μια δύναμη στα ηλεκτρόνια) in the antenna elements**, causing them to **move back and forth**, creating **oscillating electric currents in the antenna**
  - The produced **oscillating electric current** is **applied to the Radio Receiver to be amplified and demodulated** so as to **extract the information included**.

Antennas

- According to their **applications** and **technology available**, antennas generally fall in one of **two categories (Omni-Directional and Directional)**:
  - **Omni-directional (Όμοιο-κατευθυντικές)** which **receive or transmit (radiate) radio waves equally more or less in all directions (Two types are the Isotropic** (Ισοτροπικές κεραίες) and **Dipoles** (Κεραίες Διπόλων)**)**.

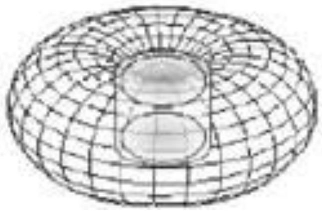
    - Employed when **the relative position of the other station is unknown or arbitrary (αυθαίρετη, τυχαία)**.
    - Omni-directional antennas have **shorter range (μικρότερη εμβέλεια) than Directional antennas**, but the **orientation (προσανατολισμός) of the antenna** is relatively **inconsequential (ασήμαντος)**.

Antennas

- **Isotropic** Antenna **(Ισοτροπική κεραία)**
  - Εκπέμπει το σήμα με την ίδια δύναμη σε όλες τις κατευθύνσεις (σφαιρικά)
- **Dipole Antenna (Κεραίες Διπόλων)**
  - Οι κεραίες διπόλων έχουν ένα διαφορετικό διάγραμμα ακτινοβολίας συγκρινόμενες με μια ισοτροπική κεραία.
  - Το **διάγραμμα ακτινοβολίας διπόλων** είναι **360^o στο οριζόντιο επίπεδο** και συνήθως περίπου **75^o στο κάθετο επίπεδο** (υποθέτοντας φυσικά ότι το δίπολο στέκεται κατακόρυφα)

Radiation Pattern
Διάγραμμα Ακτινοβολίας

Isotropic

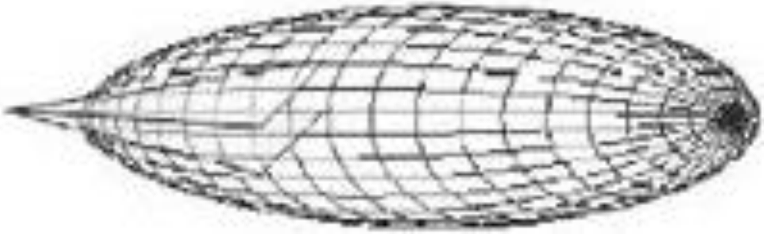


Dipole

Antennas

- **Directional** antennas (Κατευθυντικές Κεραίες) **transmit (εκπέμπουν) radio waves in a particular direction covering a specific sector** and **receive radio waves from that direction/sector only**.
  - Directional antennas have the advantage of **longer range (μεγαλύτερη ραδιοκάλυψη)** and **better signal quality (καλύτερο σήμα)**, but **must be aimed carefully in a particular direction**

Radiation Pattern
Διάγραμμα Ακτινοβολίας



Directional Antenna

Antennas

- For example:
  - **Directional antenna**: A dish antenna (receiving a TV signal) must be pointed to the satellite to be effective.
  - **Omnidirectional antenna (isotropic or dipole)**: A typical Wi-Fi antenna in a smartphone (isotropic) or in an Access Point (isotropic or dipole). As long as the Base Station is within range, the antenna can be in any orientation in space.

Modulation for Wireless

Digital Modulation

- The **modulation** that will be applied on the (analog) **carrier signal to include the data that will be carried (e.g., 1 or 0, etc.)** are **chosen** from a **finite number** of **M alternative symbols (or signal units** or **signal elements) based on the Digital Modulation Technique** and the ***Modulation Alphabet*** **that will be used**. (Η διαμόρφωση που θα γίνει στον (αναλογικό) μεταφορέα σήματος για να συμπεριλάβουν την πληροφορία που θα μεταφερθεί (π.χ., 1 ή 0) επιλέγονται από ένα πεπερασμένο αριθμό από εναλλακτικά σύμβολα (σήματα) ανάλογα με την **Τεχνική διαμόρφωσης και** το ***Αλφάβητο Διαμόρφωσης*** που θα χρησιμοποιηθεί.
  - Symbol Pattern 1 → 0
  - Symbol Pattern 2 → 1
- This **same Modulation Alphabet** have to be **used both** from the **Transmitter** (for modulating the signal) **and the Receiver** (for demodulating the signal)

Digital Modulation

- The general form (pattern) of the modulated signal is (Η γενική μορφή ενός διαμορφωμένου σήματος):

$$s(t) = A(t)\sin(2\pi \times (f_c + f_m(t))\, t + \phi(t)$$

Digital Modulation

- **The three essential parameters that can be modulated (**Οι τρείς βασικές παράμετροι που μπορούμε να διαμορφώσουμε**)**

$$s(t) = A \sin(2\pi f t + \phi)$$

  - Amplitude value (**A**) — **ASK** (Amplitude Shift Keying)
  - Frequency value (**f**) — **FSK** (Frequency Shift Keying)
  - Phase value (**ϕ**) — **PSK** (Phase Shift Keying)

- **Digital modulation**: Amplitude (***A***), frequency (***f***) and Phase (ϕ) are used to represent a **digital state**. (Στην Ψηφιακή διαμόρφωση το **πλάτος**, η **συχνότητα**, και η **φάση** του σήματος χρησιμοποιούνται για να αναπαραστήσουν μία **ψηφιακή κατάσταση ή τιμή**)

Basic Digital Modulation Techniques

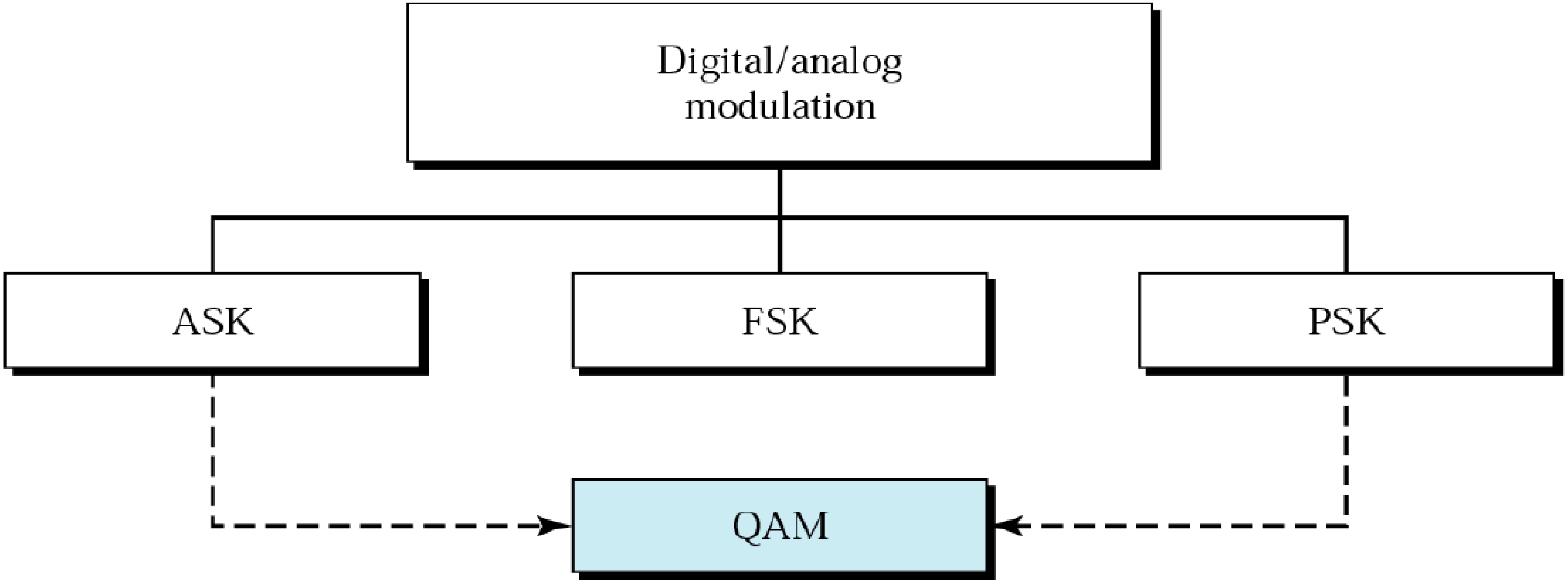
- **Basic Digital Modulation Techniques** work by **varying** the **Amplitude**, **Frequency** or **Phase** (**or a combination of them**) of **a sinusoidal carrier wave** depending on the **information (data)** that will be transmitted and the **Modulation Alphabet** that will be used.

  - **ASK**: Amplitude Shift Keying $s(t) = A \sin(2\pi f t + \phi)$
  - **FSK:** Frequency Shift Keying $s(t) = A \sin(2\pi f t + \phi)$
  - **PSK:** Phase Shift Keying $s(t) = A \sin(2\pi f t + \phi)$
  - **Quadrature Amplitude Modulation (QAM)** or **Amplitude Phase Shift Keying (APSK)**

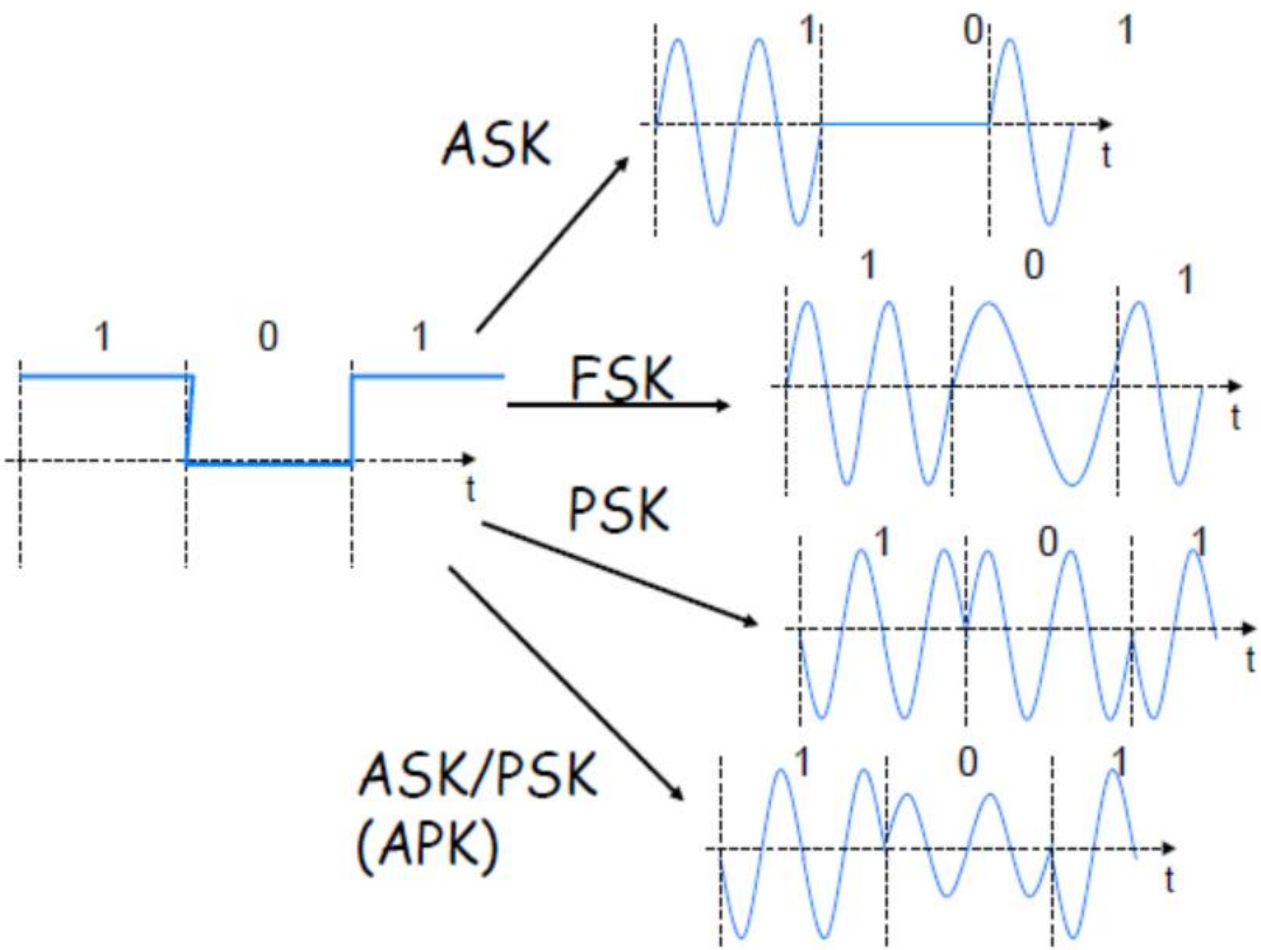
$$s(t) = A \sin(2\pi f t + \phi)$$

Basic Digital Modulation Techniques

- Types of Digital to Analog Modulation



Basic Digital Modulation Techniques Illustration



$A(t).\sin[2.\pi.f_c.t]$

$\sin[2.\pi.(f_c+f_m(t)).t]$

$\sin[2.\pi.f_c.t + \theta(t)]$

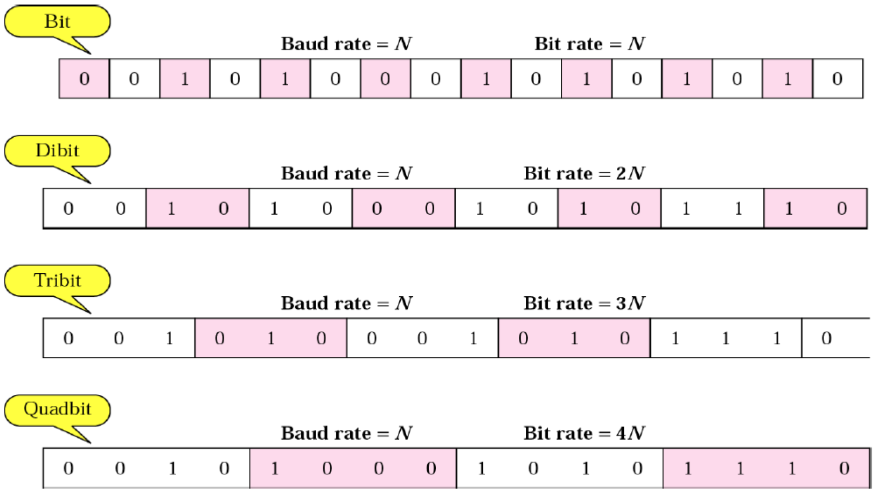
$A(t).\sin[2.\pi.f_c.t + \theta(t)]$

Bit Rate and Baud Rate

- **Bit Rate** is the **number of bits (data) that can be carried per second**.
- **Baud Rate** is the **number** of **signal units (or symbols) per second used for carrying the bits (and achieve the Bit Rate).**
  - **Baud Rate** can be **less than** or **equal** to the **bit rate** → Note that **each symbol can carry one or more bits!**
  - **Baud Rate** is important in **Bandwidth efficiency**.
    - Baud rate **determines the bandwidth required** to send the **message signal (**Καθορίζει το εύρος ζώνης που απαιτείται για να σταλεί μήνυμα**)**
    - **Baud Rate = Bit Rate / Number of Bits per Symbol**
    - Thus, the **lower the Baud Rate (symbols/second)** the **less the bandwidth required**
  - **The number of bits that can be carried by one Symbol**, depends on the **Modulation Technique used**.
    - The **Baud Rate** depends on the **type of Modulation** used.

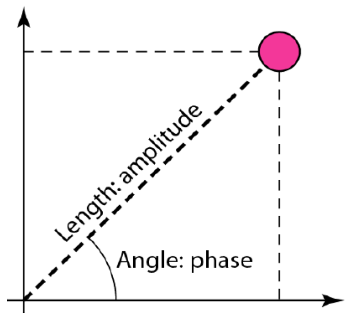
Bit Rate and Baud Rate Examples

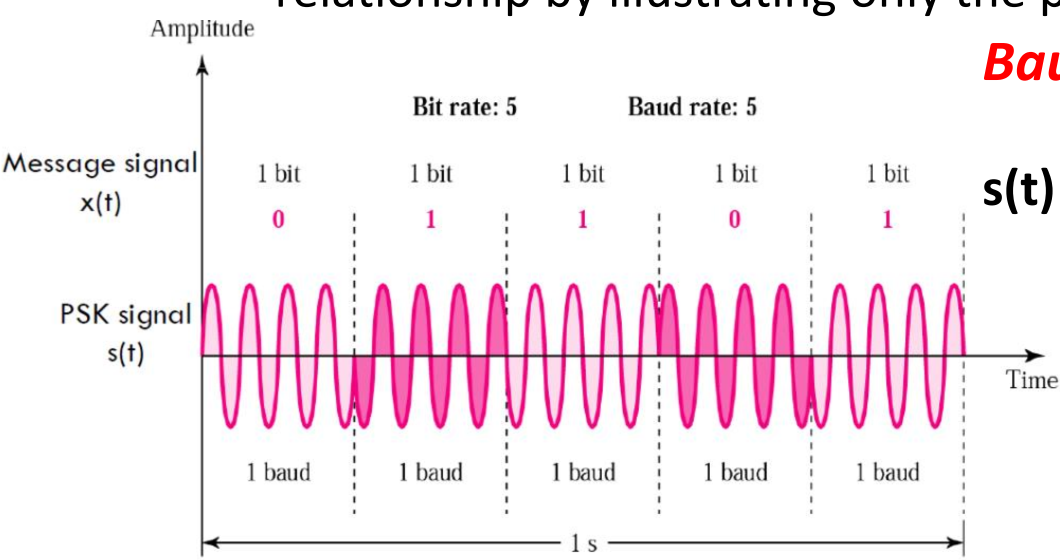
- **Example 1**: A modulated signal **carries 4 bits** in **each signal unit (i.e., symbol)**. If **1000 signal units (symbols)** are sent per second, find the Baud Rate and the Bit Rate
  - **Baud Rate** = **1000 baud/s**
  - **Bit Rate** = 1000 x 4 = **4000 bps**
- **Example 2:** The **bit rate** of a modulated signal is **3000 bps**. If each **signal unit** carries **6 bits**, what is the baud rate?
  - **Baud Rate =** 3000/6 = **500 (baud/s)**
- **Example 3**: A modulated signal has a **bit rate of 8000 bps** and a baud rate of **1000 baud**. How many bits are carried by each signal element?
  - **Bits/Baud** = **8000/1000 = 8**



Phase Shift Keying (PSK)

- The **phase of the carrier signal** is varied to represent digital data (binary 0 or 1), i.e., **Binary PSK (BPSK)**
- Both **peak amplitude** and **frequency remain constant** as the phase changes.
- **Phases are separated by 180 degrees.**
  - If we start with a **phase of 0º** to represent **bit 0**, then we can change the **phase to 180º** to send **bit 1** (or inversely).
  - The **Constellation** or **phase-state Diagram** shows the relationship by illustrating only the phases.



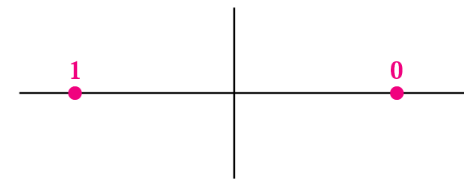


Baud Rate = Bit Rate

$$s(t) = \begin{cases} A \sin(2\pi f t + 0^o) & 0 \\ A \sin(2\pi f t + 180^o) & 1 \end{cases}$$

Bit	Phase
0	0
1	180

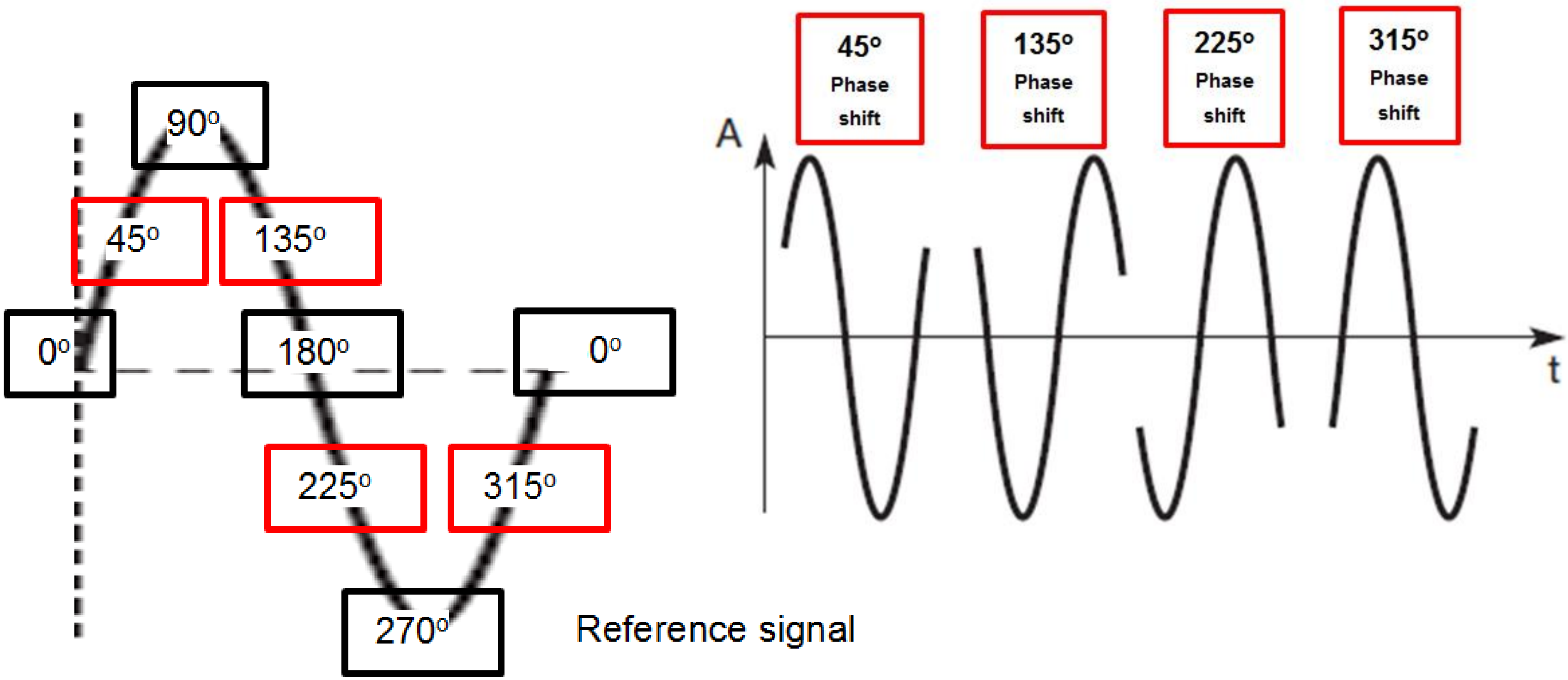
Bits



Constellation diagram

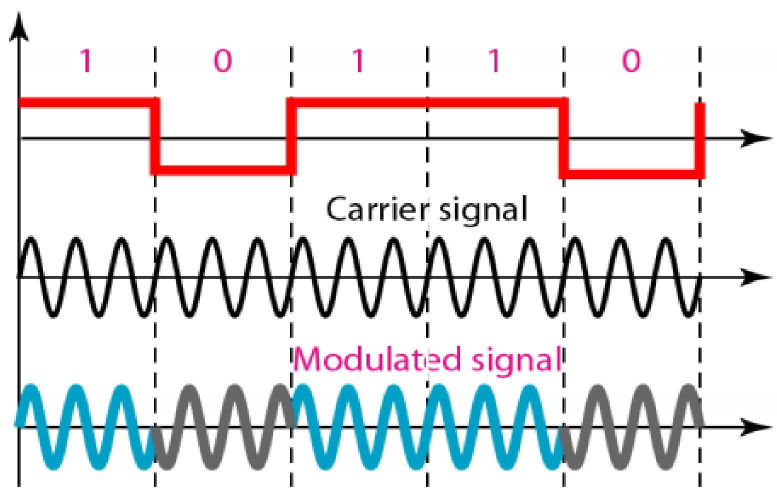
Phase Shift Keying (PSK)
Phase Shifts Examples

- **Phase Shifts Example**



Phase Shift Keying (PSK)

- PSK is **not susceptible to noise degradation** that affects **ASK, neither has the limitation of FSK that needs to repeatedly tune at different frequencies (i.e., no need for filtering the signal of different frequencies → simpler demodulator needed).**
- **Simple to implement**, and is used extensively in wireless communication.



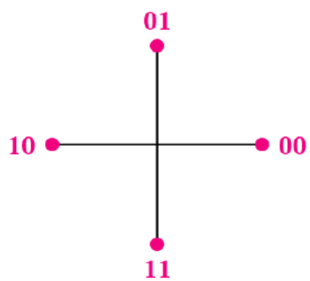
Quadrature Phase Shift Keying (QPSK)

- **QPSK** refers to **PSK with 4 states**.
- The "Q - *Quadrature*" in QPSK refers to **four phases** in which **a carrier is modulated and send in QPSK**. Also, called **4-PSK**.
- Because QPSK has **4 possible states**, QPSK can encode **two bits per symbol**.
  - Because **2 bits are allocated to each symbol**, QPSK can achieve **twice the Data Rate** of a **comparable BPSK** scheme **for a given bandwidth.**

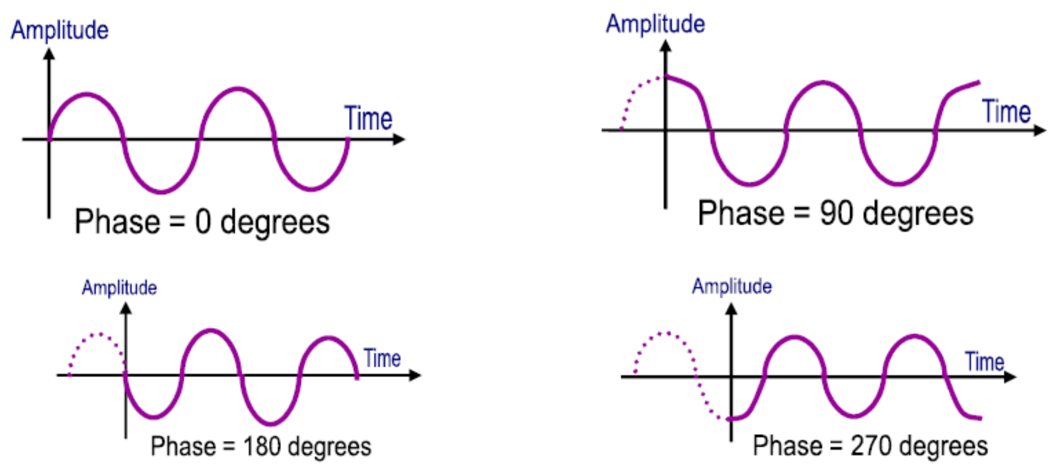
Example: Relationship between different phases:

Dibit	Phase
00	0
01	90
10	180
11	270

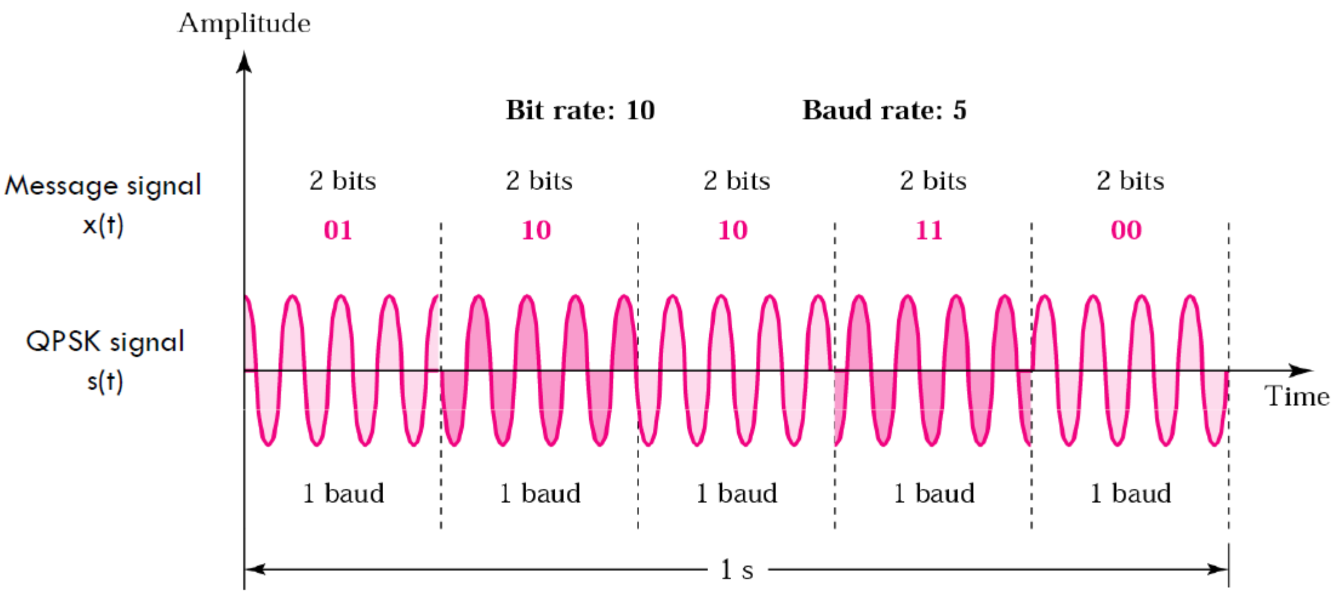
Dibit
(2 bits)



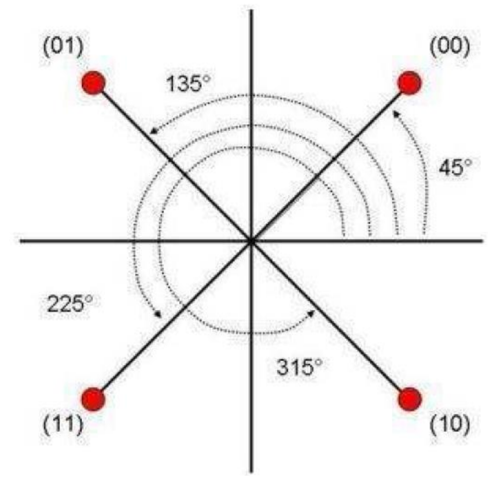
Constellation diagram



Quadrature Phase Shift Keying (QPSK)



Phase	Data
45	00
135	01
225	11
315	10



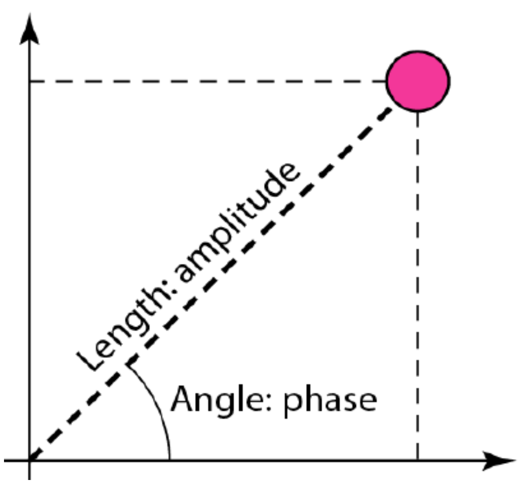
Two Modulation Alphabets

$$s(t) = \begin{cases} A \sin(2\pi f t + \phi_1) \\ A \sin(2\pi f t + \phi_2) \\ A \sin(2\pi f t + \phi_3) \\ A \sin(2\pi f t + \phi_4) \end{cases}$$

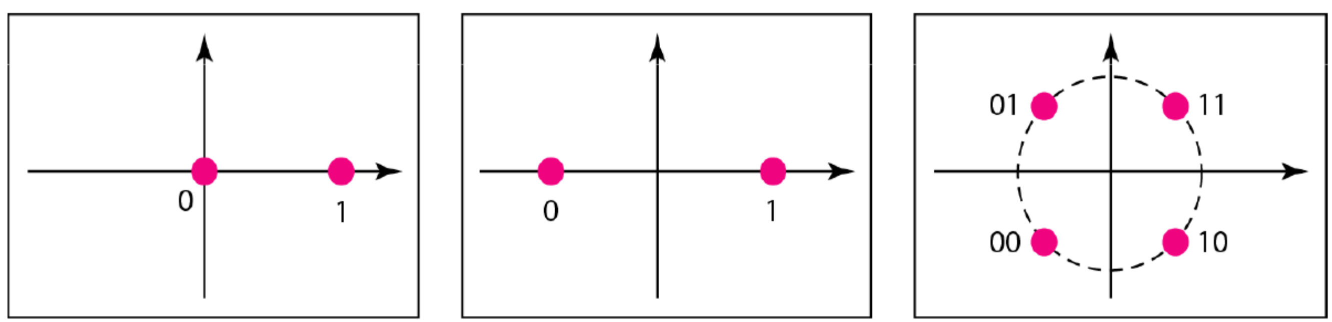
$$\begin{cases} \phi_1 = 0^o \\ \phi_2 = 90^o \\ \phi_3 = 180^o \\ \phi_4 = 270^o \end{cases} \quad \text{OR} \quad \begin{cases} \phi_1 = 45^o & 00 \\ \phi_2 = 135^o & 01 \\ \phi_3 = 225^o & 10 \\ \phi_4 = 315^o & 11 \end{cases}$$

Constellation Diagrams
Διαγράμματα Αστερισμού

- It is a **convenient way** to **represent the symbols (define the amplitude and phase)** of the **Modulation Alphabet** that will be used for **modulating signal carrier** and **transmitting the signal**. (Είναι ένας εύκολος τρόπος για να αναπαραστήσουμε **τα σύμβολα του Αλφαβήτου Διαμόρφωσης** που θα χρησιμοποιηθούν για τη διαμόρφωση του μεταφορέα σήματος για την αποστολή του σήματος)



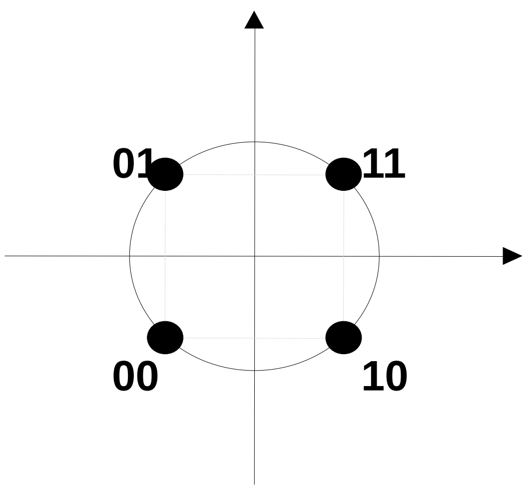
Examples:



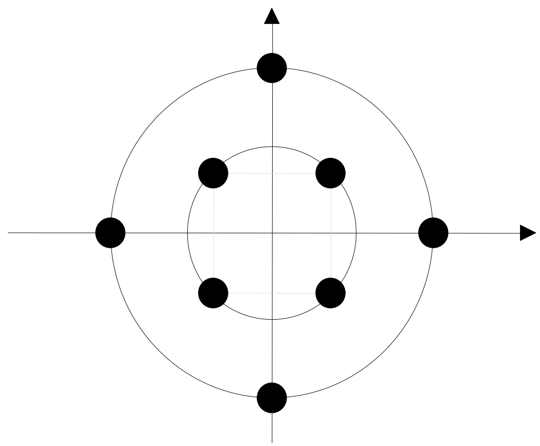
a. ASK (OOK) b. BPSK c. QPSK

Constellation Diagrams
Circular Constellation Diagrams

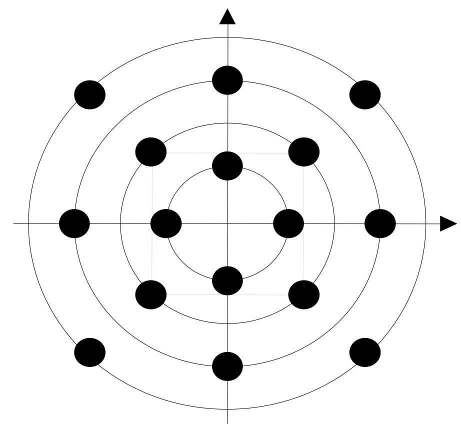
Examples:



(a) Circular 4-QAM



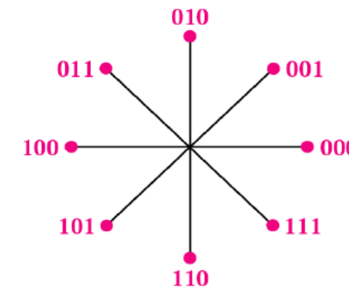
(b) Circular 8-QAM



(c) Circular 16-QAM

Higher Order Modulation: 8-PSK

- We **can extend the Modulation Alphabet**, by varying the **signal by shifts of 45º** (instead of 90º in QPSK). (Μπορούμε να επεκτείνουμε το Αλφάβητο Διαμόρφωσης με το μεταβάλλουμε το σήμα με μετατοπίσεις 45º παρά 90º όπως το QPSK)
- With 8 (2^3) different phases, each phase (i.e., signal unit or symbol) can represent **3 bits.**



Constellation diagram

Baud Rate = Bit Rate/3 → Reduces the Required Bandwidth to one third

$$s(t) = \begin{cases} A\sin(2\pi f t + \phi_1) & 000 \\ A\sin(2\pi f t + \phi_2) & 001 \\ A\sin(2\pi f t + \phi_3) & 010 \\ A\sin(2\pi f t + \phi_4) & 011 \\ A\sin(2\pi f t + \phi_5) & 100 \\ A\sin(2\pi f t + \phi_6) & 101 \\ A\sin(2\pi f t + \phi_7) & 110 \\ A\sin(2\pi f t + \phi_8) & 111 \end{cases}$$

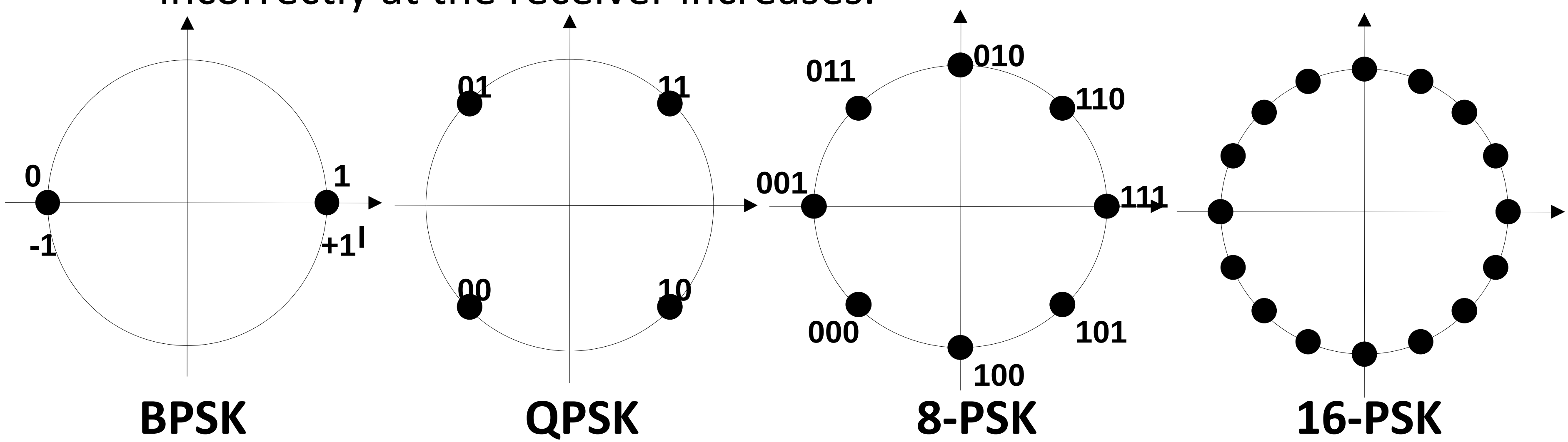
$$\begin{cases} \phi_1 = 0^o \\ \phi_2 = 45^o \\ \phi_3 = 90^o \\ \phi_4 = 135^o \\ \phi_5 = 180^o \\ \phi_6 = 225^o \\ \phi_7 = 270^o \\ \phi_8 = 315^o \end{cases}$$

Using the Constellation Diagram we can easily produce the Modulation Alphabet

Tribit	Phase
000	0
001	45
010	90
011	135
100	180
101	225
110	270
111	315

Higher Order Modulation: M-PSK

- Obviously **the** **bandwidth efficiency** of a M-ary PSK scheme increases as **M (the number of possible states) increases** because **more bits per symbol can be sent**
- ...however **the distance between 2 points** in the **constellation** is **reduced** and therefore the possibility for decoding the symbol incorrectly at the receiver increases.



- As M increases, **the** **bandwidth efficiency** **increases** but the **waveform energy (i.e., the transmission power used to send the symbol)** must **be increased to keep the BER at a certain level**.

Quadrature Amplitude Modulation (QAM) – Phase and Amplitude Modulation

- **PSK is limited** by the ability of the equipment to **distinguish between small differences in phases**.
  - Limits the potential data rate. (Περιορίζει το πιθανό data rate)
- The principle of **Quadrature Amplitude Modulation** (QAM) or **Amplitude Phase Shift Keying** (APSK) is to have **X possible variations** in **Phase** (X πιθανές διαφορετικές φάσεις) and **Y possible variations** of **Amplitude** (Y πιθανά διαφορετικά πλάτη) .
  - Up to **X • Y** possible variations → **More different states** that the **carrier signal can be modulated**, therefore **more bits can be carried per symbol →** Therefore greater Data Rates and Throughput.
  - **QAM (or APSK) is an application of ASK to PSK (**Εφαρμογή του ASK πάνω στο PSK**)**

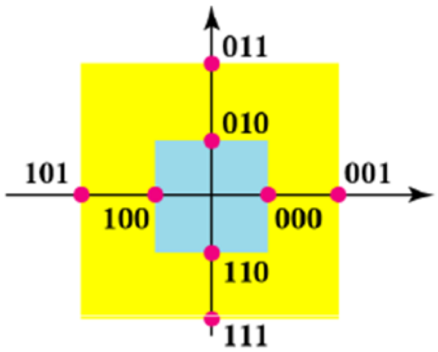
Quadrature Amplitude Modulation (QAM) – Phase and Amplitude Modulation

Example: **8-QAM example**

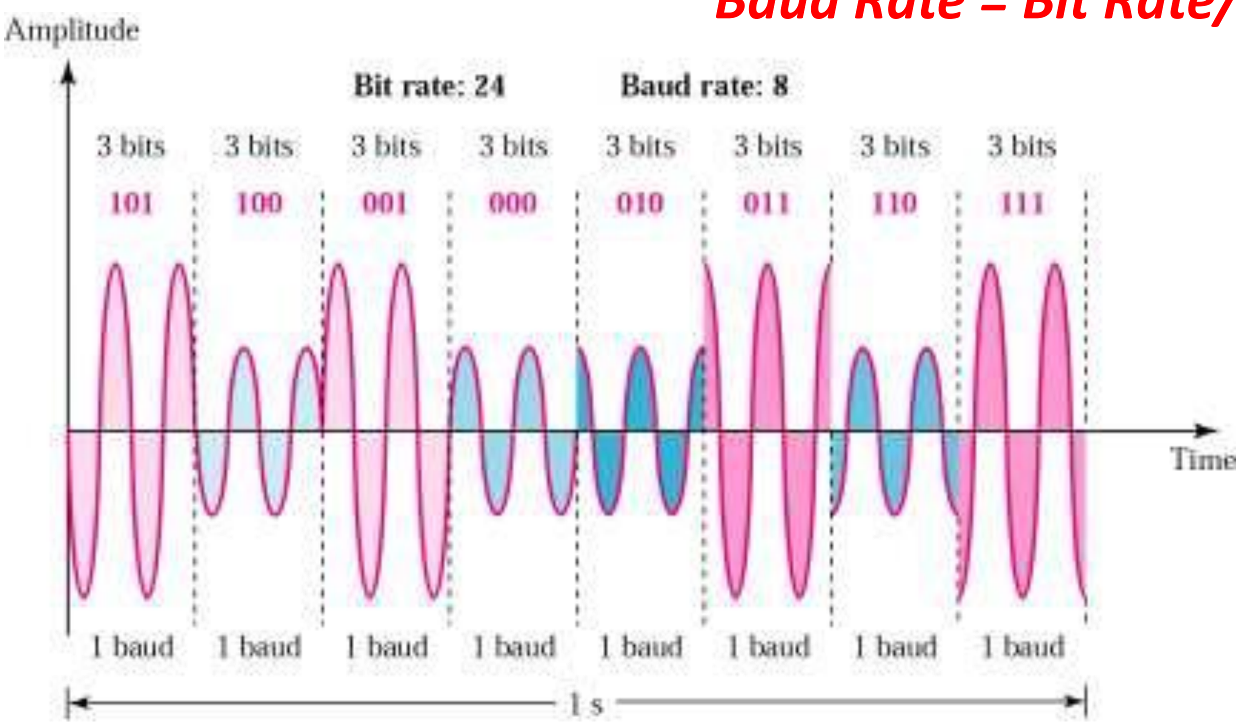
Two (2) possible *different* ***Amplitudes*** *(A1 = 1; A2 = 2)*

Four (4) possible *different* ***Phases*** *(0º, 90º, 180º, 270º)*

Total *of* ***8*** **QAM symbols** → ***3 bits per symbol***



Baud Rate = Bit Rate/3

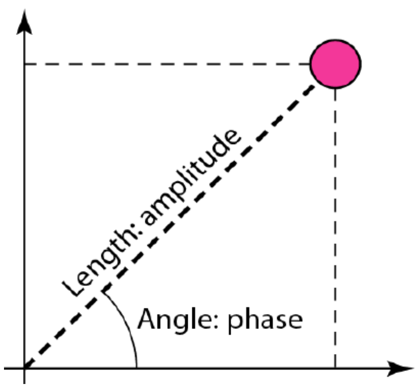


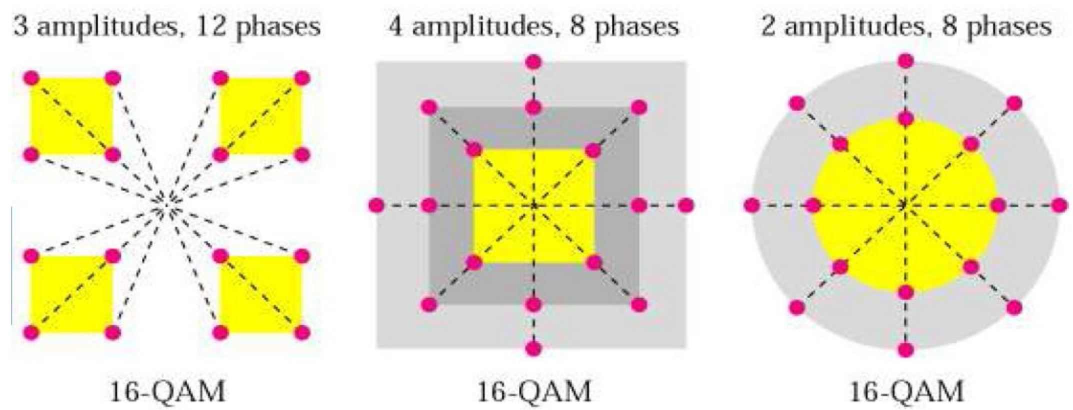
Modulation Alphabet

A = 1, Phase = 0º:	000
A = 2, Phase = 0º:	001
A = 1, Phase = 90º:	010
A = 2, Phase = 90º:	011
A = 1, Phase = 180º:	100
A = 2, Phase = 180º:	101
A = 1, Phase = 270º:	110
A = 2, Phase = 270º:	111

Quadrature Amplitude Modulation (QAM) or APSK

- We can have **numerous possible variations** (Διάφορες πιθανές παραλλαγές) of **Phase Shifts** and **Amplitude shifts**
  - However the **Number of Phase Shifts** should selected to be **GREATER** than **Number of Amplitude shifts**. (Why??)





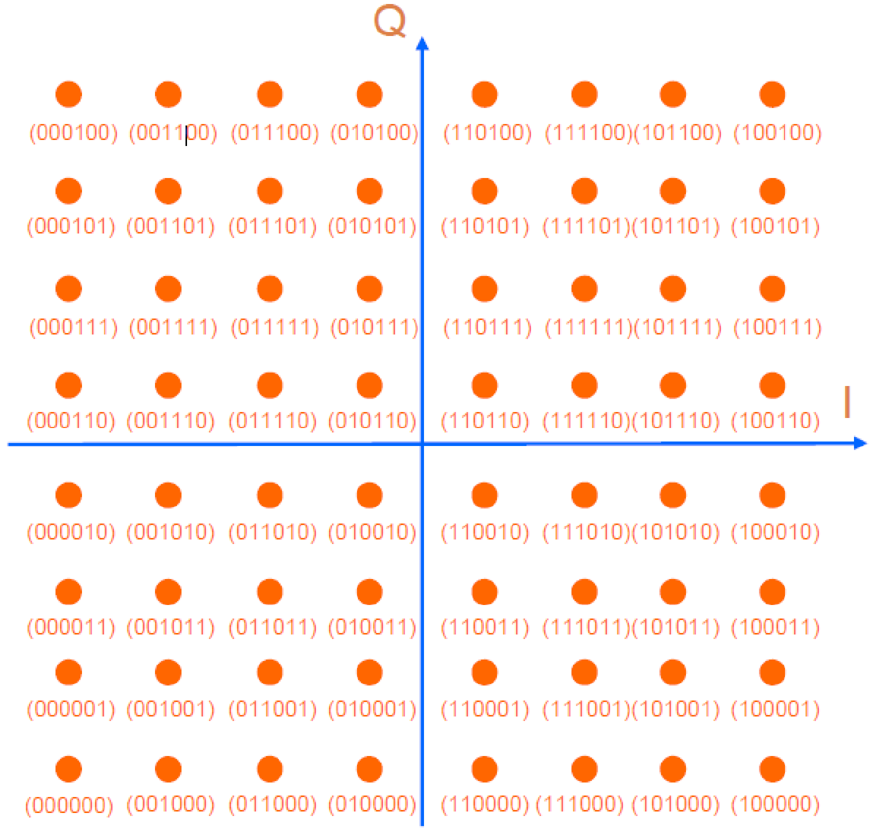
16-QAM for example:

- There are **sixteen QAM symbols** → ***4 bits per symbol***.
- **A variety of constellations diagrams can be used**

Quadrature Amplitude Modulation (QAM)

More higher order modulation

- **64-QAM** (64-Quadrature Amplitude Modulation)
  - Each symbol now **carries 6 bits (i.e., $\log_2(64)$)**



Going higher:

- **256-QAM**
  - **8bits/symbol ($\log_2(256)$)**
- **1024-QAM**
  - **10bits/symbol ($\log_2(1024)$)**
- ....

Why Not Just Keep Going?

- **With Higher Order Modulation schemes**
  - **Minor errors** during **modulation** could **create symbol errors** in transmission
  - **Even a little noise** in the transmission channel could create symbol errors
  - **Minor inaccuracies** in the Receiver could create errors
  - **Signal-to-Noise requirements increases** with higher order modulations (thus more power have to be used during transmission → more interference caused in the cells)

Factors that influence the choice of Digital Modulation Scheme

- **The performance of a modulation scheme is often measured in terms of its:**
  - **Power Efficiency:** Refers to the **ability to preserve the fidelity (no errors) of a digital message at low power levels (i.e., low SNIR)** (Περιγράφει την ικανότητα διατήρησης της ακεραιότητα ενός μηνύματος (no errors) σε χαμηλά επίπεδα ισχύος του σήματος)
  - **Bandwidth (or Link Spectral) Efficiency**: Refers to the **ability to "squeeze" as much data** into the **least amount of bandwidth available** (Περιγράφει την ικανότητα "συμπίεσης" όσον περισσότερων δεδομένων στο ελάχιστο διαθέσιμο εύρος ζώνης)

Factors that influence the choice of Digital Modulation Scheme

Power Efficiency:

- In order to **increase noise immunity**, it is necessary to **increase the signal power**. (Για να αυξήσουμε την ανοσία ενός σήματος στο θόρυβο πρέπει να αυξήσουνε την ενέργεια (ισχύ) με την οποία θα το στείλουμε)
  - The **amount** by which the **signal power should be increased** to **maintain a certain BER depends on the modulation scheme.**
  - **Higher Order Modulation → Higher Signal Power.**
- The **Power Efficiency is expressed by** the value of **SNIR required at the Receiver** to **decode the signal correctly** and **guarantee a certain BER** (The **lower the SNIR required** the **higher the Power Efficiency**).

Factors that influence the choice of Digital Modulation Scheme

Bandwidth (Link Spectral) Efficiency:

- Is typically used to **analyse how efficiently the allocated bandwidth is used by the modulation technique** (Χρησιμοποιείται για να αναλύσουμε πόσο αποδοτικά χρησιμοποιείται το διαθέσιμο εύρος ζώνης από την τεχνική διαμόρφωσης).
- It is defined as the **average number of bits per unit of time** (bits per second) that can be transmitted **per unit of bandwidth** (per Hertz).

Factors that influence the choice of Digital Modulation Scheme

Bandwidth (Link Spectral) Efficiency:

- Is the ***net* data rate** (**useful information rate excluding error-correcting codes**) or **maximum throughput*** **divided** by the available **Bandwidth (in hertz)** of a communication channel.
- It is measured in bits per second per Herz (**bps/Hz**)

$$\eta_B = \frac{R}{B} \text{ bps/Hz}$$

R : data rate *B*: RF BW

*** *Throughput*** *or* ***network throughput*** *is the* ***rate of successful message delivery over a communication channel****. A typical method of performing a measurement is to transfer a 'large' file from one system to another system and measure the time required to complete the transfer or copy of the file. The* ***throughput is then calculated*** *by* ***dividing*** *the* ***file size by the time required to complete the transfer****. Then the throughput can be measured in megabits, kilobits, or bits per second.*

Factors that influence the choice of Digital Modulation Scheme

- **Bandwidth Efficiency Examples:**

  - **Example 1: What is the bandwidth efficiency of the modulation technique when 2 Kilohertz of bandwidth is required to transmit 1000 bps?**
    - 1000bps/2000Hz = 0.5 bps/Hz

  - **Example 2: What is the bandwidth efficiency of the modulation technique when 3 Kilohertz of bandwidth is required to transmit 12000 bps?**
    - 12000bps/3000Hz = 4bps/Hz

Factors that influence the choice of Digital Modulation Scheme

Very often there is a tradeoff:

- **M-ary** schemes **increase the Bandwidth Efficiency** but **require Higher Transmission Power (than Binary modulation schemes)** to **keep the same Bit Error Rate → Lower Power Efficiency**. (Κάνουν την χρήση του εύρους ζώνης πιο αποδοτική άλλα χρειάζεται περισσότερη ισχύς κατά την αποστολή των δεδομένων για να είναι το σήμα πιο δυνατό και να μπορεί ο Receiver να το αναγνωρίσει και να το αποκωδικοποιήσει σωστά διατηρώντας έτσι το BER στα επίπεδα που πρέπει)

Factors that influence the choice of Digital Modulation Scheme

Very often there is a tradeoff:

- **Power Efficiency can be increased by adding Error Control Coding in the packets transmitted** but **reduces** the **Bandwidth Efficiency** as **Redundancy** is transmitted too. (Μπορούμε να αυξήσουμε το Power Efficiency με το να προσθέσουμε error control codes κατά την αποστολή των πακέτων αλλά αυτό μειώνει το Bandwidth Efficiency αφού στέλλουμε επιπλέον (μη χρήσιμη) πληροφορία)

Error control (error detection and correction) *are techniques that **enable reliable delivery of digital data** over **unreliable communication channels**. Many communication channels are subject to channel **noise**, and **thus errors may be introduced during transmission** from the source to a receiver. Error detection techniques allow **detecting such errors**, while error correction enables **reconstruction of the original data in many cases**.*

Spread Spectrum Techniques
Τεχνικές Διασποράς Φάσματος

- Spread Spectrum techniques **use a transmission bandwidth** that is **several orders of magnitude greater** than **the required bandwidth to spread the data (**Χρησιμοποιούν ένα εύρος ζώνης πολύ μεγαλύτερο από αυτό που πραγματικά χρειάζεται για διασπείρουν τα δεδομένα**).**

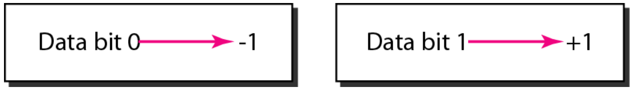
Spread Spectrum Techniques
Τεχνικές Διασποράς Φάσματος

- **Each bit** of the data that we want to transmit is **encoded** using **a sequence of digits (chips)** known as a **Spreading Code** → Κάθε bit των δεδομένων που θα διαδοθούν κωδικοποιείται χρησιμοποιώντας μια ακολουθία ψηφίων (τα ψηφία αυτά ονομάζονται **chips**) η οποία είναι γνωστή ως ο **Κώδικας Διασποράς**.
  - **Each bit (0 or 1)** that will be transmitted by the transmitter in the specific channel is encoded using the same **Spreading Code.**
  - During Spreading, data bit 0 is represented as -1 and data bit 1 is represented as +1.

Spread Spectrum Techniques
Τεχνικές Διασποράς Φάσματος

Example: We want to transmit **Data = (0, 1)** using the **Spreading Code = (1, 1, 1, -1, 1, -1, -1, -1)**

- Data = (-1, +1)



- **Bit 0** will be encoded and transmitted using the following **chip sequence**:
  - (-1).(1, 1, 1, -1, 1, -1, -1, -1) = **(-1, -1, -1, 1, -1, 1, 1, 1)**
- **Bit 1** will be encoded and transmitted using the following **chip sequence**:
  - (+1). (1, 1, 1, -1, 1, -1, -1, -1) = **(1, 1, 1, -1, 1, -1, -1, -1)**

Spread Spectrum Techniques
Spreading and Despreading

Example: Spreading

Step	Encode Sender (Spreading)
0	Spreading Code (SC) = (1, 1, 1, -1, 1, -1, -1, -1), Data = (0, 1) → Data' (-1, +1)
1	Encode (Spread) Data' = ((-1 . SC), (+1 . SC)) = ((-1, -1, -1, 1, -1, 1, 1,1), (1, 1, 1, -1, 1, -1, -1,-1))
2	Spread Data = (-1, -1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, 1, -1, -1, -1)

Data bit 0 → -1

Data bit 1 → +1

Spread Spectrum Techniques Spreading and Despreading

- **The Receiver** will use the **same Spreading Code** to Despread (Decode) the chip sequence received.
- Example: The Receiver receives the chip sequence

  (-1, -1, -1, 1, -1, 1, 1, 1)

- Decoding of the chip sequence (applying dot product) using the Spreading Code (1, 1, 1, -1, 1, -1, -1, -1):
  - (-1, -1, -1, 1, -1, 1, 1, 1).(1, 1, 1, -1, 1, -1, -1, -1) =
  - = (-1, -1, -1, -1, -1, -1, -1, -1) =
  - = (-8)

If **decoded data < 0**	→ Data bit **0**
If **decoded data > 0**	→ Data bit **1**
If **decoded data == 0**	→ **No data**

Spread Spectrum Techniques
Spreading and Despreading

Example: Despreading

Step	Decode Receiver (Despreading)
0	**Spreading Code (SC)= (1, 1, 1, -1, 1, -1, -1, -1)** **Received Spread Data (RSD) = (-1, -1, -1, 1, -1, 1, 1, 1, 1, 1, 1, -1, 1, -1, -1, -1)**
1	**Decode = RSD . SC =** **((-1, -1, -1, 1, -1, 1, 1, 1), (1, 1, 1, -1, 1, -1, -1, -1)) . (1, 1, 1, -1, 1, -1, -1, -1) =** **((-1-1-1-1-1-1-1-1), (1, 1, 1, 1, 1, 1, 1,1))**
2	**Decoded Data' = (-8 , 8) → Data (0, 1)**

If **decoded data < 0**	→ Data bit **0**
If **decoded data > 0**	→ Data bit **1**
If **decoded data == 0**	→ **No data**

Spread Spectrum Techniques Spreading Factor & Processing Gain

- As illustrated in the previous example, after despreading **the amplitude** of the signal **increases** by a **factor of 8** (**analogous to the length of the Spreading Code → this is called the Spreading Factor (SF)**)
- This effect is termed **'Processing Gain'** and is a **fundamental aspect** (είναι ένα θεμελιώδες στοιχείο) of all **Spread Spectrum** systems.

$$\textbf{Processing Gain}_{(dB)} = 10 \log_{10} (SF)$$

Spread Spectrum Techniques
Spreading Factor & Processing Gain

- In the previous example the **Processing Gain is 9dB** (**10 x** $\log_{10}(8)$) → This means that the **signal energy** can be **increased by 9dB** after despreading.

- Thus, assuming that the **minimum SNIR required by the Receiver (Demodulator) for decoding the signal correctly** is **5dB**, the **SNIR that the signal can have before despreading** is therefore **5 dB minus** the **Processing Gain** (i.e., **5dB – 9dB = – 4 dB**).

- **In other words, the signal power, can be 4 dB under the interference or thermal noise power, and the Receiver (Demodulator) can still decode the signal correctly.**

Spread Spectrum Techniques
Spreading Factor & Processing Gain

- The **number of chips that will be used (i.e., the length of the Spreading Code)** to spread one bit of data is defined by the **Spreading Factor**.
- The Spreading Factor is given by:

$$Spreading\_Factor = \frac{Chip\_Rate}{Bit\_Rate}$$

Spread Spectrum Techniques
Spreading Factor & Processing Gain

- Using **W-CDMA** (Wideband-Code Division Multiple Access, which is used in 3G Networks) we have **5Mhz** carrier bandwidth and a **Chip Rate of 3.84 Mcps** to Spread the data.
  - Note: **CDMA** uses a carrier bandwidth of **1.25 MHz** and a **Chip Rate of 1.22Mcps.**
- Thus, if we transmit a video clip with **Bit Rate of 128Kbps** the **Spreading Factor** will be:

$$Spreading\_Factor = \frac{3{,}840{,}000 chips/\sec}{128{,}000 bits/\sec} = 30$$

- **Each bit** will be **spread** using a **Spreading Code of length 30**.
- **Processing Gain = 10 x $\log_{10}(30)$ = 14.77 dB**

Spread Spectrum Techniques
Spreading Factor & Processing Gain

- **Processing Gain** allows the **received signal power** to be **under the interference or thermal noise power (i.e., improves reception)**, and the **Receiver can still detect the signal**.
  - **Detection of a Spread signal** is **difficult without knowledge** of the **Spreading Code**.
  - Spread Spectrum systems **originated** in **military applications** as it is very **difficult to interfere with** (πολύ δύσκολα παρεμβάλλεται) and **difficult to identify the signal** (πολύ δύσκολα αναγνωρίζεται η πληροφορία που μεταφέρει το σήμα) **without knowing** the **Spreading Code**.

Spread Spectrum Techniques Advantages

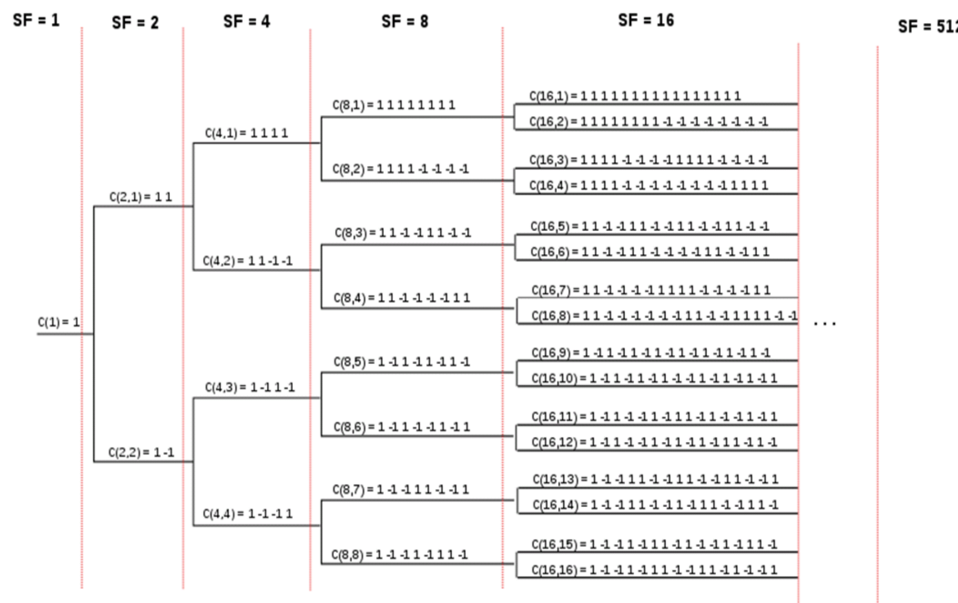
- **Several advantages** can be gained from this **apparent waste of spectrum (από αυτή την προφανή "σπατάλη" του φάσματος)** by this approach:
  - The signals **gains immunity from various kinds of noise and interference** (Τα σήματα αποκτούν μεγαλύτερη ανοσία στο θόρυβο και στις παρεμβολές) – Due to the **Processing Gain** that can be achieved
    - The earliest applications of spread spectrum were military, where it was used for its **immunity to jamming** (ανοσία σε θόρυβο και παρεμβολές με σκοπό το μπλοκάρισμα των καναλιών).

Spread Spectrum Techniques Advantages

- It can also be used **for hiding and encrypting signals** (Χρησιμοποιούνται για **απόκρυψη** και **κρυπτογράφηση** των σημάτων).
  - Only a recipient who **knows the spreading code can recover the encoded** information.
- **Several users can independently use the same bandwidth at the same time** with **very little interference**.
  - This property is **used in cellular telephony applications (e.g., in UMTS Networks)**, with a technique known as **Code Division Multiple Access (CDMA)**.

Code Division Multiple Access (CDMA)

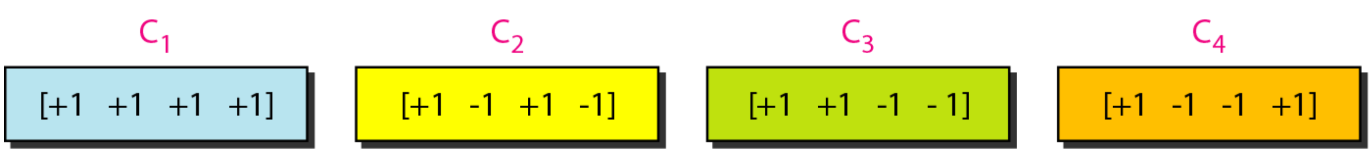
- Divides up a radio channel **not by frequency** (as in FDMA), **not by time** (as in TDMA), but instead by using **Code Sequences (Spreading Codes)** for **each user**.
- **Guard Spaces (For keeping the different channels independent)** are realized **by using codes** with the necessary 'distance' in code space, e.g., **Orthogonal Codes**.
- These codes are derived from an **Orthogonal Variable Spreading Factor (OVSF)** code tree, and **each user is given a different, unique code**.



Code Division Multiple Access

Orthogonal Codes

- Orthogonal codes have a **cross-correlation equal to zero**; in other words, they **do not interfere with each other**
- Their **dot product** (**_operation of vectors_**) is **equal to zero**
- An example of orthogonal codes (vectors) is provided below:
  - C1 = (1, 1, 1, 1),
  - C2 = (1, -1, 1, -1),
  - C3 = (1, 1, -1, -1),
  - C4 = (1, -1, -1, 1),
- These vectors (codes) will be **assigned to individual users** and are called the **Spreading Codes**



Code Division Multiple Access

- **Orthogonal Codes Examples:**
  - Question 1: Is SC1 = (1, -1, 1, -1) and SC2 = (1, 1, -1, -1), orthogonal?
  - Answer 1: For these two Spreading Codes to be orthogonal their dot product (SC1 . SC2) must be equal to 0.

$$(1, -1, 1, -1) \cdot (1, 1, -1, -1) = (+1 -1 -1 +1) = 0$$

Their dot product is equal to 0, therefore these two Spreading Codes are orthogonal

Code Division Multiple Access

- **Orthogonal Codes Examples:**
  - Question 2: Is SC1 = (1, -1, 1, -1) and SC2 = (1, -1, -1, -1), orthogonal?
  - Answer 2: For these two Spreading Codes to be orthogonal their dot product (SC1 . SC2) must be equal to 0.

(1, -1, 1, -1) . (1, -1, -1, -1) = (+1 +1 -1 +1) = +2

Their dot product is not equal to 0, therefore these two Spreading Codes are NOT orthogonal

Code Division Multiple Access -
Example of Spreading and Despreading a Signal

- Each user is associated with a different Spreading Code, say **C**
- **During the Spreading of the Data bits:**
  - **Data bit 0** will be represented as **-1**
  - **Data bit 1** will be represented as **+1**
- For example:
  - **C = (1, -1, -1, 1)** (this is the **Spreading Code** and in this case the **Spreading Factor** is equal with **4**)
  - The **Data Bit Stream** (1, 0, 1, 1) would correspond to (C, -C, C, C)
  - The **Spread Data** will be:
    - ((1, -1, -1, 1), (-1, 1, 1, -1), (1, -1, -1, 1), (1, -1, -1, 1)).

Code Division Multiple Access - Example of Spreading and Despreading a Signal

- **Example of encoding (Spreading) and decoding (Despreading) a signal**
  - "**Sender 1**" has a
    - Spreading Code (C_1) = (1, -1, -1, 1)
    - Data (D_1) = (1, 0, 1, 1), and
  - "**Sender 2**"
    - Spreading Code (C_2) = (1, 1, -1, -1)
    - Data (D_2) = (0, 0, 1, 1), and
  - Both senders **transmit simultaneously**

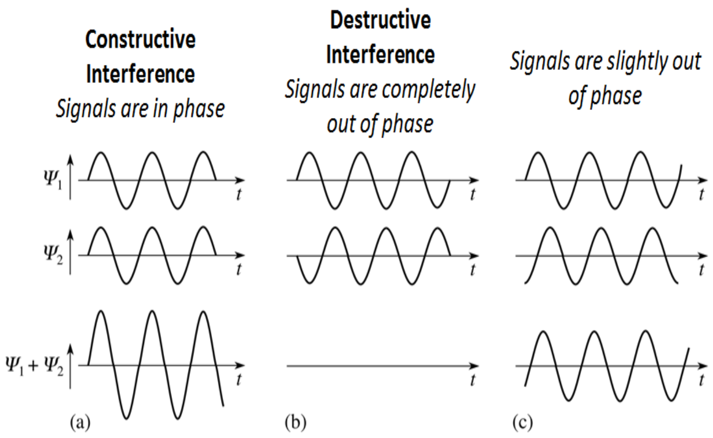
Code Division Multiple Access - Example of Spreading and Despreading a Signal

Step	Encode Sender 1 (Spreading)
0	C_1 = (1, -1, -1, 1), D_1 = (1, 0, 1, 1)
1	Encode 1 = (C_1, -C_1, C_1, C_1) = ((1, -1, -1, 1),(-1, 1, 1, -1),(1, -1, -1, 1),(1, -1, -1, 1))
2	Spread Signal 1 = (1, -1, -1, 1, -1, 1, 1, -1, 1, -1, -1, 1, 1, -1, -1, 1)

Step	Encode Sender 2 (Spreading)
0	C_2 = (1, 1, -1, -1), D_2 = (0, 0, 1, 1)
1	Encode 2 = (-C_2, -C_2, C_2, C_2) = ((-1, -1, 1, 1),(-1, -1, 1, 1), (1, 1, -1, -1), (1, 1, -1, -1))
2	Spread Signal 2 = (-1, -1, 1, 1, -1, -1, 1, 1, 1, 1, -1, -1, 1, 1, -1, -1)

Code Division Multiple Access - Example of Spreading and Despreading a Signal

- *The physical properties of interference say that if two signals at a point are in phase, they will "add up" to give twice the amplitude of each signal, but if they are out of phase, they will "subtract" and give a signal that is the difference of the amplitudes.*



- *Because Signal 1 and Signal 2* ***are transmitted at the same time using the same frequency band****, we'll add them together to model the* ***raw signal*** *in the air. This raw signal may be called an* ***Interference Pattern****.*
- **Interference Pattern**:

	1	-1	-1	1	-1	1	1	-1	1	-1	-1	1	1	-1	-1	1
+	-1	-1	1	1	-1	-1	1	1	1	1	-1	-1	1	1	-1	-1
	0	-2	0	2	-2	0	2	0	2	0	-2	0	2	0	-2	0

Code Division Multiple Access -

Example of Spreading and Despreading a Signal

- **Question:** How does a Receiver make sense of this Interference Pattern?

- **Answer:** The receiver **knows the Spreading Codes of the senders.** Using these Spreading Codes on the received interference pattern can extract an intelligible signal for any known sender.

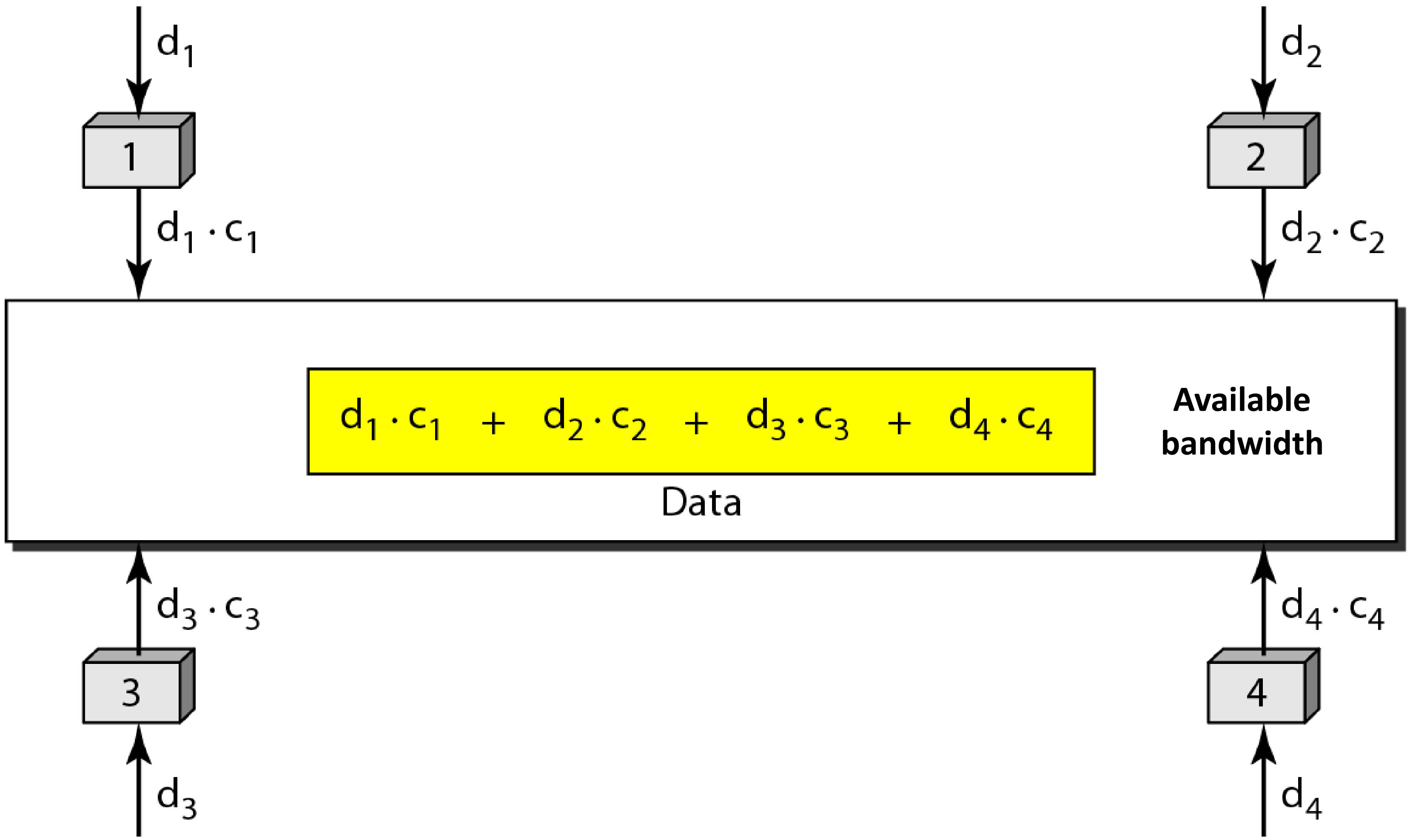
Code Division Multiple Access -
Example of Spreading and Despreading a Signal

Step	Decode Sender 1 (Despreading)
0	C_1 = (1, -1, -1, 1), Interference Pattern = (0, -2, 0 ,2, -2, 0, 2, 0, 2, 0, -2, 0, 2, 0, -2, 0)
1	Decode 1 = Interference_Pattern . C_1 = ((0, -2, 0, 2), (-2, 0, 2, 0), (2, 0, -2, 0), (2, 0, -2, 0)).(1, -1, -1, 1) = ((0 + 2 + 0 + 2), (-2 + 0 - 2 + 0), (2 + 0 + 2 + 0), (2 + 0 + 2 + 0))
2	Data 1 = (4, -4, 4, 4) = (1, 0, 1, 1)

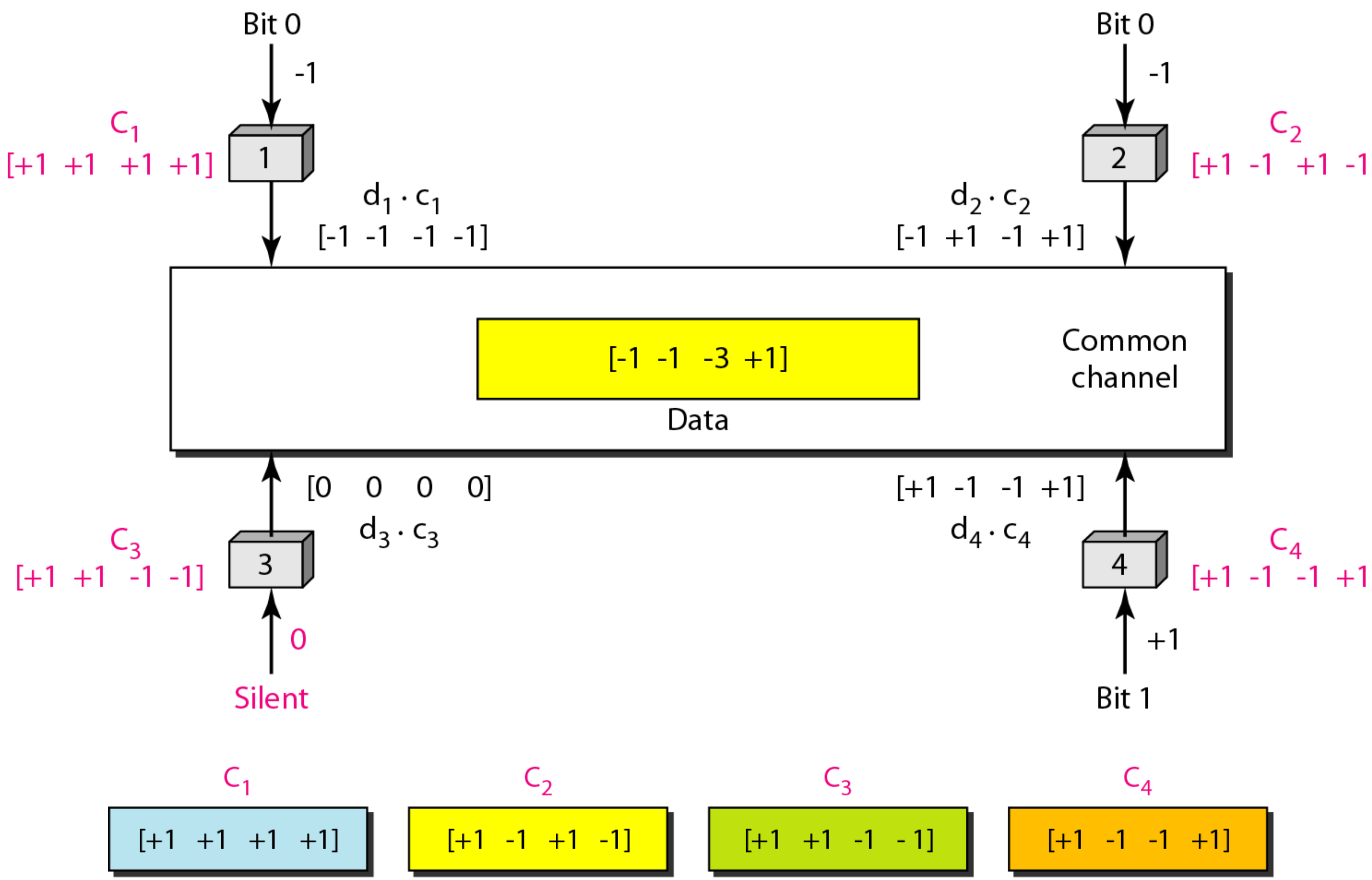
Step	Decode Sender 2 (Despreading)
0	C_2 = (1, 1, -1, -1), Interference Pattern = (0, -2, 0 , 2, -2, 0, 2, 0, 2, 0, -2, 0, 2, 0, -2, 0)
1	Decode 1 = Interference_Pattern . C_2 = ((0, -2, 0, 2),(-2, 0, 2, 0),(2, 0, -2, 0),(2, 0, -2, 0)).(1, 1, -1, -1) = ((0 - 2 + 0 - 2), (-2 + 0 - 2 + 0), (2 + 0 + 2 + 0), (2 + 0 + 2 + 0))
2	Data 2 =(-4, -4, 4, 4) = (0, 0, 1, 1)

Code Division Multiple Access

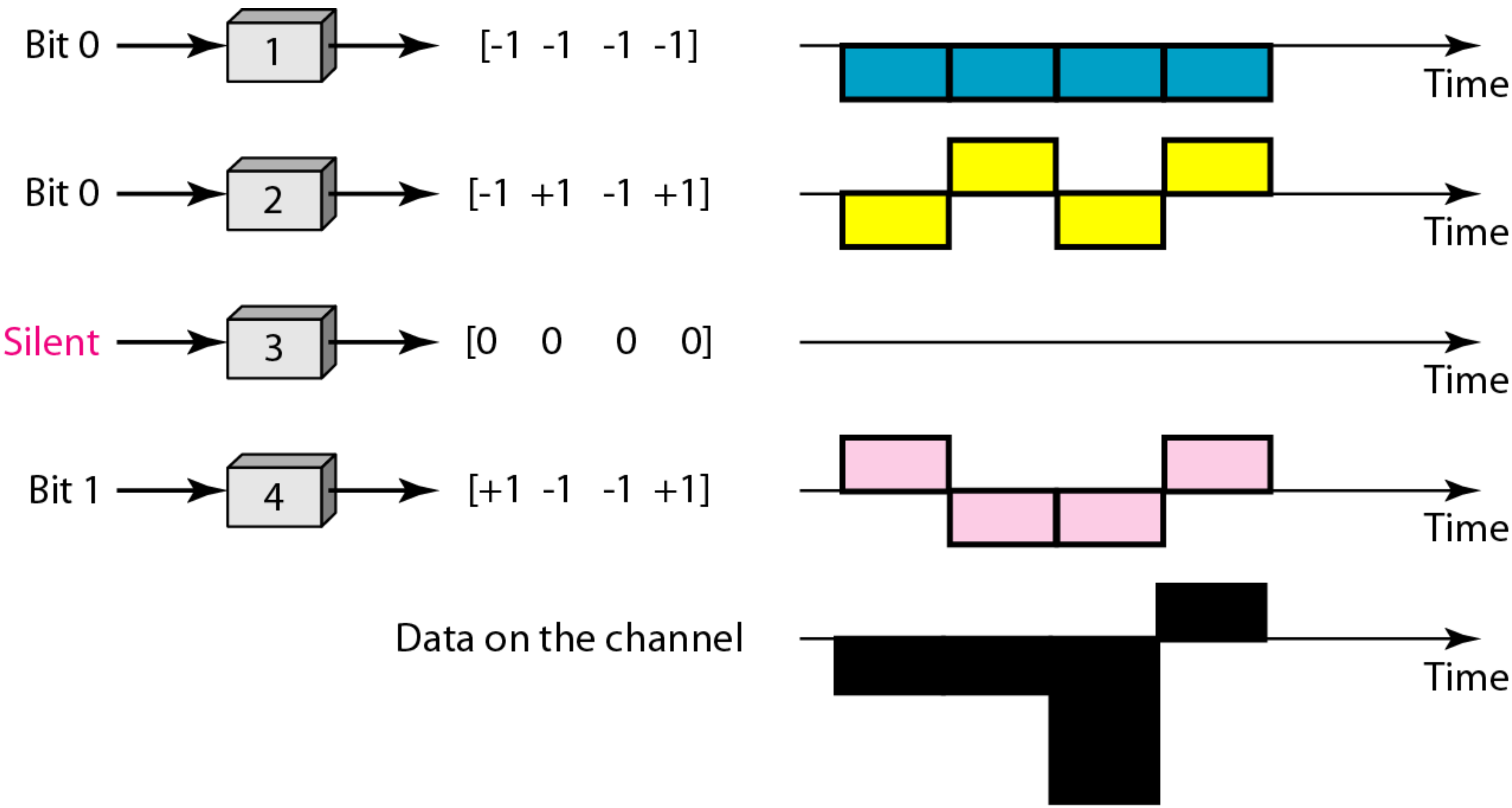
Example of Spreading and Despreading a Signal



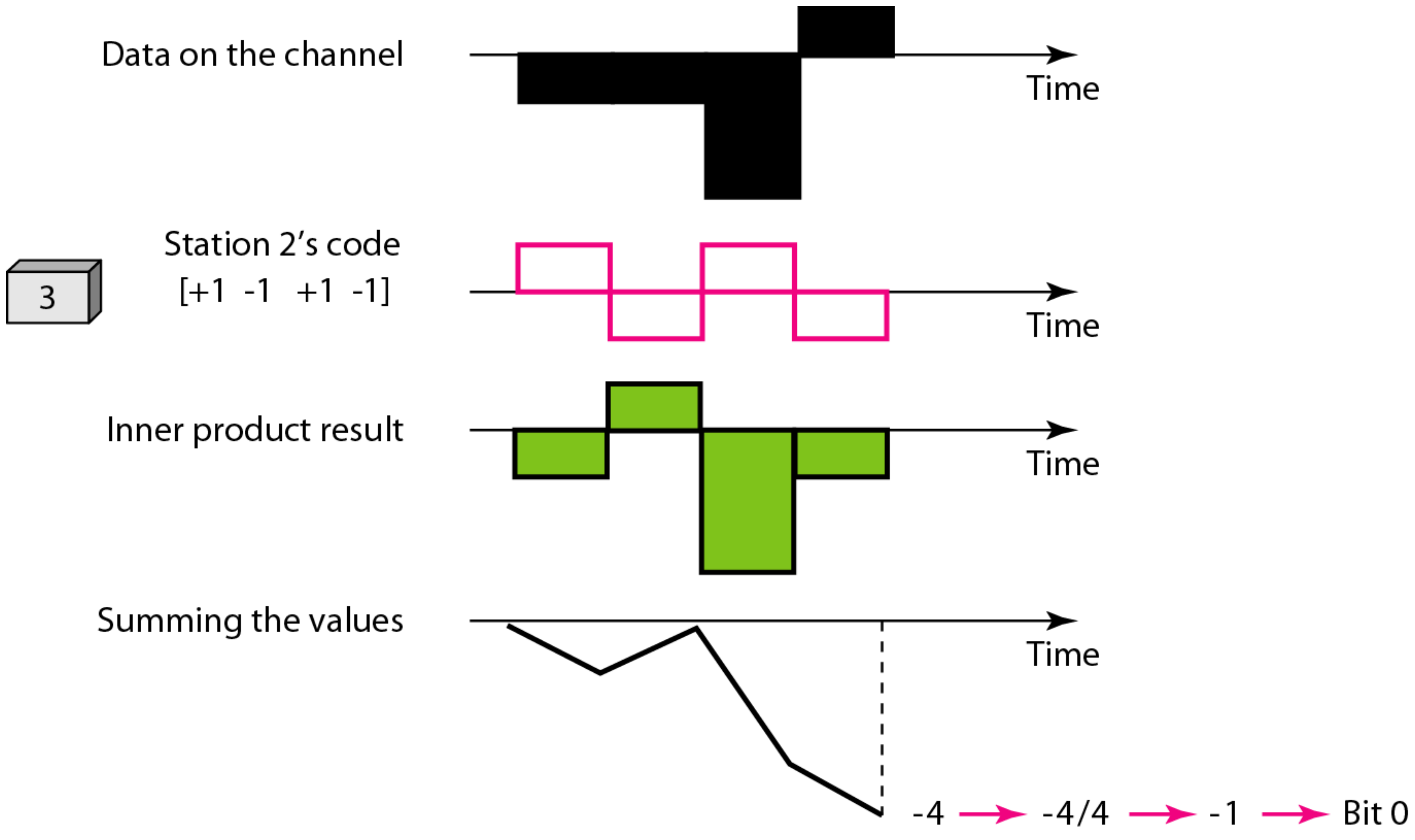
Code Division Multiple Access - Example of Spreading and Despreading a Signal



Code Division Multiple Access - Example of Spreading and Despreading a Signal



Code Division Multiple Access - Example of Spreading and Despreading a Signal

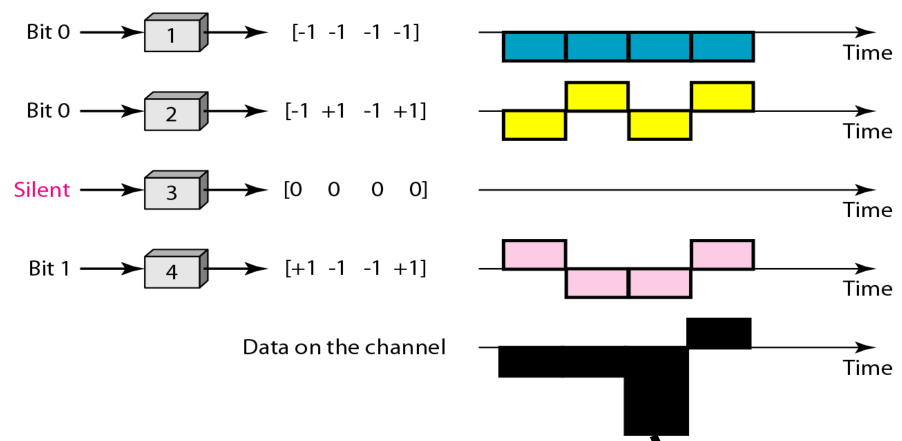


Code Division Multiple Access -

Example of Spreading and Despreading a Signal

- **Question:** **In the example provided Station 3 (S3) did not send any data to the channel. What will happen when the receiver, during Despreading, correlates the Spreading Code of S3 on the Interference Patter (i.e., the data on the channel)?**

- **Answer:** **When the receiver correlates the interference pattern with the Spreading Code of S3, the summing of the values of the despread signal will be equal to 0 → Thus no data are included in the channel for S3.**



For example:

Interference Pattern: (-1, -1, -3, 1)

S3 → C_3 = (1, 1, -1, -1)

Despreading of S3:

(-1, -1, -3, 1) . (1, 1, -1, -1) =

= -1 -1 + 3 -1 = -3 + 3 = 0 → No Data

Code Division Multiple Access -
Example of Spreading and Despreading a Signal

- **FOR HOME PRACTICE → Example of encoding (Spreading) and decoding (Despreading) a signal with 4 users →**
  - "**Sender 1**" has a
    - Spreading Code (C_1) = (1, 1, 1, 1), Data (D_1) = (0, 0)
  - "**Sender 2**"
    - Spreading Code (C_2) = (1, -1, 1, -1), Data (D_2) = (0, 1)
  - "**Sender 3**"
    - Spreading Code (C_3) = (1, 1, -1, -1), Data (D_3) = (1, 0)
  - "**Sender 4**"
    - Spreading Code (C_4) = (1, -1, -1, 1), Data (D_4) = (1, 1)
  - All senders **transmit simultaneously**

Code Division Multiple Access - Example of Spreading and Despreading a Signal

- **Example of encoding (Spreading) and decoding (Despreading) a signal with 4 users,**
  - **"Sender 1" Spread Signal**:
    - (-1, -1, -1, -1, -1, -1, -1, -1)
  - **"Sender 2" Spread Signal:**
    - (-1, 1, -1, 1, 1, -1, 1, -1)
  - **"Sender 3" Spread Signal:**
    - (1, 1, -1, -1, -1, -1, 1, 1)
  - **"Sender 4" Spread Signal:**
    - (1, -1, -1, 1, 1, -1, -1, 1)

  - **Interference Pattern (We add all the signals together)**
    - **(0, 0, -4, 0, 0, -4, 0, 0)**

Code Division Multiple Access -
Example of Spreading and Despreading a Signal

- **Example of encoding (Spreading) and decoding (Despreading) a signal with 4 users (Interference Pattern: (0, 0, -4, 0, 0, -4, 0, 0))**
-
  - **"Sender 1" Despread Signal (C_1 = (1, 1, 1, 1))**
    - ((0, 0, -4, 0), (0, -4, 0, 0)) . (1, 1, 1, 1) = (-4, -4) → **Data (0, 0)**
  - **"Sender 2" Despread Signal (C_2 = (1, -1, 1, -1))**
    - ((0, 0, -4, 0), (0, -4, 0, 0)). (1, -1, 1, -1) = (-4, +4) → **Data (0, 1)**
  - **"Sender 3" Despread Signal (C_3 = (1, 1, -1, -1))**
    - ((0, 0, -4, 0), (0, -4, 0, 0)) . (1, 1, -1, -1) = (+4, -4) → **Data (1, 0)**
  - **"Sender 4" Despread Signal (C_4 = (1, -1, -1, 1)):**
    - ((0, 0, -4, 0), (0, -4, 0, 0)) . (1, -1, -1, 1) = (+4, +4) → **Data (1, 1)**

Code Division Multiple Access

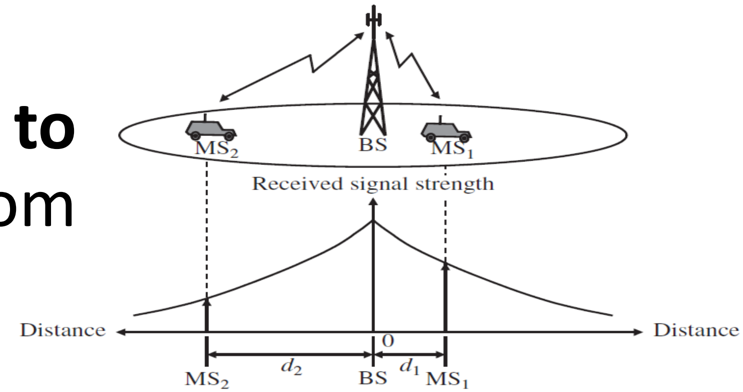
- In contrast with FDMA and TDMA which are **bandwidth and time limited**, CDMA is **interference limited**.
- Because **all users transmit on the same frequency and at the same time, internal interference generated by the users (related to the transmission power used by each one of them)** is the **most significant factor** in **determining system capacity** and **call quality**.
  - **Each user** is a **source of interference to all the other users** in the cell.

Code Division Multiple Access

- To increase capacity, the **transmit power for each user** must be **reduced to limit interference**.
- However, **the Received signal power (at the BS) should be enough to maintain the minimum required** ***SNIR needed by the Receiver, so as to decode the signal (symbol) correctly,*** for a **satisfactory call quality**.
- Thus, the goal is **all MSs' transmitted signals to reach the Base Station and received with about the same signal power (and equal to the minimum required SNIR) from the BS → Otherwise some signals could drown others**.

Code Division Multiple Access
Near Far Problem

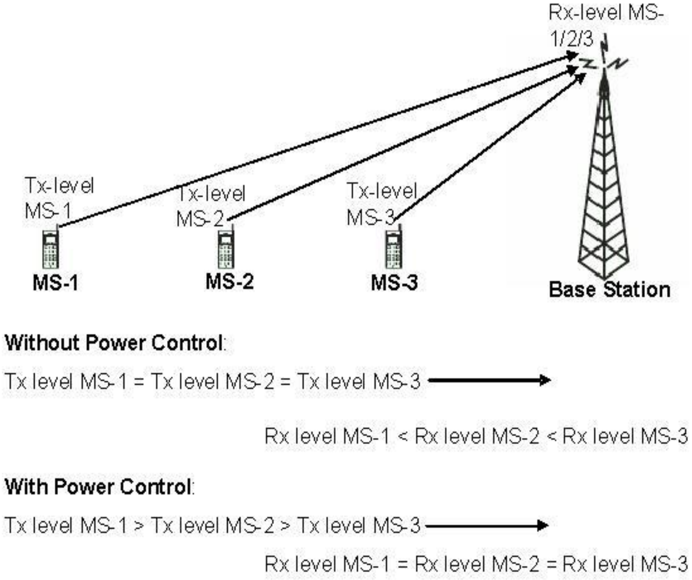
- If all **MSs** **transmit** **with the** **same power**, **signals** transmitted from **MSs closest to the BS** will be **received with** **much larger power** than **signals** from **MSs further away**.
  - Due to the difference in the **path lengths** **higher propagation path loss** is **experienced** for **users further away from the BS.**
  - The **received SNIR** **for signals transmitted from** **MSs far from the BS** **will be** **low**.
- Thus, **signals** from **MSs close to the BS** will **drown out signals** from **MSs far away from the BS.**



- **Solution: Power Control!!!**

Code Division Multiple Access
Near Far Problem – Power Control

- **Power control is essential** in order to **maintain the transmission power levels used by the MSs to the lowest level necessary → Reduce interference to the minimum** and **maximize the capacity of the system**.



One of the main objectives of Power Control is to ensure that the power of all signals received at the BS is almost equal and at a lowest level aiming to reduce the interference to the minimum, however adequate for the Receiver to be able to decode the signal correctly (i.e., received signal SNIR ≈ minimum required SNIR).

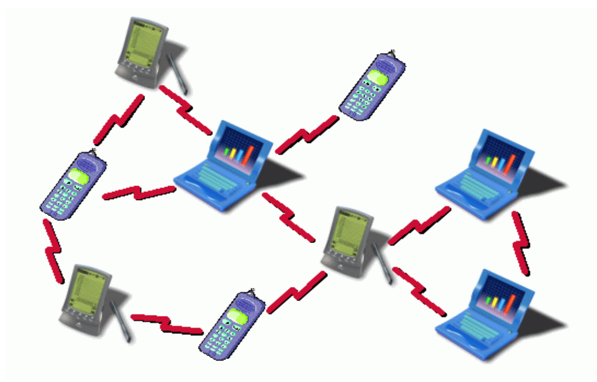
Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

- In general wireless systems (either infrastructure or infrastructure-less based) are **multi-users systems,** while **radio resources** are **limited.**
- **Thus**, the **radio resources must be shared among multiple users.**

Infrastructure based

Wireless LAN, Cellular Network

Infrastructure-less based



Ad Hoc Network

Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

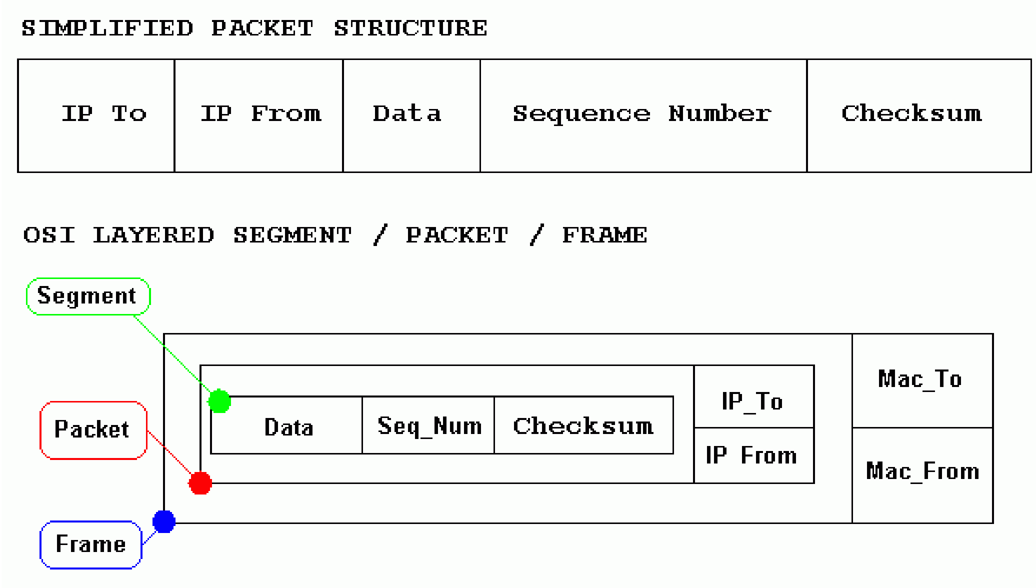
- **Problem**: When two or more stations **using the same radio resources (i.e., frequency band or bandwidth or channel)**, **transmit their frames at the same time**, their **frames will collide** and the **radio resources will be wasted during the time collision** (Όταν δύο ή περισσότερα stations που χρησιμοποιούν τους ίδιους ασύρματους πόρους στείλουν τα frames τους την ίδια ώρα, τα frames των stations θα συγκρουστούν με αποτέλεσμα το διαθέσιμο εύρος ζώνης εκείνη τη χρονική περίοδο της σύγκρουσης να πάει χαμένο).
  - How to **coordinate the access** (Πώς να γίνει ο συντονισμός πρόσβασης) of multiple sending/receiving stations to the shared channel in **order to avoid collisions** and thus **avoid waste of the radio resources**???

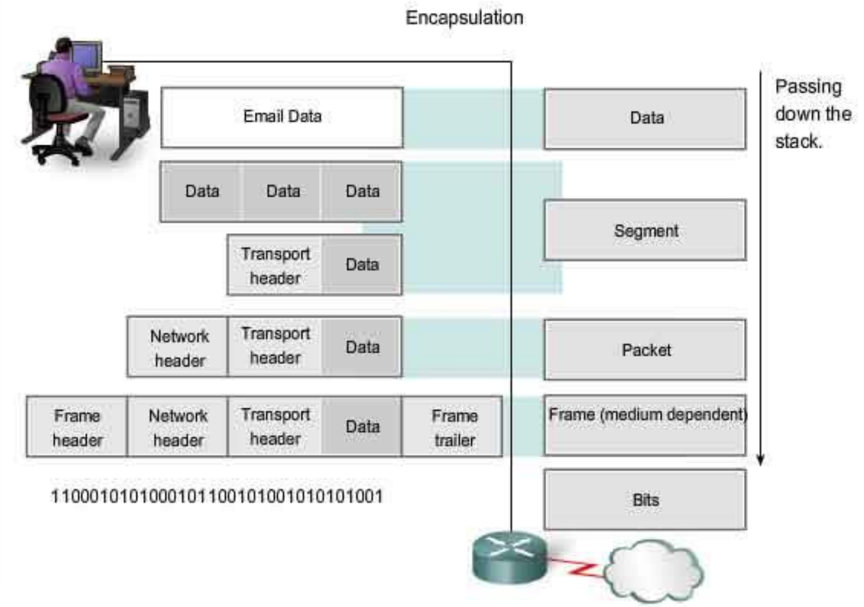
Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

- **Solution:** We need a **protocol** to **coordinate the frame transmissions** of the active stations (Χρειαζόμαστε ένα πρωτόκολλο για να συντονίσει τις εκπομπές των active stations - **active stations** είναι αυτά που **έχουν frames έτοιμα να σταλούν**).
  - These protocols are called **Medium or Multiple Access Control (MAC) Protocols.**

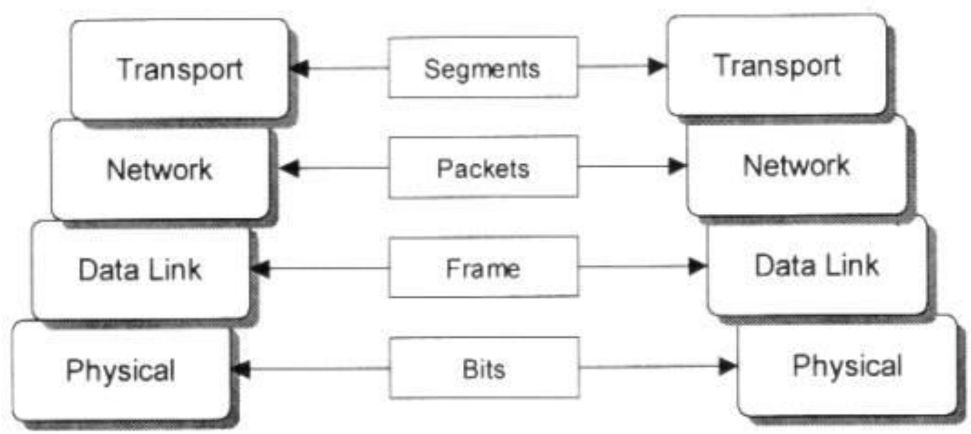
Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

Remember what a frame is?





***MAC address** is a **unique identifier assigned to network interfaces** for communications at the data link layer of a network segment. MAC addresses are most often **assigned by the manufacturer** of a **Network Interface Controller** (NIC; the hardware component that connects a computer to the network) and are **stored in its hardware**. A network node may have multiple NICs and **each NIC must have a unique MAC address**.*



Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

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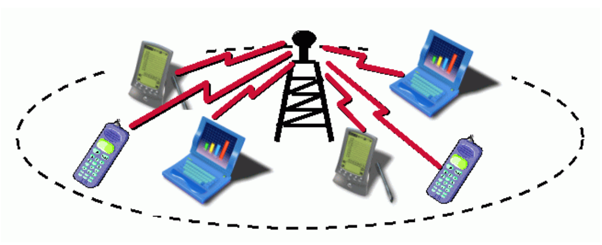
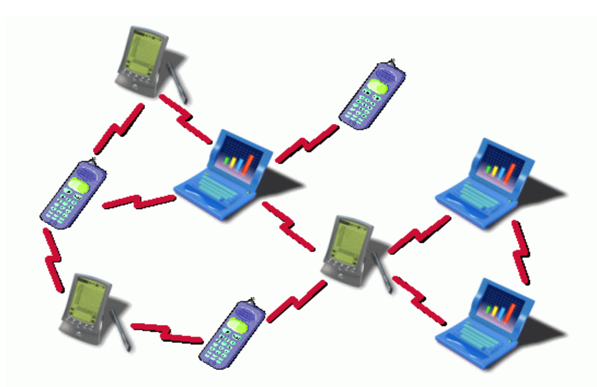
Wireless LAN, Cellular Network



Infrastructure-less based



Ad Hoc Network

Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

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Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

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Multiple Access Control
Έλεγχος Πολλαπλής Πρόσβασης

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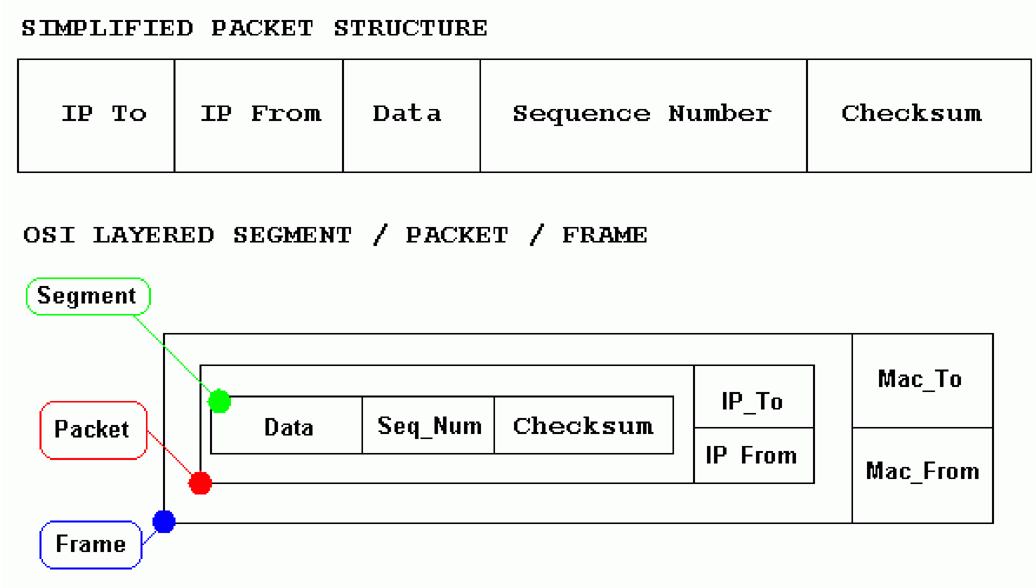

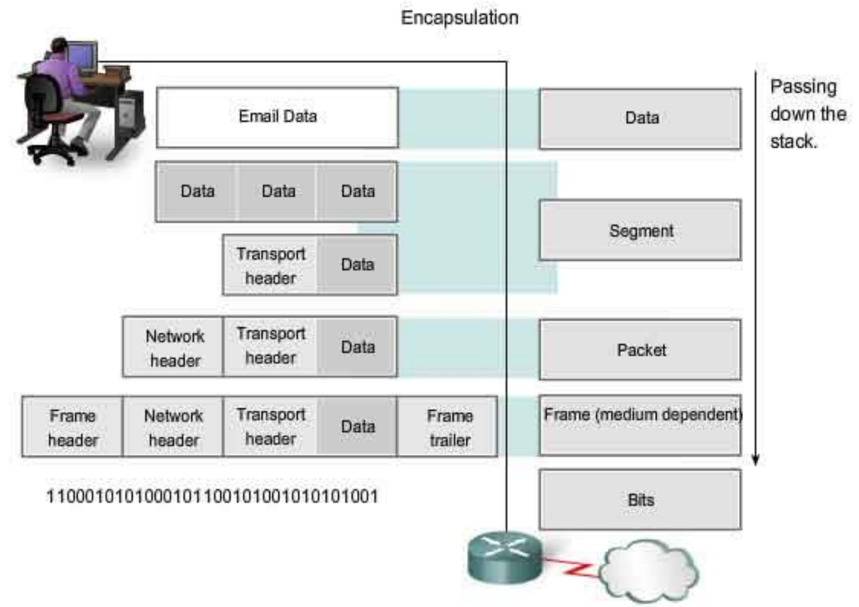

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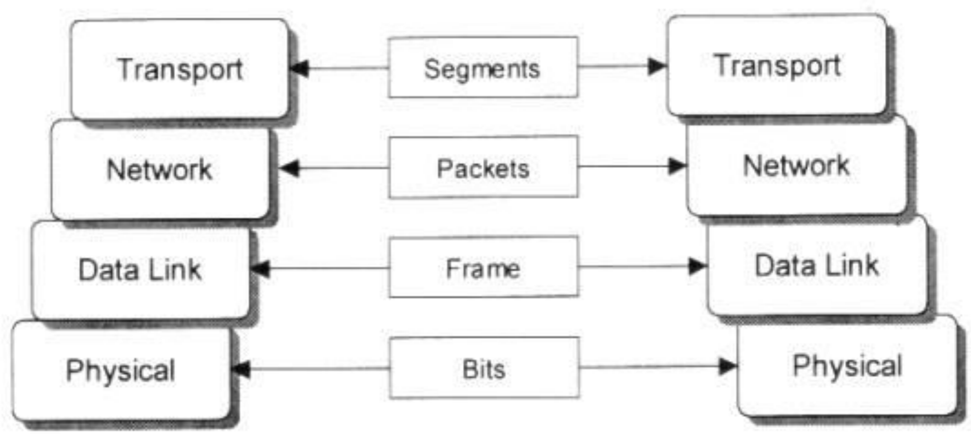


Multiple Access Protocols Contentionless-based

- **Contentionless-based (Μη Ανταγωνιστικά) Protocols:**
  - A **central controller** (Base Station or Access Point) **is needed** to **coordinate (**να συντονίσει**) the transmissions** of **all the stations.**
  - The **controller informs each station when** and **on which channel** it can **transmit its data.**
    - **So, each station has its own channel.**
    - **By doing this collisions can be avoided entirely**
  - With **Contentionless-based Protocols**, the stations transmit in an **orderly scheduled manner (**Τα stations εκπέμπουν με ένα μεθοδικό προγραμματισμένο τρόπο**)** so **every transmission** will **be successful (No collisions)**.

Multiple Access Protocols Contentionless-based

- **Contentionless-based (Μη Ανταγωνιστικά) Protocols:**
  - **Examples (Basic Channelization Protocols):**
    - **FDMA** (Frequency Division Multiple Access),
    - **TDMA** (Time Division Multiple Access),
    - **CDMA** (Code Division Multiple Access)
    - ***OFDMA*** *(Orthogonal Frequency Division Multiple Access)*
  - **Typically used in Infrastructure based Networks (e.g., WLANs, Cellular Networks, etc.)**

Multiple Access Protocols Contention-based

- **Contention-based (Ανταγωνιστικά) Protocols:**
  - **No central controller** (No Base Station or Access Point) is **needed to coordinate** the transmissions of the stations.
  - **All stations transmit using the same channel**, **without having a central controller** to **coordinate** them.
  - If several stations **start their transmissions** more or less at the **same time**, **all of the transmissions will fail**.
  - These **contention-based protocols** **resolve the contention** **(**επιλύουν τον ανταγωνισμό**)** that occur **when several users want to transmit simultaneously** and a **central controller is not present**.

Multiple Access Protocols
Contention-based

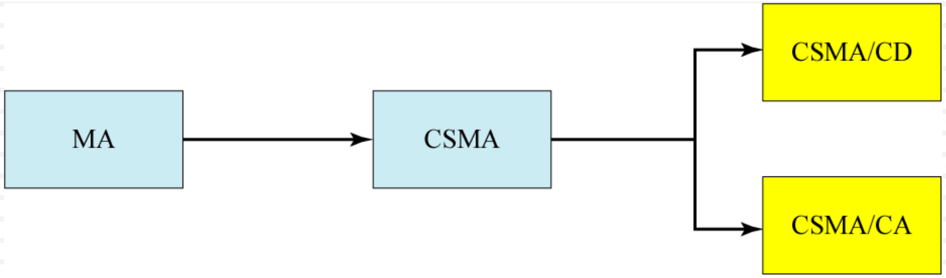
- **Contention-based (Ανταγωνιστικά) Protocols:**
  - The aim is to **minimize collisions** and **better utilize the bandwidth by determining**:
    - **When** a station **can use the channel**.
    - **What** a station **should do** when the **channel is busy.**
    - **What** a station **should do** when is **involved in a collision.**
  - Examples of Contention-based protocols are the **Random Access Protocols (Πρωτόκολλα Τυχαίας Πρόσβασης)**:
    - Pure (P) - ALOHA,
    - Slotted (S) - ALOHA,
    - Carrier Sense Multiple Access (CSMA) & its variants (και οι διαφορετικές εκδοχές του)

Multiple Access Protocols Contention-based

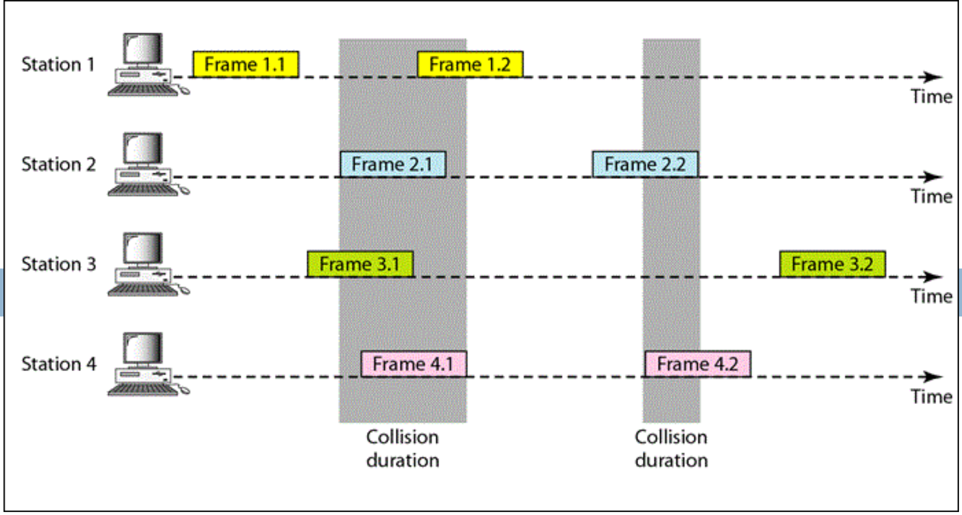
- **Contention-based (Ανταγωνιστικά) Protocols:**
  - Typically used in **Infrastructure-less based Networks (e.g., Ad Hoc Networks),** where all the stations transmit using **the same channel**.
  - Also can be used **in an infrastructure based network** (i.e., Cellular Network), for **exchanging control information** between a Mobile Station and the Base Station **before a (control and traffic) channel is established between them.**
    - **Note that, in infrastructure-based networks, before a control channel is established between the Base Station and the Mobile Station, the Base Station is not aware about the existence of the Mobile Station and thus have no control over it.**

Random Access Protocols

- ALOHA
  - Pure (P)-ALOHA
  - Slotted (S)-ALOHA
- CSMA (Carrier Sense Multiple Access)
  - CSMA
  - CSMA/CD (CSMA with Collision Detection)
  - CSMA/CA (CSMA with Collision Avoidance)

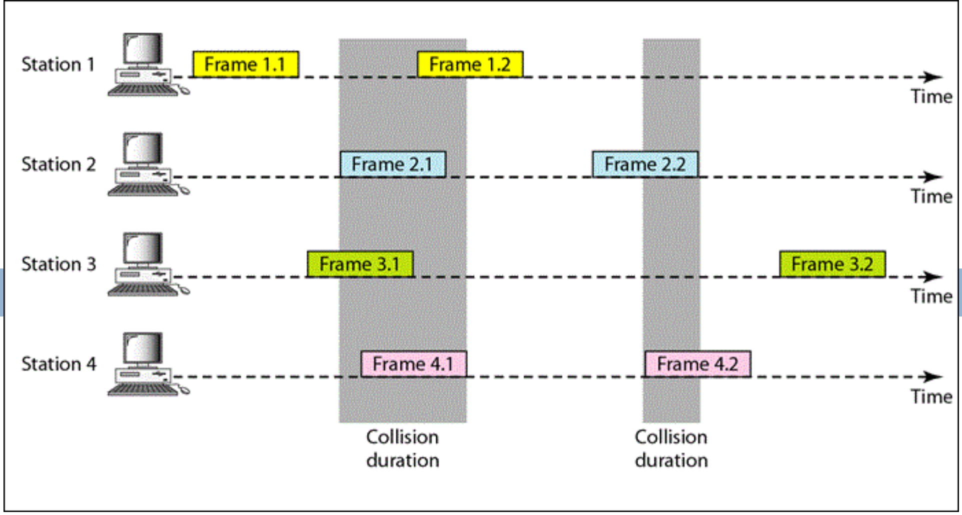


ALOHA
Pure ALOHA



- *Developed in the 1970s for a packet radio network by Hawaii University.*
- With Pure ALOHA **each station sends a frame whenever it has a frame to send (without requesting any permission)**.
- However, since there is **only one channel to share**, there is the **possibility of collision between frames from different stations**.
- The pure ALOHA protocol **relies on acknowledgments (ACK) from the receiver, to indicate if the frame have been received successfully.**
    - If the **acknowledgment does not arrive after** a **time-out period**, the **station assumes** that the **frame** has **been destroyed.**

ALOHA
Pure ALOHA



- A **collision involves two or more stations**.
- If all the stations that were involved in a collision try to **resend their frames after the time-out period**, the **frames will collide again**.
- Thus, **when the time-out period passes**, **each station waits a Random Amount of time** before resending its frame.
  - The **randomness will help avoid more collisions**. We call this time the **Back-off time** (T_B)
  - After a **maximum number of retransmission attempts (Kmax)** a **station must give up and try again later → Prevents congesting the channel** with retransmitted frames - αποφεύγει την συμφόρηση του καναλιού.

ALOHA
Pure ALOHA – Procedure used

- **With Pure ALOHA, all frames from any station** are **equal in size** and of a **fixed length** (**L bits**)
- Since **all stations produce frames with equal frame lengths**, all the stations need **equal** ***Transmission Time*** ***(T_{fr})**** to **transmit their frames.**
- A **station that has a frame ready to be send,** can **transmit at any time.**

Transmission Time (T_{fr}): *The time* ***from the first bit*** *until the* ***last bit of a frame*** *has* ***left*** *the* ***transmitting node****.*

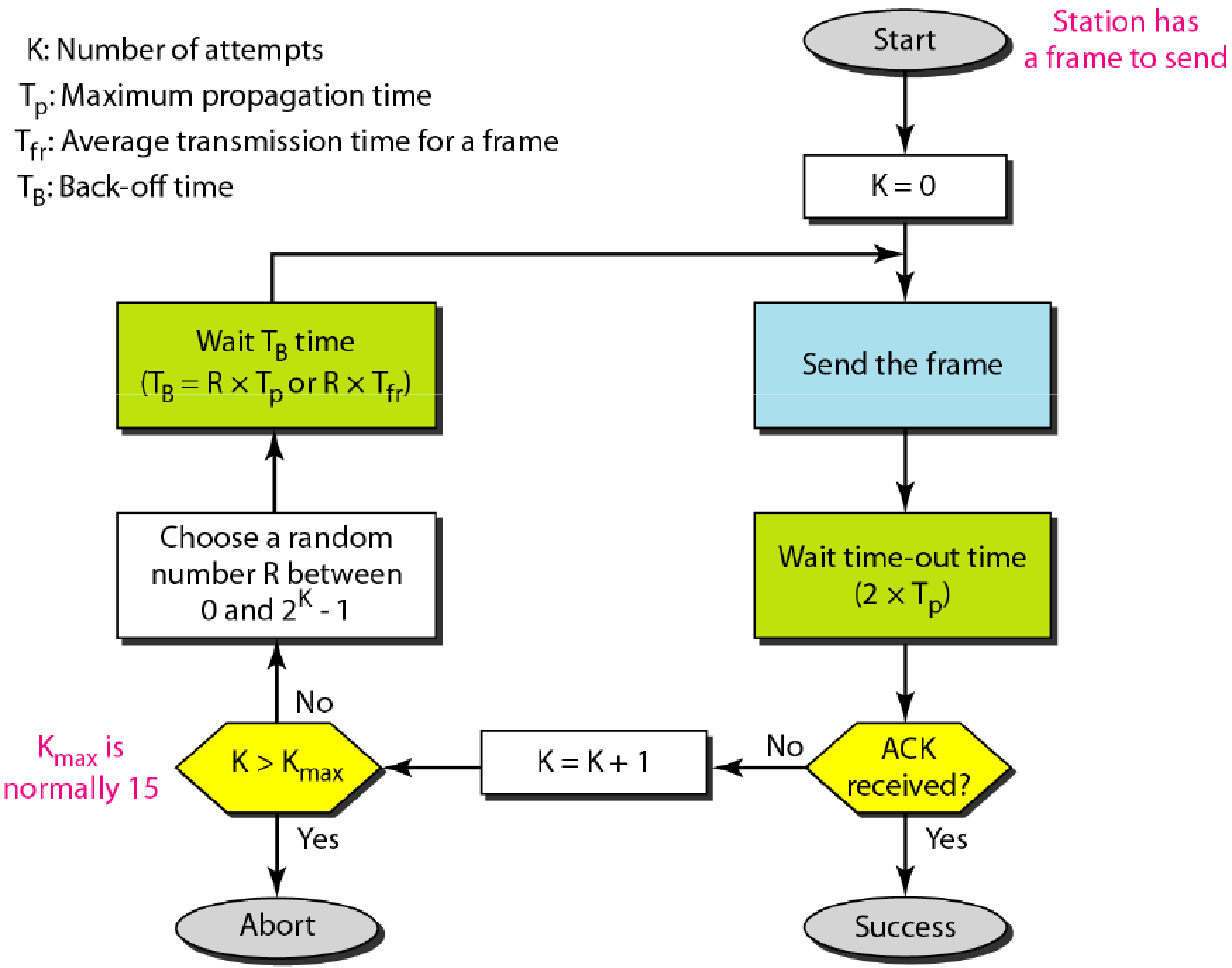
T_{fr} = Frame Size (in bits) / Bit Rate of the Channel (in bits/sec)

ALOHA
Pure ALOHA – Procedure used

- **After transmitting a frame**, the sender **waits** for **an acknowledgment (ACK)** for an **amount of time equal to** the **maximum Round-Trip *Propagation Delay**** = 2 x T_p
- If **no ACK** is received, the **sender assumes that the frame has been destroyed.**
- Then**, it waits for a Random amount of time (Back-off time)** and **resends that frame.**
- If the station **fails to receive an ACK after** a specific number of **repeated transmissions** (K_{Max}), it **gives up and tries again in a later time.**

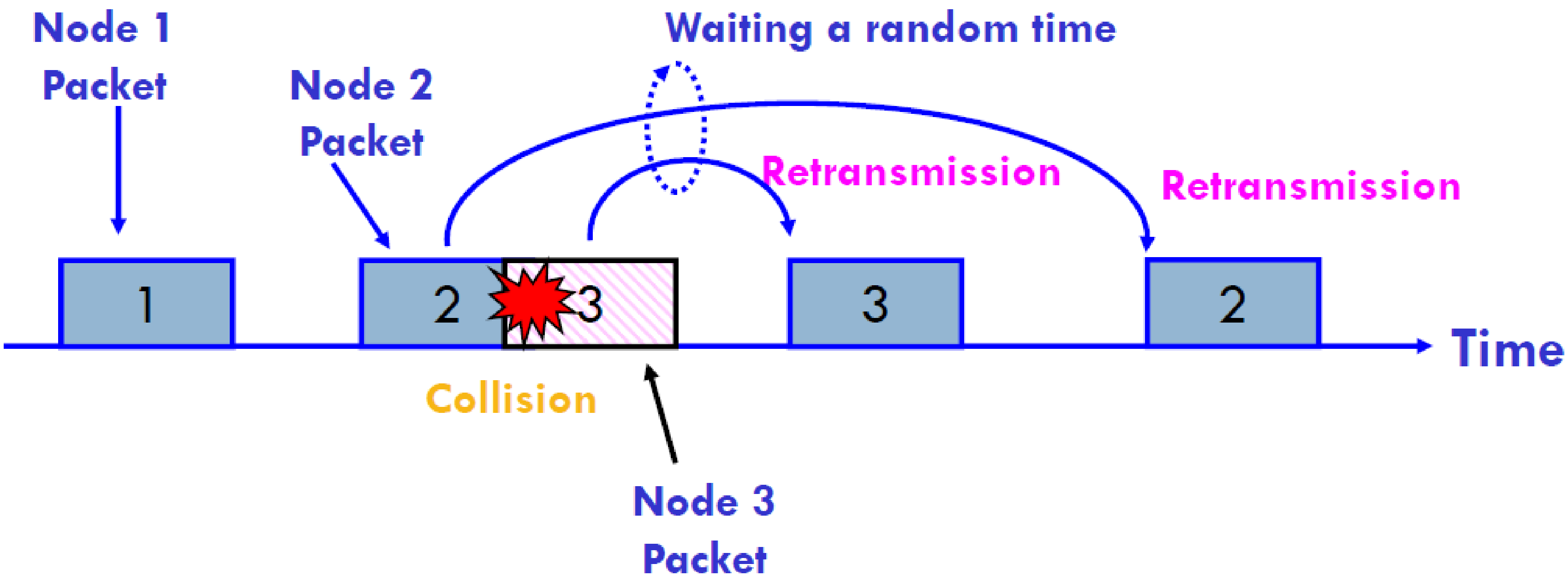
Propagation Delay(T_p): *The Time it takes for a bit of a frame to travel between two separated stations.* ***T_p = Distance / Velocity of signal (speed of light)***

ALOHA
Pure ALOHA – Procedure used



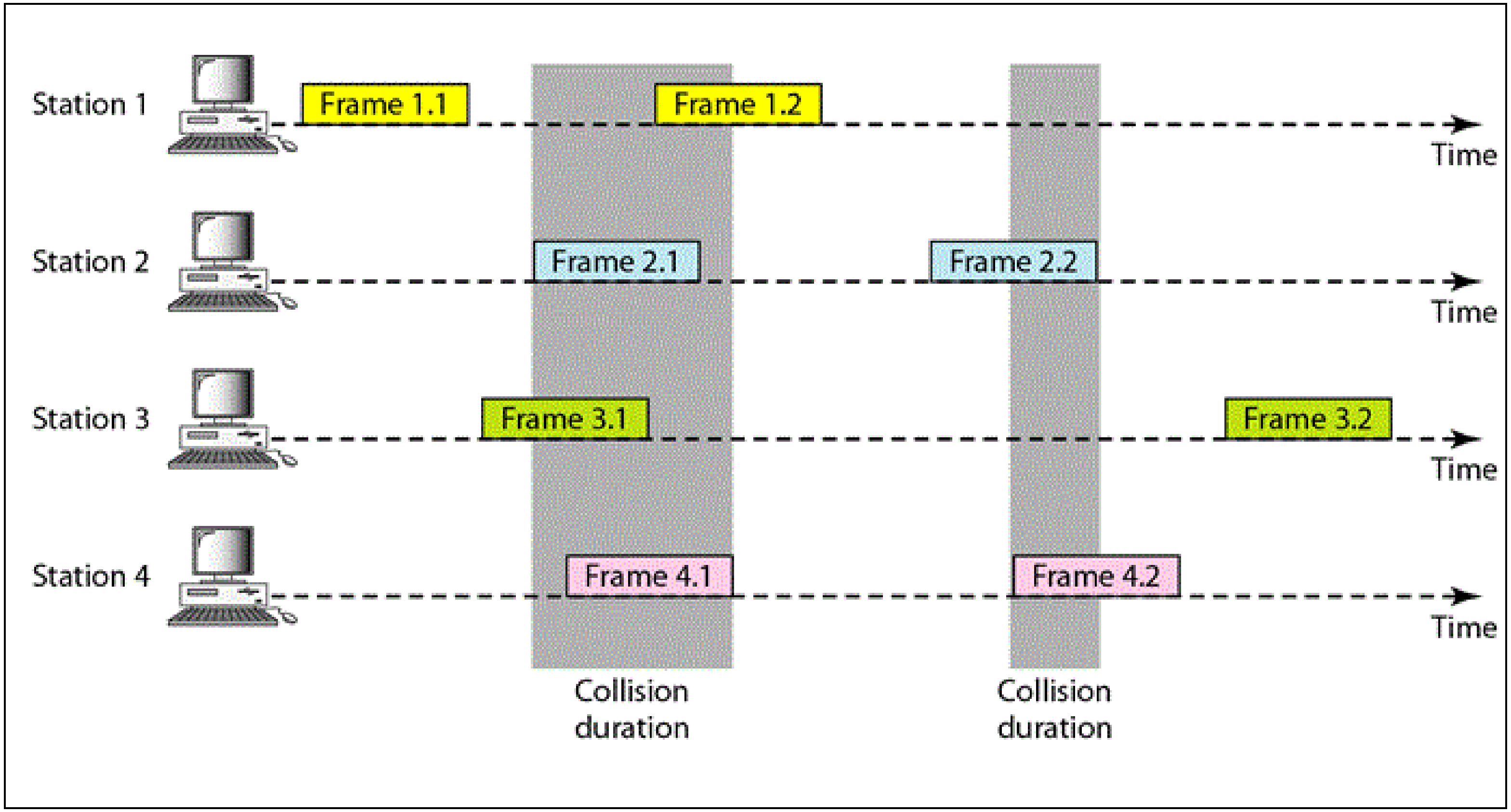
ALOHA
Pure ALOHA

- Collision avoidance mechanism
  - The stations (nodes) involved in a collision **retransmit their frames after a Random Period of time**.



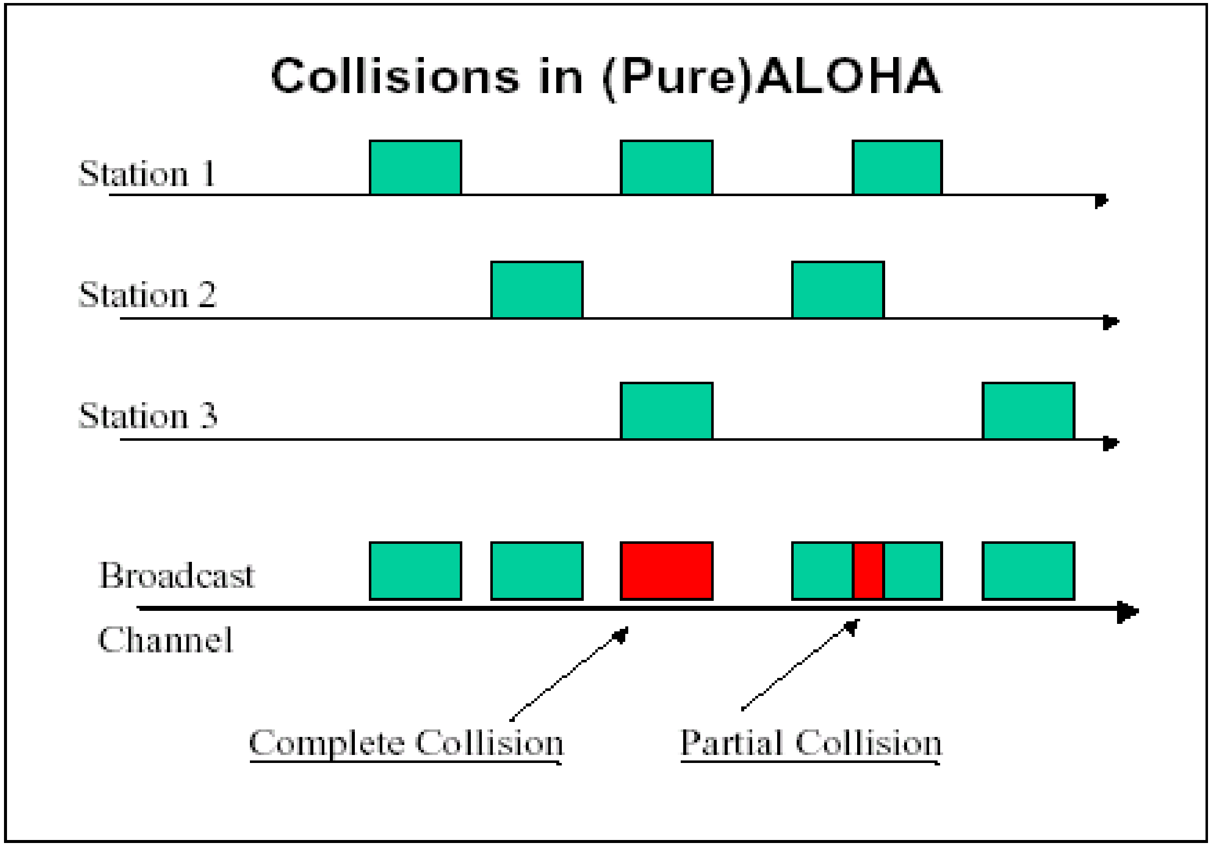
ALOHA
Pure ALOHA

- Frames transmission in a Pure ALOHA Network
  - **Collision involves two or more stations**



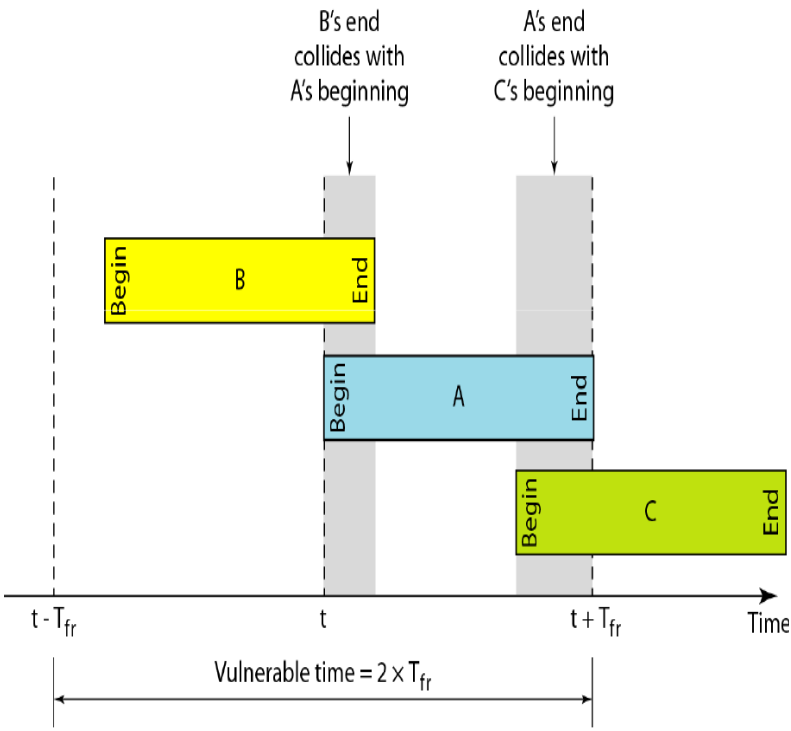
ALOHA
Pure ALOHA

- Collisions in Pure ALOHA (Complete and Partial)



ALOHA
Pure ALOHA – Vulnerable Time

- Let **t** be **the time at which the sender A wants to send a frame** and T_{fr} is the **frame time** *(Number of Bits in Frame / Bit Rate of the Channel).*
- In order to avoid any collisions, if the sender A starts transmission **at time t,** it **needs all other stations (e.g., sender C) to refrain from transmitting** during the time **from t to t +** T_{fr}.
- Also it **needs all other stations (e.g., sender B)** to **refrain from transmitting within one frame time (**T_{fr}**)** before its start. Thus **all other stations should refrain from transmitting during the time from t –** T_{fr} **to t**, otherwise they will collide.
- Thus, the **vulnerable period (η ευάλωτη περίοδος για συγκρούσεις)** for the frame of A's is **2 x** T_{fr}. **(from t -** T_{fr} **to t +** T_{fr}**)**



ALOHA
Pure ALOHA – Vulnerable Time Example

- **Example: A pure ALOHA network transmits 200-bit frames on a shared channel of 200 kbps. What is the Vulnerable time? Assuming that a station is sending a frame at time *t*, what is the requirement in order to make the frame collision-free?**

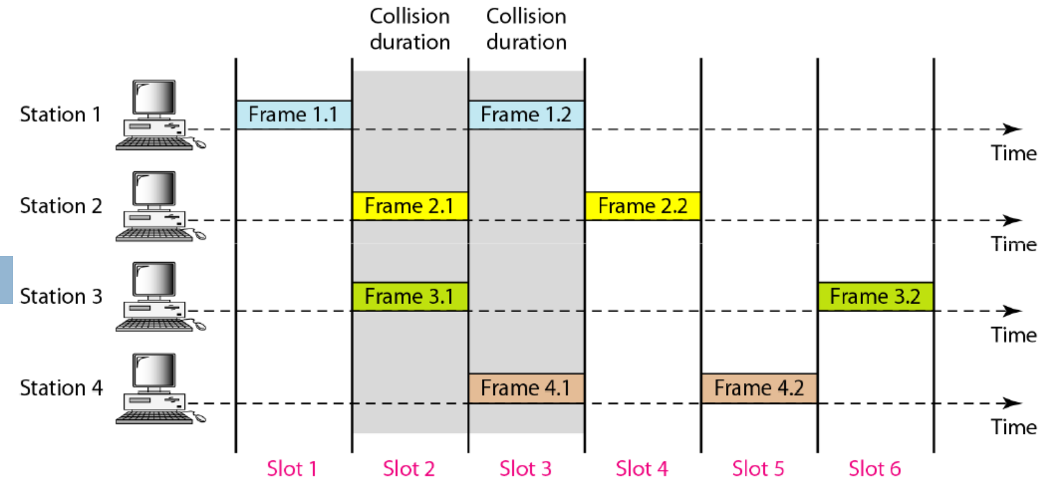
- **Solution:**
  - **Frame Transmission Time (T_{fr})** = 200 bits/200 kbps = 1 ms.
  - The **Vulnerable Time** is 2 × 1 ms = **2 ms**.
  - Assuming that **a station is sending a frame at time t,** this means that **no other station should send a frame within the period** of **t – 1 ms** and **t + 1 ms**.

ALOHA
Pure ALOHA – Efficiency of Throughput

- **Efficiency of Throughput** is the **percentage of the transmitted frames that arrive successfully** (**without collisions**).
- Pure ALOHA maximum efficiency of Throughput is ~18%. More specifically:
  - If we transmit **F** frames/s, then on average **0.18 * F frames** will **arrive successfully**, without the need of retransmission.

Throughput *or* ***network throughput*** *is the rate of successful message delivery over a communication channel. A typical method of performing a measurement is to transfer a 'large' file from one system to another system and measure the time required to complete the transfer or copy of the file. The* ***throughput is then calculated*** *by* ***dividing*** *the* ***file size*** *by the time required to complete the transfer. Then the throughput can be* ***measured*** *in* ***megabits***, ***kilobits***, *or* ***bits*** *per* ***second***.

ALOHA
Slotted ALOHA



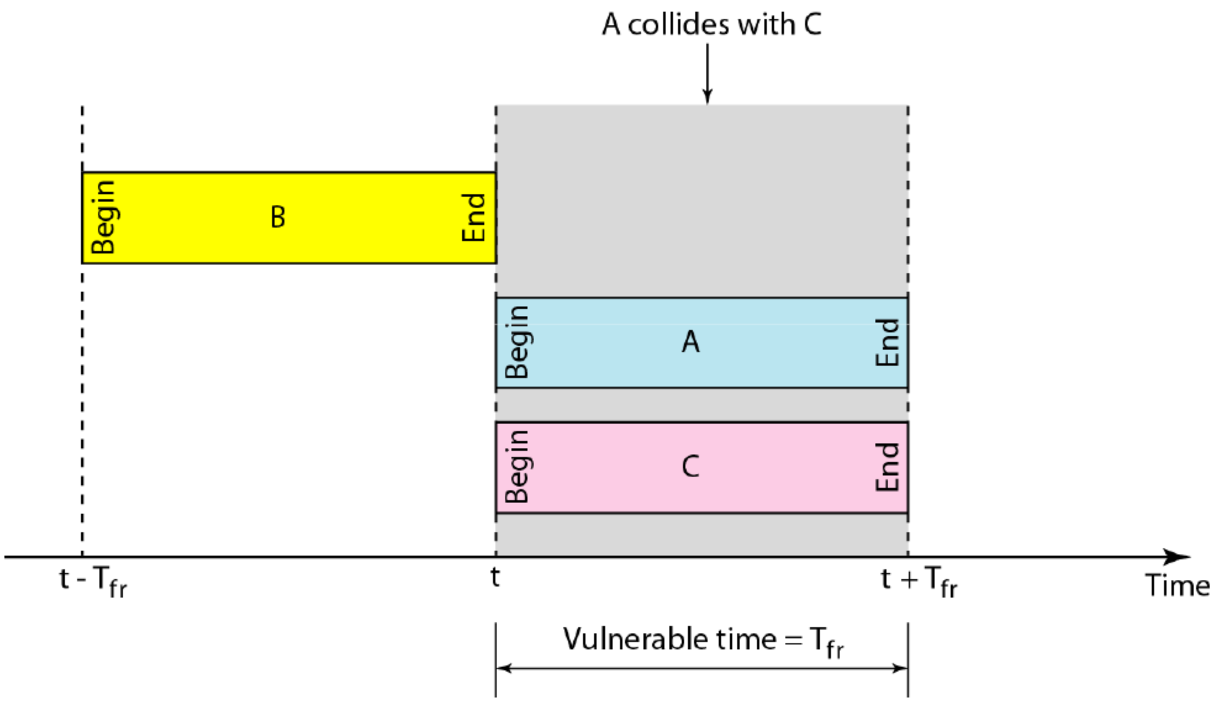
- **Was invented to improve the efficiency of throughput of Pure ALOHA, by reducing the vulnerable time of** Pure ALOHA (Pure Aloha has a **vulnerable time** of **2 x T_{fr})**
- To achieve the aforesaid, in slotted ALOHA the **time is divided into slots** (**each slot of period equal to T_{fr}**) and **force the station** to **send only at the beginning of the time slot**.
- A **central clock** or a **station, informs** all stations **about the start of a each time slot**.
- Because a station is **allowed to send** only at the **beginning of the synchronized time slot**, **if a station misses this moment**, it must **wait until the beginning of the next time slot**.

ALOHA
Slotted ALOHA

- Of course, there is **still the possibility of collision** if two stations **try to send at the beginning of the same time slot**.
- However, **the vulnerable time is now reduced to half (**equal to **T_{fr})**.
  - **By reducing the Vulnerable time from $2xT_{fr}$ to T_{fr}, Slotted ALOHA managed to increase** the **maximum channel throughput to ~37%**

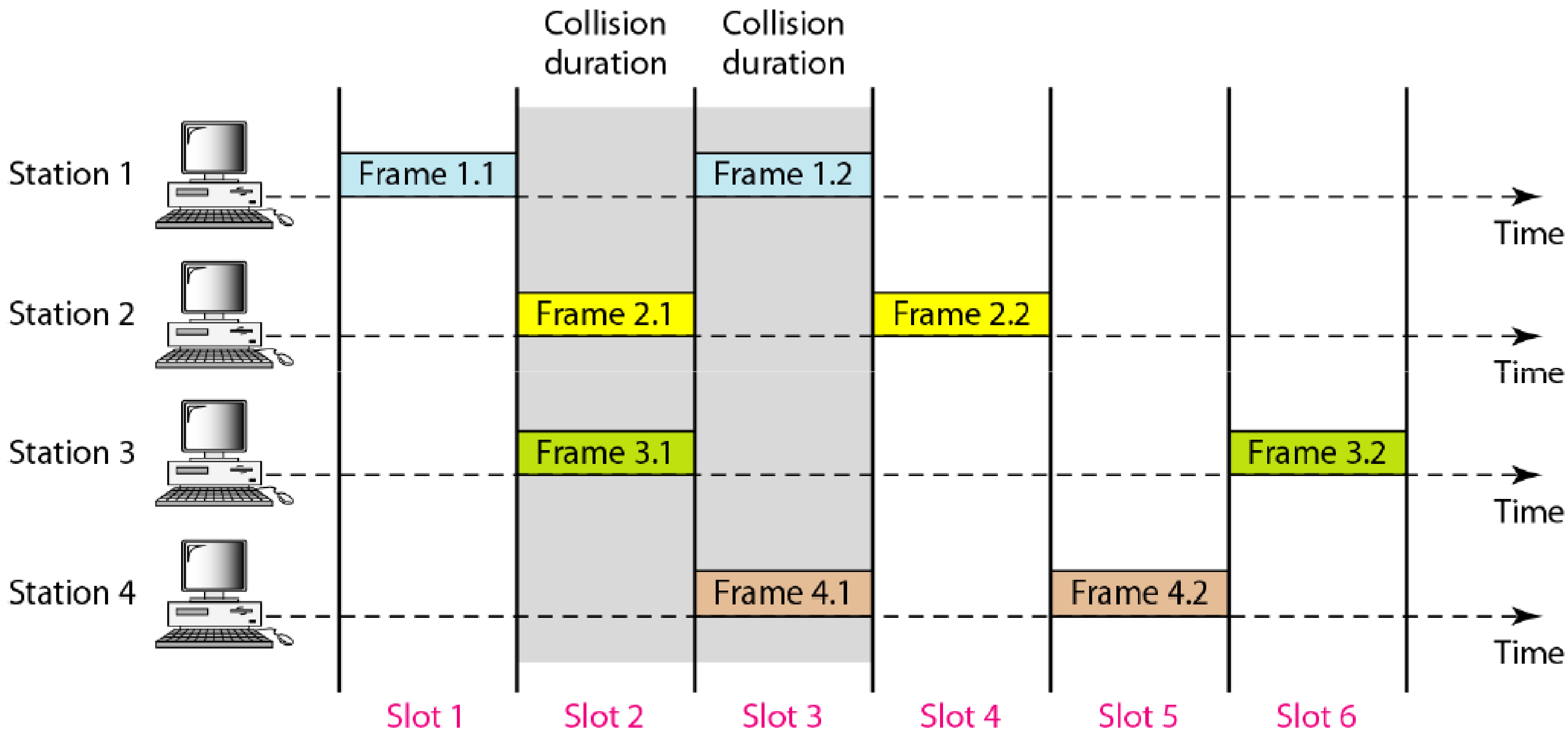
ALOHA
Slotted ALOHA – Vulnerable Time

- The only case that frames of two or more stations can collide is only when the stations transmit their frames using the same time slot → Vulnerable time = $T_{fr.}$



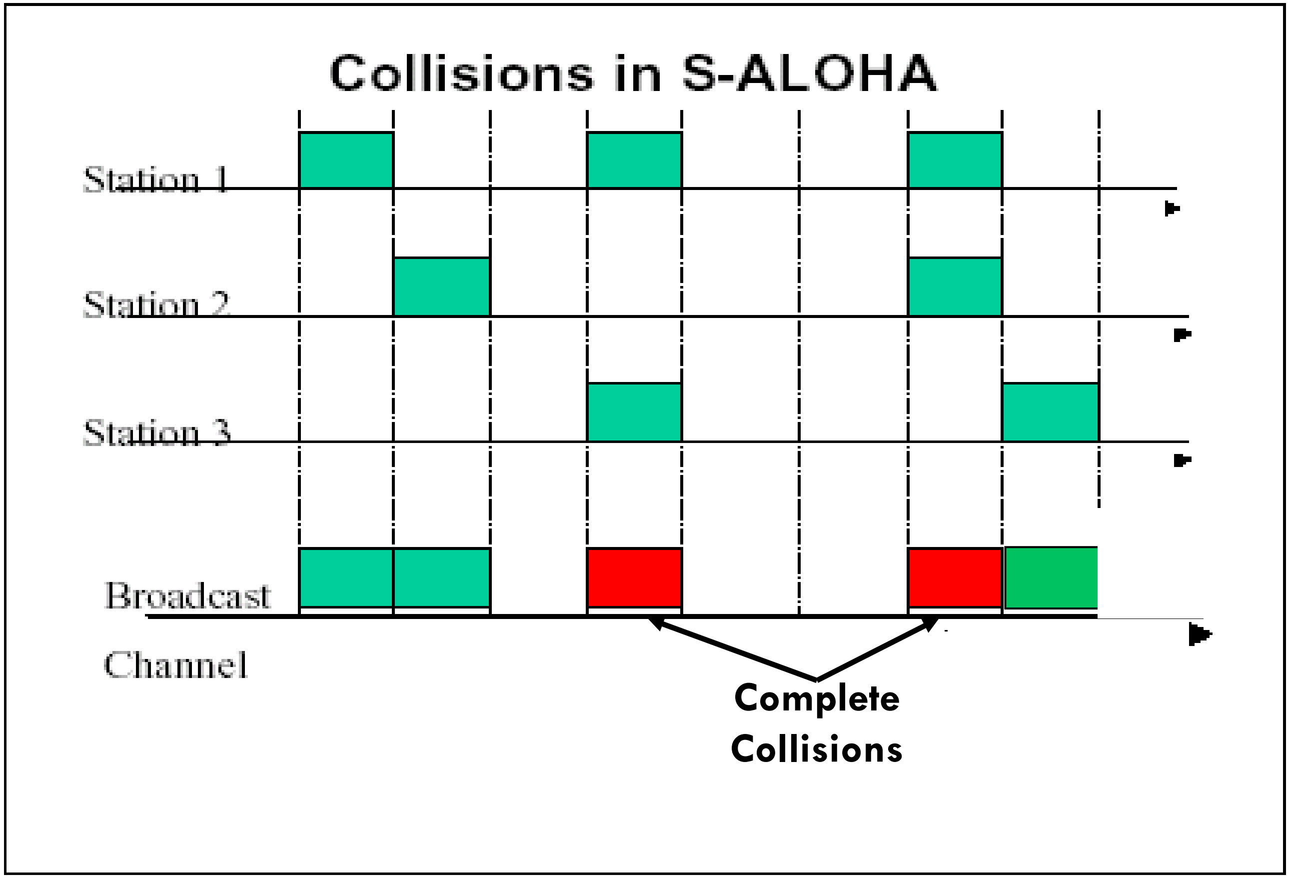
ALOHA
Slotted ALOHA

- Frames transmission in a Slotted ALOHA Network



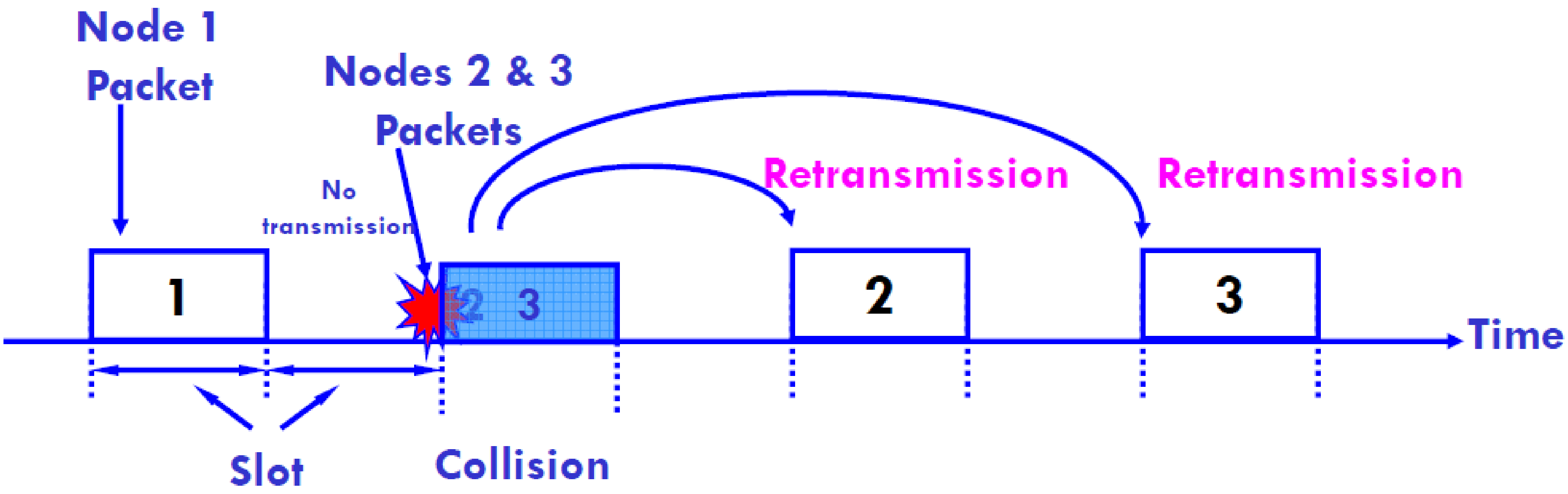
ALOHA
Slotted ALOHA

- Collisions in Slotted ALOHA (Only Complete Collisions)



ALOHA
Slotted ALOHA

- Collision avoidance mechanism
  - Similar to the Pure Aloha. **Retransmission takes place in random selection of a slot time.**



ALOHA
Advantages and Disadvantages

- **Advantage of ALOHA protocols**
  - A station that has frames to be transmitted (i.e., an active station) **can transmit continuously** at the **full rate of channel** (R bps), **if it is the only station with frames**.
  - **Very simple to be implemented**
  - **No master station** is **needed** to control the medium
- **Disadvantage of ALOHA protocols**
  - If the **number of active stations increases**, the **possibility of collisions** is also **increased**.
    - This causes **low channel utilization (i.e., low throughput)**

CSMA (Carrier Sense Multiple Access)

- **CSMA Basic**
  - **Improvement compared to ALOHA protocols:** Stations **does not** just **transmit immediately** when they have a frame to send. **First they sense the channel** and start frame transmission only **if no other transmission is ongoing**.
- **CSMA/CD (CSMA with Collision Detection)**
  - **Improvement**: Stop ongoing frame transmission if a collision is detected. → *Cannot be used with Wireless Transmissions*
- **CSMA/CA (CSMA with Collision Avoidance)**
  - **Improvement**: Senses both the medium and the "possibility of collision" before start transmitting a frame, in order to avoid collisions.
  - **CSMA/CA with ACK:** Enhances reliability of the Acknowledgements
  - **CSMA/CA with RTS/CTS:** Solves the Hidden Terminal Problem

CSMA (Carrier Sense Multiple Access)

- The maximum throughput achievable by Slotted ALOHA is only **36.8%.**
  - Thus, with Slotted ALOHA if we transmit **F** frames/s, then **0.368 * F frames** will **arrive successfully** on average without the need of retransmission)
- **We need to find another way** of **improving throughputs** and **supporting high-speed communication networks.**
- **CSMA** gives **improved throughput** **compared** to **ALOHA** protocols.
  - **Significantly minimizes potential collision** in a shared channel **by simply having the terminals listening (sensing) to the channel before transmitting a frame!!!**

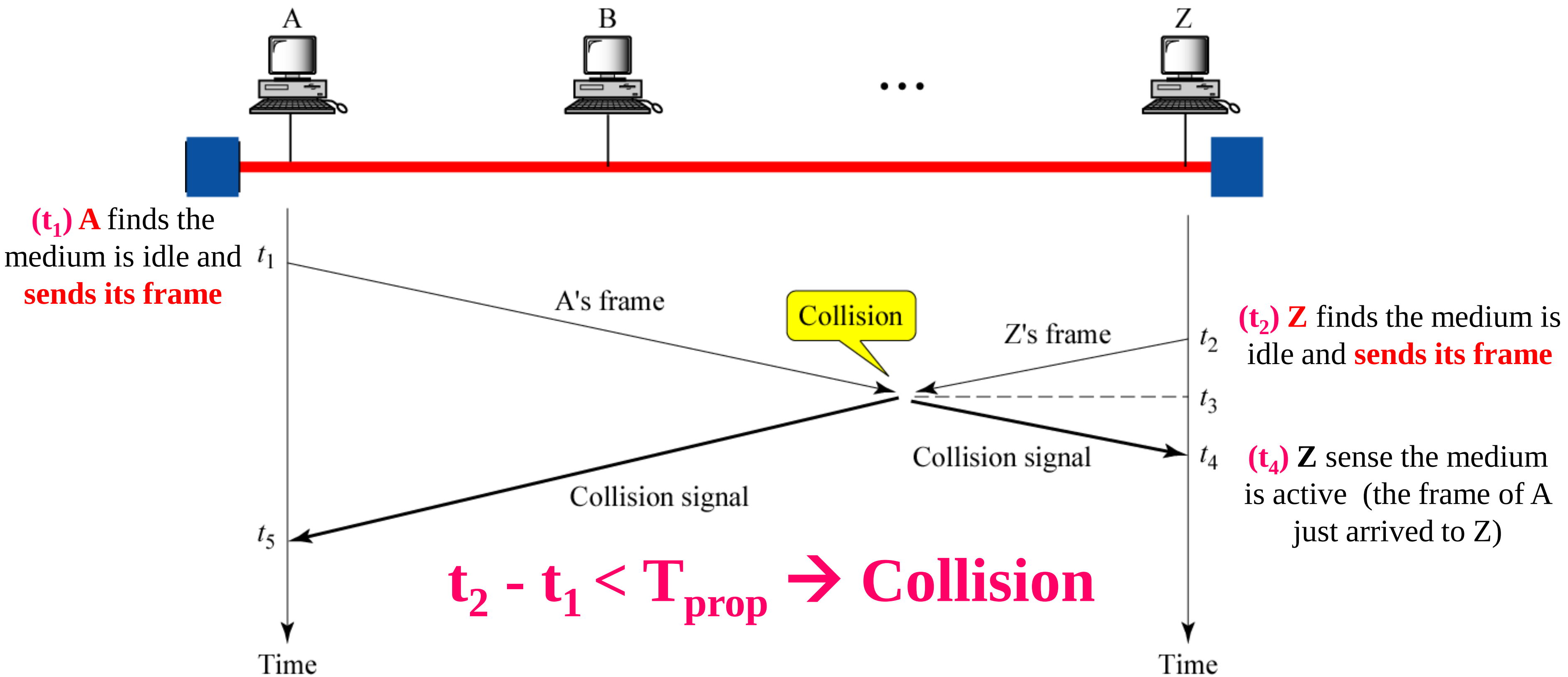
CSMA (Carrier Sense Multiple Access)

- CSMA protocols are **based on the fact** that **each station on the network is able to monitor the status of the channel before transmitting information**.
  - **Listens to the channel before transmitting a frame** (avoid avoidable collisions – αποφεύγει συγκρούσεις που θα μπορούσαν να αποφευχθούν).
  - Can **reduce the possibility** of **collision but cannot eliminate it.**

Question: Why may there be a collision, if each station listens to the channel before transmitting a frame?

Answer: Possibility of collision still exists because of Propagation Delay. When a station sends a frame, it takes time (T_p) for the first bit to reach every station and for every station to sense it.

CSMA (Carrier Sense Multiple Access) Collisions



Vulnerable period for CSMA: Equals to the Propagation Time

(T_{prop}; the time needed for the signal to propagate from one end of the channel to the other)

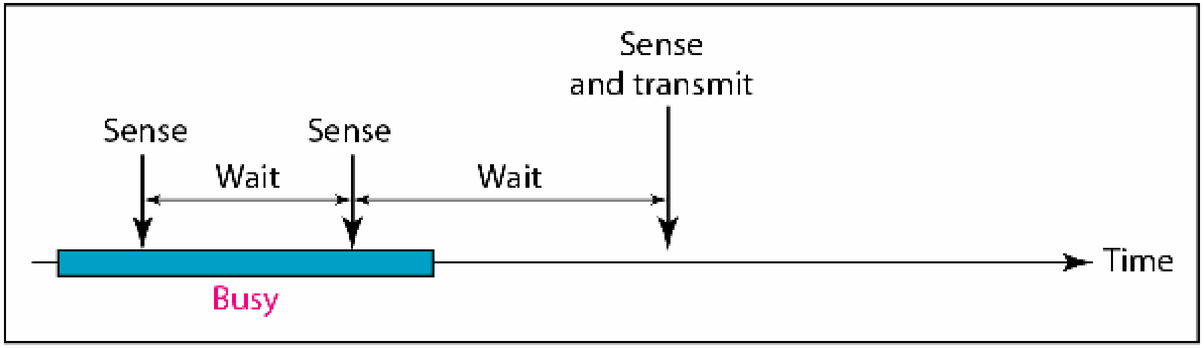
CSMA (Carrier Sense Multiple Access) Types of CSMA Protocols

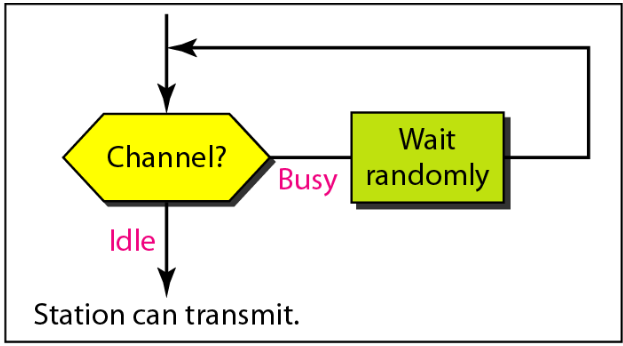
- **Types of CSMA**
  - Non-Persistent CSMA
  - Persistent CSMA
    - 1-Persistent CSMA
    - p-Persistent CSMA

- Different types of CSMA protocols that **determine**:
  - **What** a station **should do** when **channel is idle**?
  - **What** a station **should do** when **channel is busy**?

CSMA (Carrier Sense Multiple Access) Non-Persistent CSMA

- The station **senses the channel first whenever it has a frame to send**.
  - If the channel is **busy**, the station **waits for a random amount of time** and **senses the channel again**.
  - If the channel is **idle**, the station **transmits the frame immediately**.
  - If a **collision** occurs, the station **waits for a random amount of time** and **starts all over again**.
- Non-persistent Stations are **deferential (respect others)**



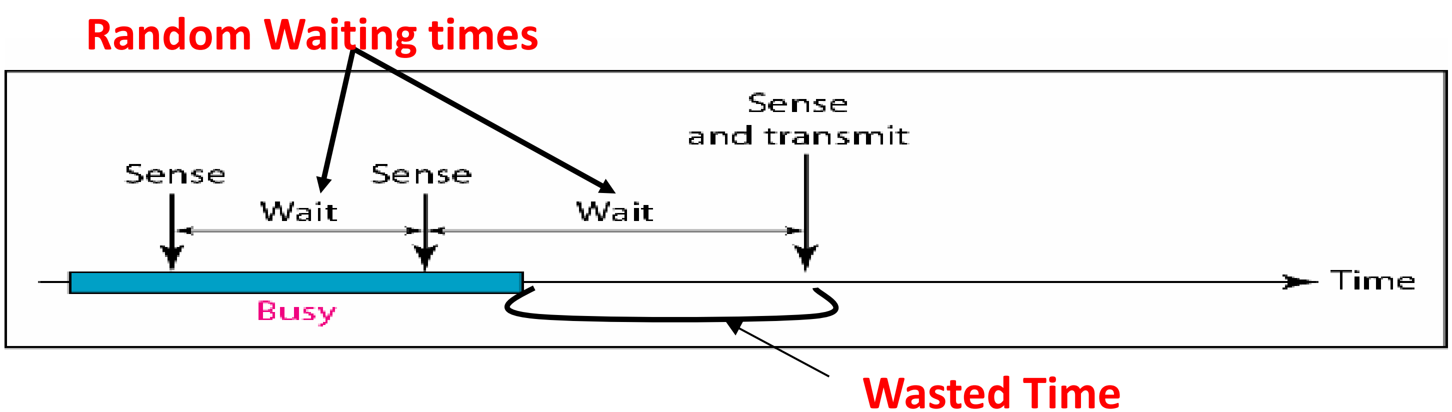


CSMA (Carrier Sense Multiple Access) Non-Persistent CSMA

- **Performance**:
  - By having the station **sensing the channel before transmitting** **its frames, the possibility of a collision is highly reduced (since the vulnerable time is Reduced to T_{prop}) and thus the throughput is increased.**
  - **Random selection of waiting time (when the medium is found busy) reduces probability of collisions** because two stations with frames to be transmitted, will **wait for different amount of times**.

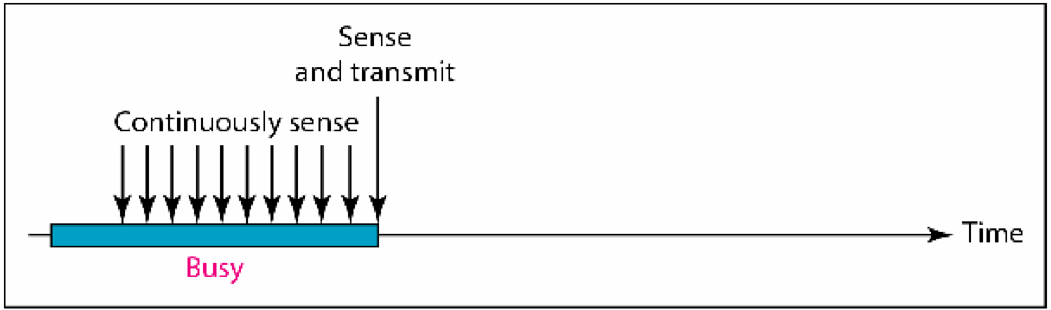
CSMA (Carrier Sense Multiple Access) Non-Persistent CSMA

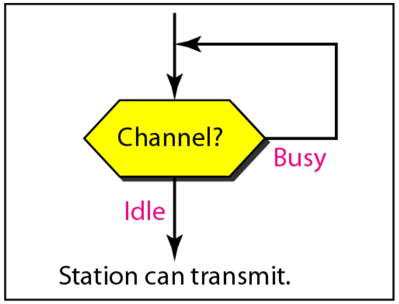
- **Performance**:
  - However, **Bandwidth is wasted** if the **waiting time** selected is **large**.
    - This is because **following an end of a transmission**, the **channel will remain idle**, **even if one or more stations have frames to send** (reduces spectral efficiency)



CSMA (Carrier Sense Multiple Access) 1-Persistent CSMA

- **1-Persistent CSMA** is used to **avoid idle channel time.**
- The **station** **continuously senses the channel** when it has a frame ready to send.
  - If the channel is **idle** the station **transmits immediately**;
  - If the channel is **busy**, the station **keeps listening to the channel** and **transmits** the frame **immediately** **after the channel becomes idle**
  - If a **collision** occurs, the station **waits** **for a** **random amount of time** and **starts all over again**.



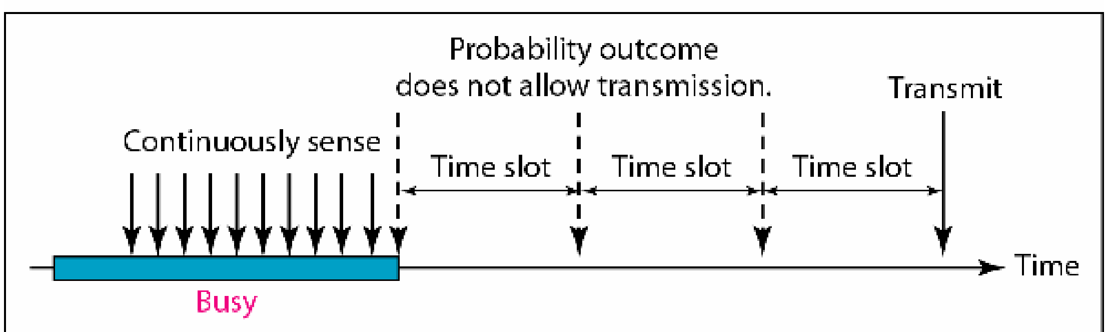


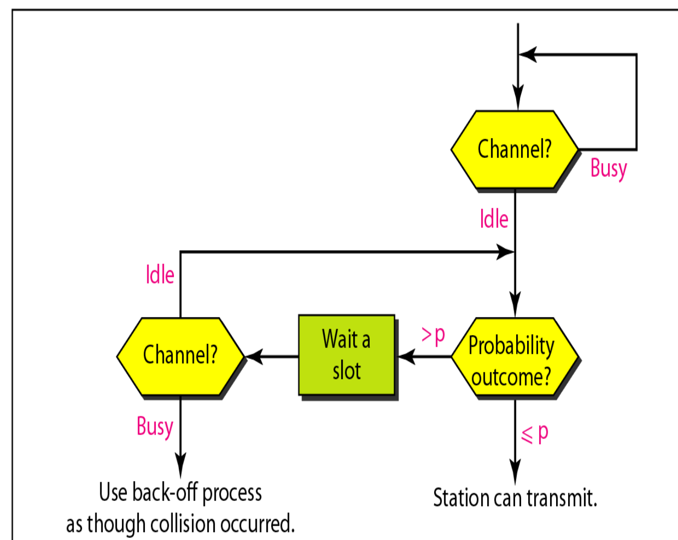
CSMA (Carrier Sense Multiple Access) 1-Persistent CSMA

- **Performance:**
  - 1-persistent stations are **selfish**
  - Is called 1-persistent because the station **transmits with a probability of 1** whenever **it finds the channel to be idle**.
  - **Increases** the **chance of collisions if two or more stations** have **ready frames** to be **transmitted** at the **same time**
  - **They will both wait for the channel to become free,** and thus they will **start transmitting their frames at the same time → Collision is Guaranteed**!

CSMA (Carrier Sense Multiple Access)
p-Persistent CSMA ($0 \le p \le 1$)

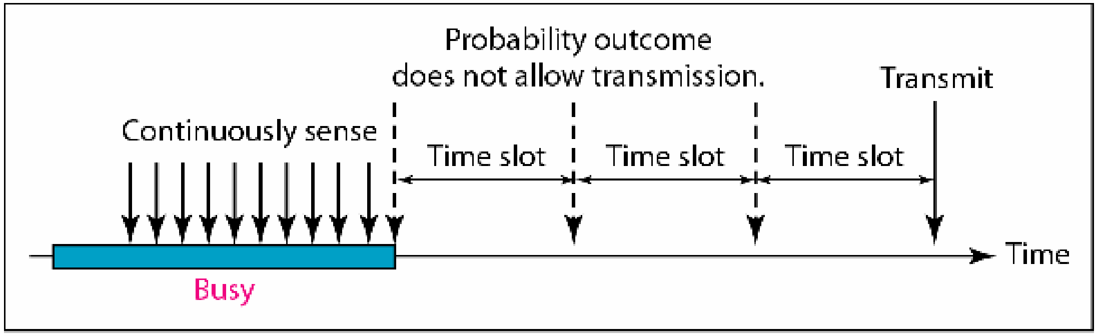
- **Time is divided into slots** where each time slot typically equals to the **Round Trip Propagation delay time (2 x T_{prop})**.
- The **MS senses** the channel **when it has a frame to send**.
  1. If the **medium is idle**, then the station **estimates a random number (P_r)** between 0 and 1.
     - **If** ($P_r \le p$) then the station will **transmit the frame, OR**
     - **If** ($P_r > p$) **the station refrains (αναβάλει) transmission** until the **next slot**, then repeat from 1**.**

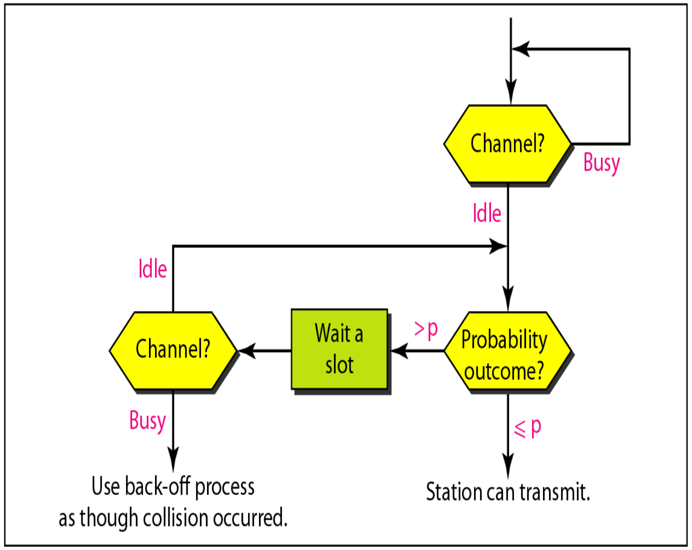




CSMA (Carrier Sense Multiple Access)
p-Persistent CSMA ($0 \le p \le 1$)

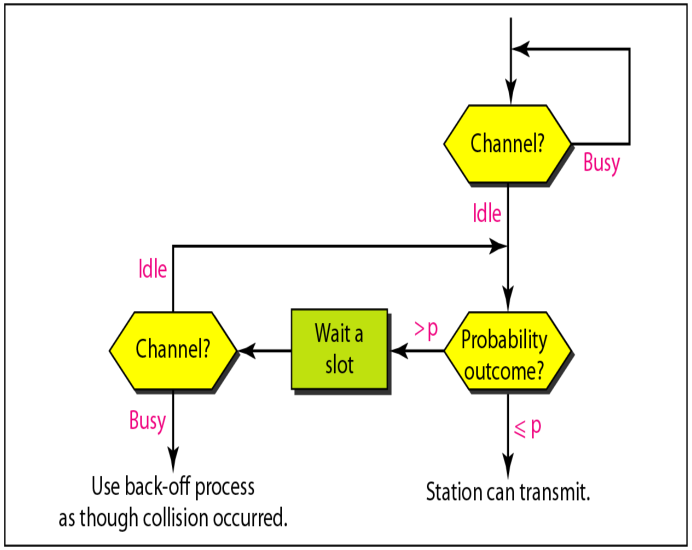
2. If the **channel is busy**, the station will **continuously listen** to the channel **until** the channel **becomes idle**, and then repeat from 1.
3. If a **collision occurs**, the MS **waits for a random amount of time** and **starts all over again by sensing the channel**.





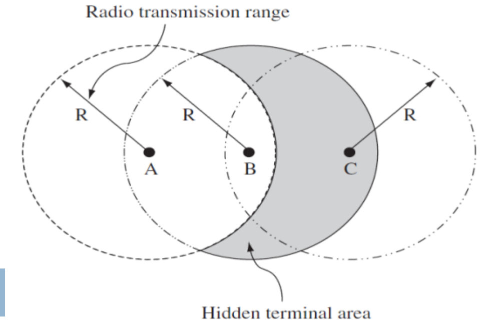
CSMA (Carrier Sense Multiple Access)
p-Persistent CSMA

- **Performance**
  - **Reduces** the **possibility** of **collisions**
  - **Reduces channel idle time**



- **p has to be selected with care**
  - If **p small**, then **more wasted time**
    - Because if **p** small, the **possibility to have**, in some cases, **all stations refraining from transmission** will be **higher**. **No station** will **use the channel** at some periods of time.
  - If **p large, more collisions**
    - Because if **p** large, the **possibility to have more than two stations transmitting** at the **same time** be higher and thus **more collisions will occur**.

Hidden Terminal Problem

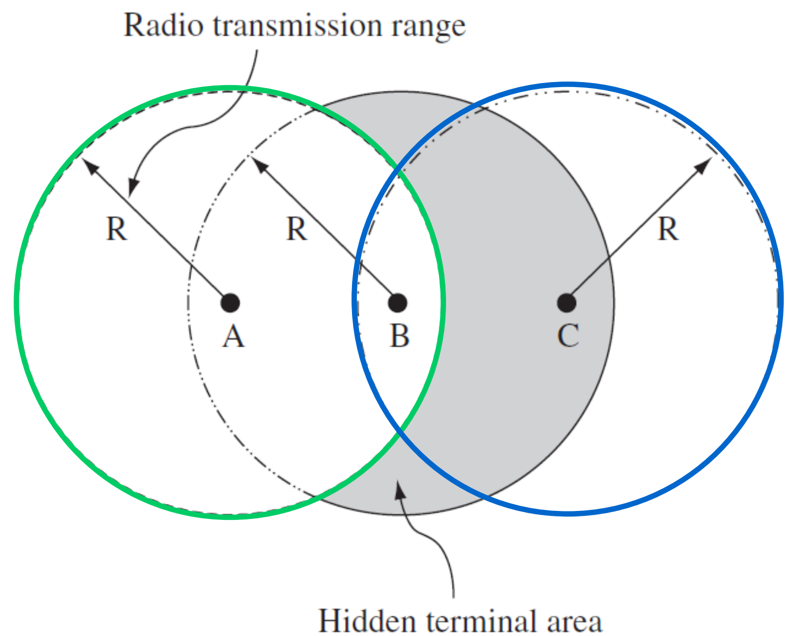


- CSMA protocol and its variants can reduce collisions drastically, however it **still suffers** from a **problem** called **Hidden Terminal.**
- **Hidden Terminals** refer to the stations that are **out of each others' radio transmission and sensing range** **(for example A and C)**.
  - For example this can occur in an **ad hoc (i.e., infrastructure-less) wireless network** where the stations are **randomly distributed** (τυχαία διασκορπισμένα).
  - Wireless stations **have limited transmission ranges** and **not all stations are within the radio range of each other (and thus cannot sense their transmissions)**.
- **The Hidden Terminal Problem** occurs when two or more **Hidden Terminals (A and C)** are **sending their frames simultaneously, to a Terminal that is located in their common coverage area (B)**.

Hidden Terminal Problem

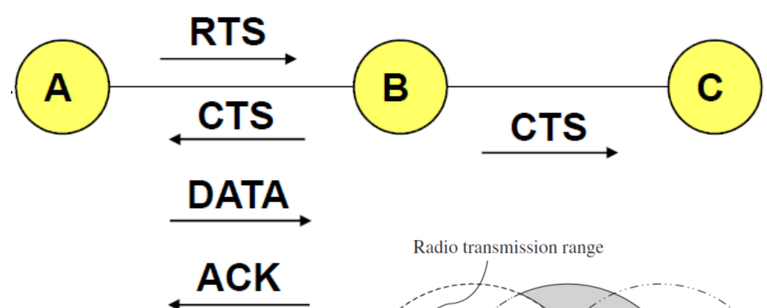
Example: Hidden Terminal Problem

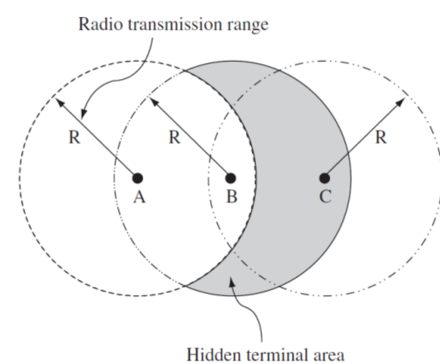
- Stations **A** and **C** can communicate with Station **B**
- But Station **A** and **C** **cannot hear each other** since they are out of each other's radio transmission/sensing range (**Hidden Terminals**).
- Station **A** transmits to Station **B**
- If Station **C** "senses" the channel, it **will not hear** Station **A**'s transmission and **falsely conclude** that it **can begin a transmission** to Station **B**.
    - Which will **cause a collision** at Station **B**.



CSMA/CA with RTS/CTS (Request To Send/Clear to Send)

- **CSMA/CA with RTS/CTS** can overcome the Hidden Terminal Problem by **using handshake frames exchange (RTS and CTS) before starting transmitting their frame.**
- Assume that Station **A** is ready for transmission to Station **B**
  - Station **A** broadcasts a **RTS** frame to Station **B**.
  - After receiving the frame, Station **B** replies with a **CTS** frame back to Station **A**, **accepting the transmission**.
  - Hidden Station **C** which is in the transmission range of Node **B**, **receives** (senses) the **CTS** frame.
    - Therefore, Node **C knows that** Node **B is in communication with another station** and it **will refrain** (enter a delayed access state) **from any transmission.**





Channelization Protocols - Multiple Division Techniques for Traffic Channels

- **FDMA (Frequency Division Multiple Access)**
- **TDMA (Time Division Multiple Access)**
- **CDMA (Code Division Multiple Access)**
- **OFDMA (Orthogonal Frequency Division Multiple Access)**

Introduction

- The Random Access Protocols discussed in the previous slides **coordinates access of multiple sending/receiving stations using the same channel** (i.e., **only one station is allowed to transmit at given point in time** otherwise their **frames will collide**)

- **These Random Access Protocols can be used in Infrastructure-less based Networks (Ad Hoc networks)** for **exchanging data** between the Mobile Stations (MSs).

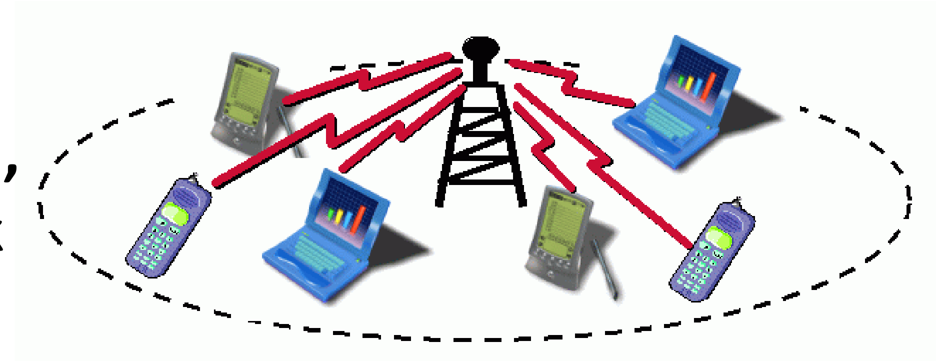
Introduction

- **They can also be used in Infrastructure based networks**, for **exchanging control information between a MS and the BS, before a dedicated channel is allocated to them.**
  - ***Note that, before a connection is established between the BS and the MS (e.g., just when the MS is switched on), the BS is not aware about its presence in its coverage area and thus have no control over the MS.***
  - *The **MS makes itself known to the BS** by sending to it a **control message** indicating **its readiness to send information to the BS.***
  - ***The channel used to send this control message is the same for all MSs in the BS's coverage area → A Random Access Protocol is used, to coordinate the transmissions of all the new MS requesting access to connect.***
  - ***The BS**, in turn, **advises the MS which particular traffic channel** is to **be used exclusively by that MS** for **actual information exchange**.*

Introduction

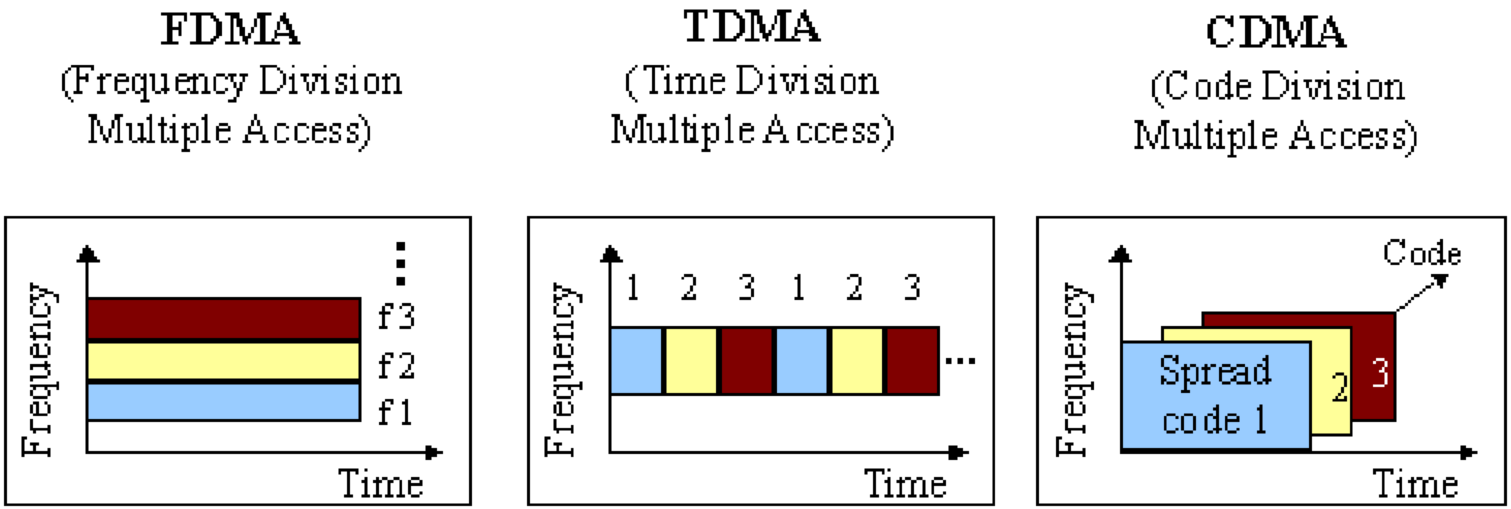
- In a wireless infrastructure-based environment, a **BS needs to establish a radio connection for all the MSs in its transmission range**.
- Thus, there is a need to address the issue of **simultaneous multiple access by numerous MSs located in the BS's coverage area**.
- To achieve this, **many channels need to be made available**.

E.g., Wireless LAN, Cellular Network

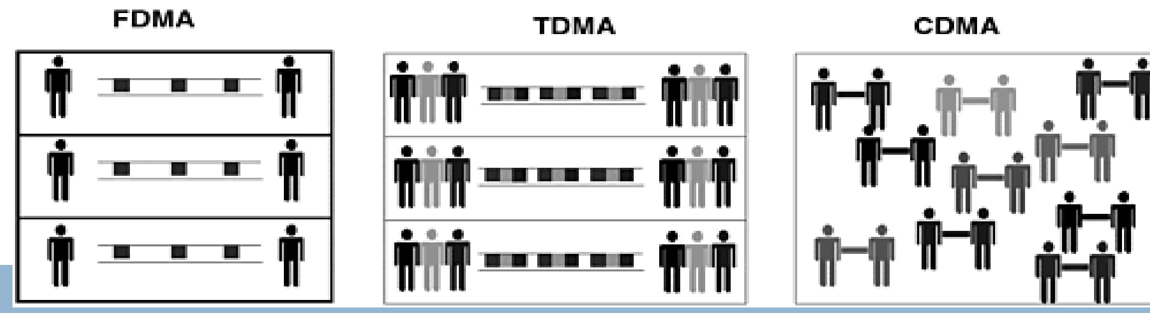


Introduction

- **Three basic ways** to **have many channels** within **an allocated bandwidth**: **Frequency**, **Time**, or **Code.**
  - **Frequency Division Multiple Access** (FDMA)
  - **Time Division Multiple Access** (TDMA)
  - **Code Division Multiple Access** (CDMA)



Introduction



FDMA, TDMA and CDMA – An Analogy:

- **FDMA**: A **Large room is** divided **into small rooms** (i.e., discussion rooms). A **pair of people** that wants to communicate will **use a discussion room**. If **another pair** of people wants to speak, they **must use another discussion room**.
- **TDMA**: A **Large room can be** divided up **into small rooms** (i.e., discussion rooms). **More than one pair** of people can be **in the same room**. **Each pair** will **get 30 seconds to communicate**. **All other pairs** should **wait for their turn**. They can speak only when their turn comes.
- **CDMA**: **All people** are **in the same room**. **All pairs** can **communicate at the same time** but **each pair communicates** in **different language** that **only those two know** (i.e., different spreading codes). If **voice volume** is **minimized**, the **number of pairs that can communicate is maximized**.

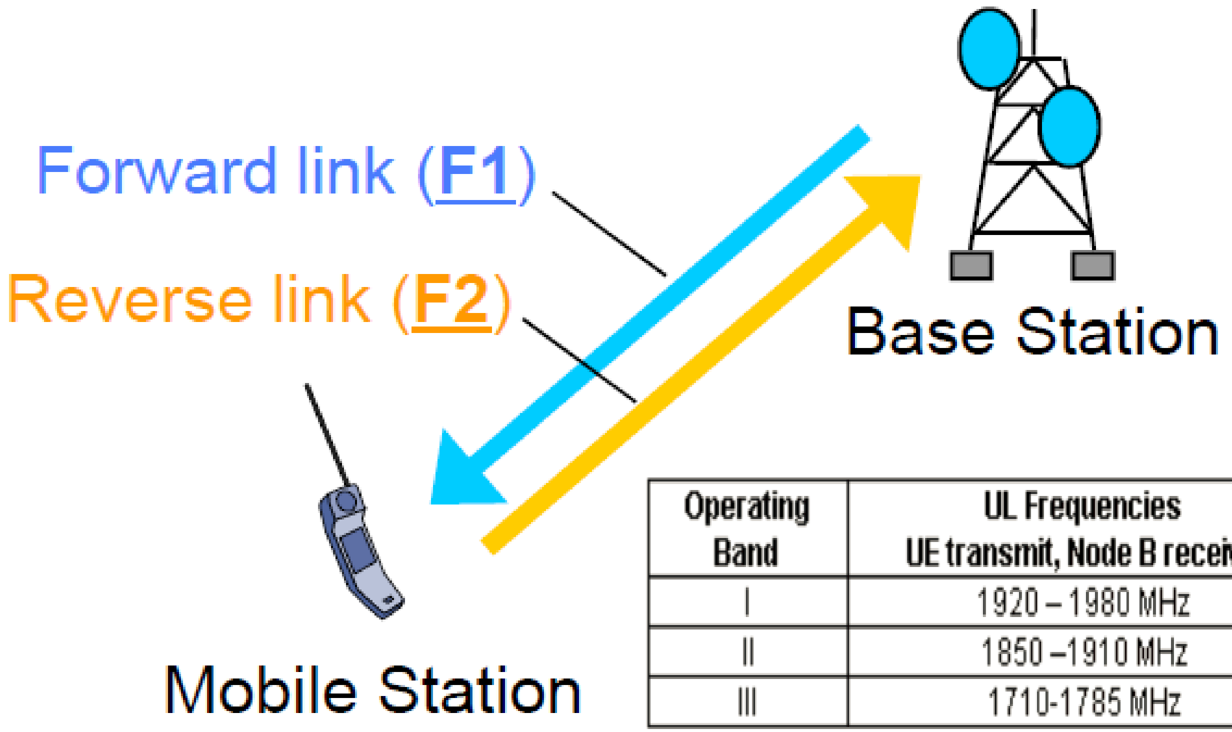
Duplex Communication

- To provide **simultaneous two-way communication** (duplex communications), a **Forward link** (referred as **Downlink channel**) from the BS to the MS and a **Reverse link (**referred as **Uplink channel)** from the MS to the BS are necessary.
- **Two types** of duplex systems are utilized:
  - Frequency Division Duplexing (**FDD**)
  - Time Division Duplexing (**TDD**)

- **FDMA** mainly uses **FDD**, while **TDMA** and **CDMA** systems use either **FDD** or **TDD**

Duplex Communication - FDD

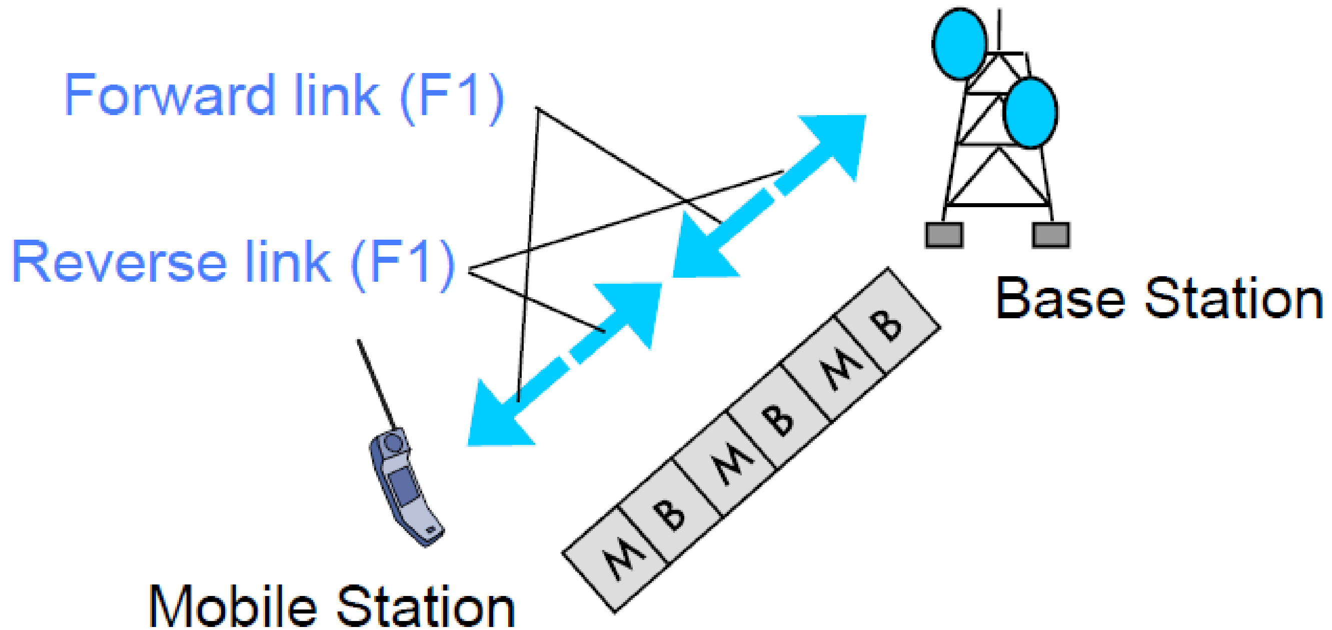
- **Forward Link** (Downlink (DL) channels) and **Reverse Link** (Uplink (UL) Channels) use **different frequency bands**.



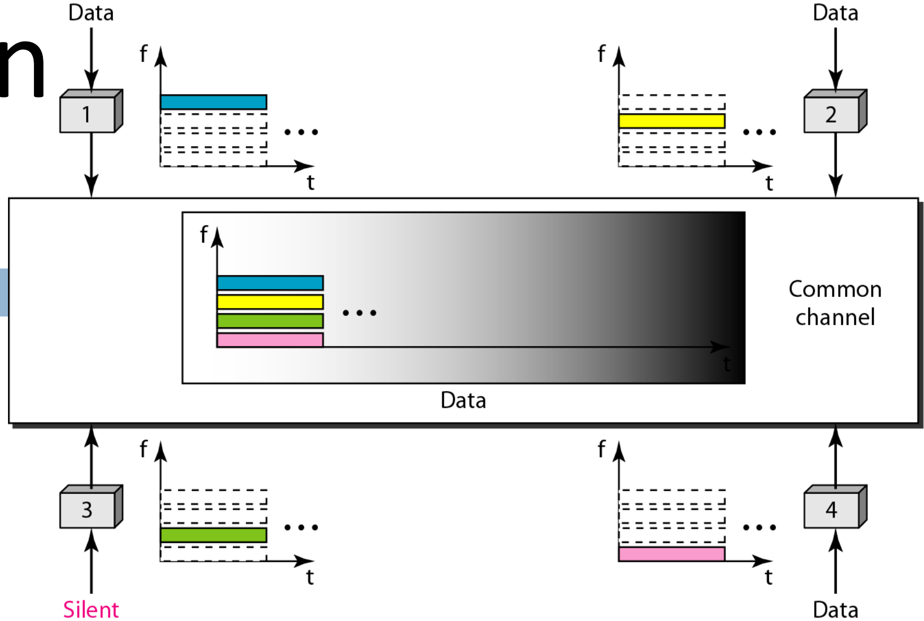
Operating Band	UL Frequencies UE transmit, Node B receive	DL frequencies UE receive, Node B transmit
I	1920 – 1980 MHz	2110 –2170 MHz
II	1850 –1910 MHz	1930 –1990 MHz
III	1710-1785 MHz	1805-1880 MHz

Duplex Communication - TDD

- **Forward Link** (Downlink channels) and **Reverse Link** (Uplink Channels) use the **same frequency band**. The Uplink and Downlink channels are **divided** into **time slots**. The **Mobile Station** and **Base Station transmit sequentially,** using the **time slots designated to them**.

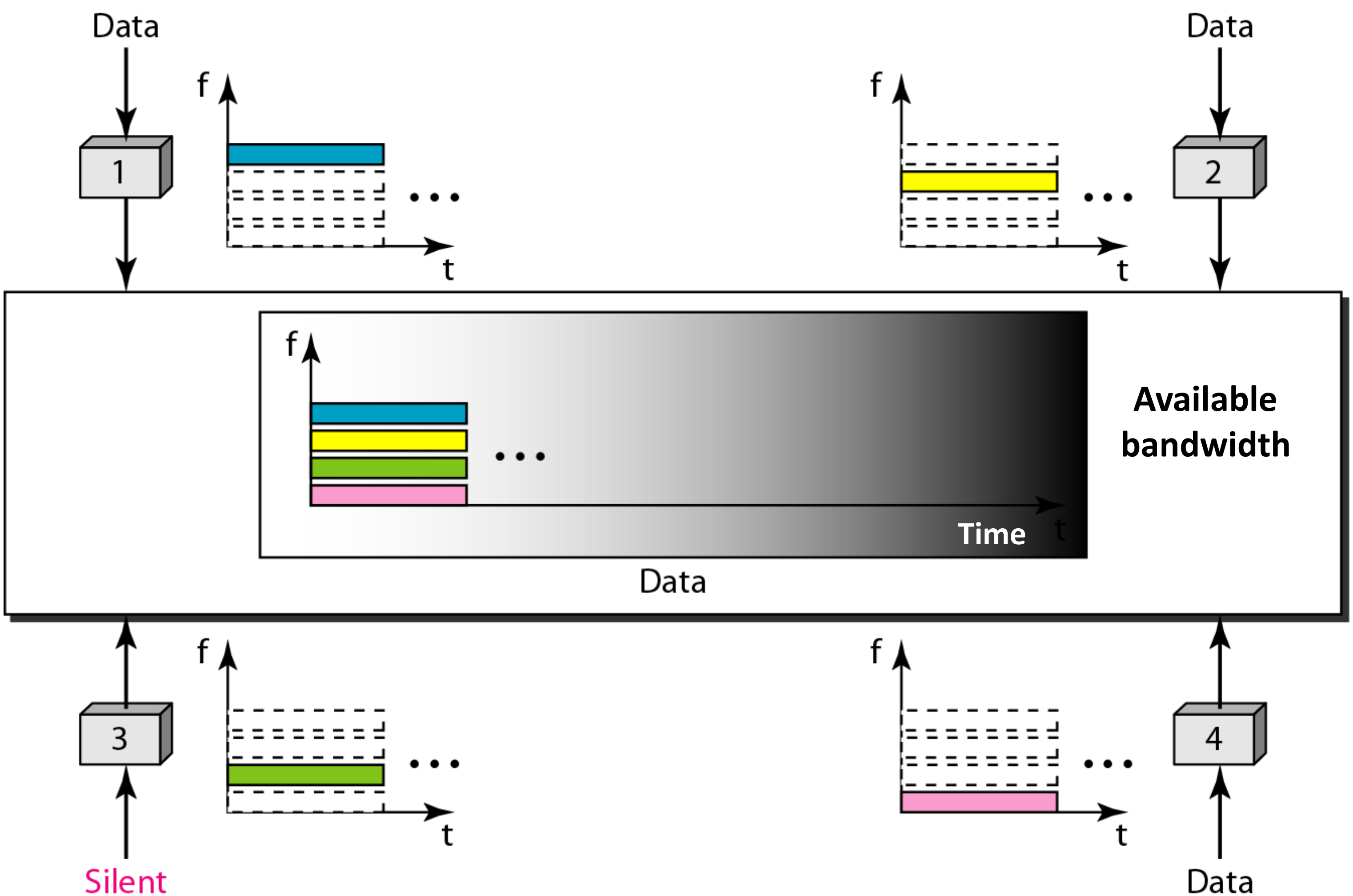


Frequency Division Multiple Access



- **Separates a large band** (i.e., the available bandwidth) **into smaller sub-bands** (frequency bandwidths) that **forms the channels.**
- The **BS dynamically assigns a different channel** (**carrier frequency**) to **each active user** (MS)
- **Guard Bands** are used to **separate channels** and **minimize adjacent channel interference**
- Uses **Frequency Division Duplexing (FDD)**

Frequency Division Multiple Access



Frequency Division Multiple Access

- **Channels** can be **assigned on-demand,** when a user needs to communicate
- **Each user** can **only be assigned one channel.**
- FDMA is used in **narrowband systems** (e.g., 30 kHz frequency bands) → E.g., FM Radio
- FDMA was the **initial multiple-access technique used in** the 1^{st} Generation systems.
  - Used in **analog cellular phone systems** (AMPS; Advanced Mobile Phone System)

Frequency Division Multiple Access

Advantages:

- Provides **large time between subsequent symbols compared** to the **average Delay Spread.**
  - **This reduces InterSymbol Interference** (ISI) - No serious ISI is likely to occur if the **time between symbols** is **longer than, say, Ten times the Average delay spread.**
- **No need for synchronization** (network timing) required because **transmission is continuous in FDMA → Reduces Overhead**
- **Algorithmically simple and easy to implement**.

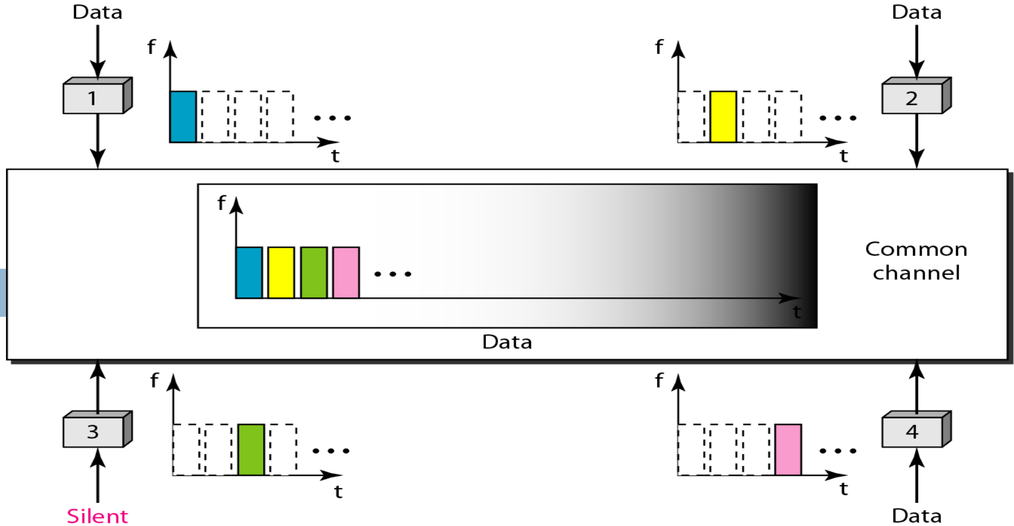
*Depending on the **propagation environment** and the **distance of the MS from the BS**, the **Delay Spread** can be in the **range from some nanoseconds** (**10^{-9} seconds**) **to some microseconds**(**10^{-6} seconds**))*

Frequency Division Multiple Access

Disadvantages:

- If there are **not enough users** **for the number of available channels**, the **channels that are not used**, **will** **remain idle** → **the radio spectrum is wasted** **(spectral inefficient)**
- **Presence of** **guard bands** **(idle unused frequency bands – 500 Hz on each side of the channel)** between adjacent channels **are needed** → **Reduces spectral efficiency**
- A Channel (frequency band) allocated to a user is **reserved for the whole call duration** (even when silent)→ **Reduces spectral efficiency**
- **Channel bandwidth** is relatively **narrow** (30KHz) → **Low data rates** **achieved in FDMA based systems.**
- The **maximum bit rate** per channel **is** **fixed**.
- **Requires** **expensive narrowband filters** to **reduce adjacent channel interference** **(i.e., interference from channels that uses adjacent frequencies)**

Time Division Multiple Access



- In TDMA, the **available bandwidth** is **timeshared between the users** → TDMA **splits the time** into **several time slots** and **assigns the slots among multiple users**.
  - **Only one user** can **transmit or receive data per slot**
- The **users are synchronized in time** using a **network-wide clock** and **each of the users takes turn in transmitting and receiving** data in its assigned time slot in a **Round Robin fashion**.
- There is a **Guard Time between** the subsequent **time slots so that interference caused due to multipath propagation delays (i.e., due to delay spread),** can be **minimized.**

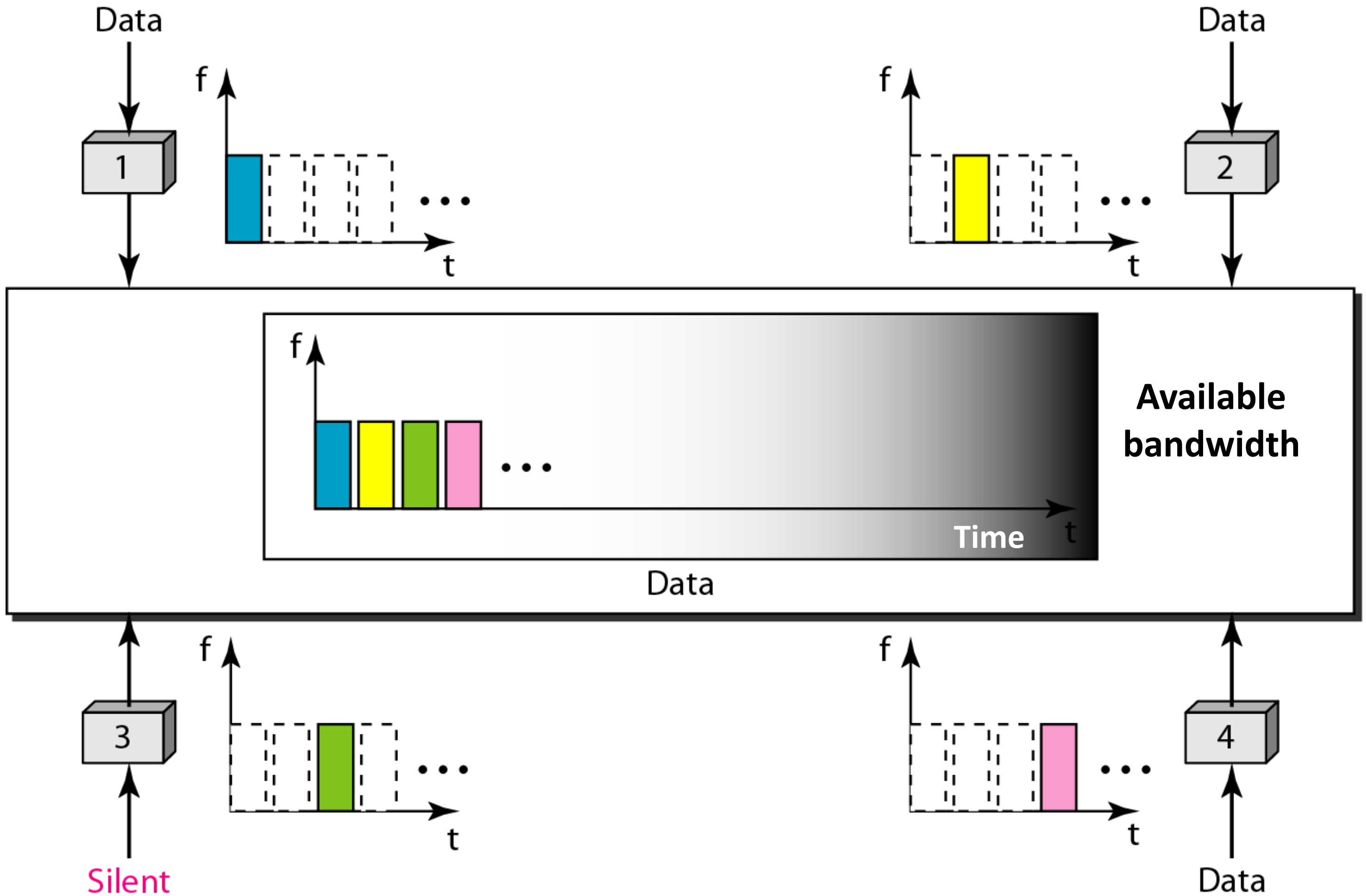
Time Division Multiple Access

- The **Guard Time used between subsequent time slots** is usually **estimated by considering**:
  - **Time inaccuracies due to clock** (synchronization) **instability**
  - **Delay Spread** of transmitted symbols (so as to avoid Intersymbol Interference between the different users)
  - **Transmission Time Delay** (the time **from the first bit** until the **last bit of a packet** has **left** the **transmitting station**) → **Depends on the bit rate of the channel**.
- Uses **Time Division Duplexing (TDD)**
- **Channels can be assigned on-demand** when a **user needs to communicate**.

Time Division Multiple Access

- Widely used in the field of mobile telephones (GSM) and mobile satellite communication systems
- In radio systems, **TDMA is usually used alongside with FDMA**. This is the case for GSM (**Global System for Mobile** Communications).

Time Division Multiple Access



Time Division Multiple Access

Advantages:

- **No Guard Band required → Enhances spectral efficiency** as all frequencies of the available bandwidth are utilized
  - **Higher bit rates** achieved and **more users** can be **supported using the same bandwidth**, than FDMA.
- **Extended battery and Talk time:**
  - **Mobile Devices** can **save battery power** by **turning off Transmitter/Receiver, during time slots they are not transmitting or receiving data.**
- **Can support Flexible Bit Rates →** Can **allocate multiple time slots to a user, if needed,** to provide **increased data rate.**

Time Division Multiple Access

Disadvantages:

- Requires **network-wide timing synchronization →** **Increases complexity and signaling overhead**
- **Guard Time (10 x average delay spread) between time slots have to be considered** to **separate users → Spectral Inefficiency, as the available bandwidth remains idle between subsequent time slots**
  - **However, these Guard Times are minor (some nano- or micro-seconds, depending on the environment)**.
- **Too few users** result in **idle channels**
- A Channel (time slots) allocated to a user is **reserved for the whole call duration** (even when silent)→ **Reduces spectral efficiency**
- **Higher costs** due to **greater equipment sophistication**

Code Division Multiple Access

* For further info see Slides of Spread Spectrum Techniques

- In contrast with FDMA and TDMA which are **bandwidth and time limited**, CDMA is **interference limited**.
- Because **all users transmit on the same frequency and at the same time, internal interference generated by the users** is the **most significant factor** in **determining system capacity** and **call quality**.
  - **Each user** is a **source of interference to all the other users** in the cell.

Code Division Multiple Access

* **For further info see Slides of Spread Spectrum Techniques**

- To increase capacity, the **transmit power for each user** must be **reduced to limit interference**.
- However, **the Received signal power (at the BS) should be enough to maintain the minimum required** ***SNIR needed by the Receiver (for allowing it to decode the signal correctly)*** for a **satisfactory call quality**.
- Thus, the goal is **all MSs' transmitted signals to reach the Base Station and received with about the same signal power (and equal to the minimum required SNIR) from the BS (**also known as Node-B**)** → **Otherwise some signals could drown others**.

Code Division Multiple Access

*For further info see Slides of Spread Spectrum Techniques

Advantages:

- **Better Spectral Efficiency** than FDMA and TDMA → **The available bandwidth is much better utilized**.
- **No absolute limit on the number of users.**
  - **CDMA** is **interference limited**, NOT bandwidth limited.
  - **If interference is kept low, more users can be included.**
- **Flexible allocation of resources** is supported (variable bit rates supported) → Depending on the bit rate requested, a **different Spreading Code**, with a different **Spreading Factor** will be assigned.
- **Impossible for hackers to decode the signal without knowing the Spreading Code** used (Provides better security and privacy)

Code Division Multiple Access

* **For further info see Slides of Spread Spectrum Techniques**

Advantages:

- **Better signal quality** and **greater resistance to interference and noise** (due to the **Processing Gain** achieved)
- **Increased talk time** and **standby time for Mobiles** (Uses Fast **Power Control that saves battery life for MS**)
- **No sense of handovers** when a MS is changing cells (**Soft Handover** can be used; The MS can have simultaneous connection with more than one BSs)
- The **CDMA channel is 1.23 MHz wide** (**higher data bits rates can be supported** compared to FDMA and TDMA
  - Wideband – CDMA (WCDMA) supports a 5 MHz channel and thus much higher bit rates; used in UMTS networks.

* For further info see Slides of Spread Spectrum Techniques

Disadvantages:

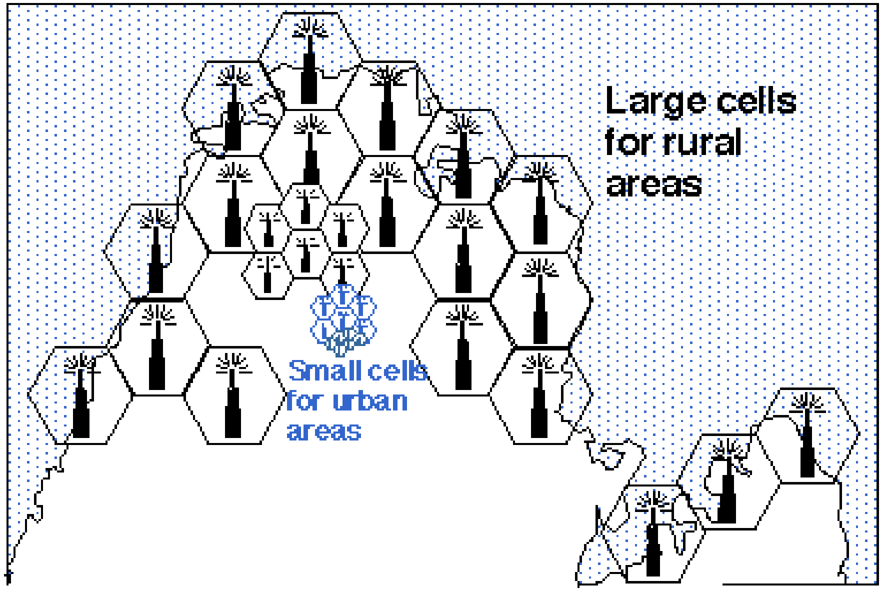
- Requires **more complex transmitter and receiver** for **spread spectrum signal generation** and **reception** (**more expensive equipment**)
- **Near-far problem arises: If all users transmit with the same power,** signals received from MSs closer to the receiver will be stronger than signals transmitted from MSs farther away.
  - **The BS requires to Power Control all the MSs in its coverage** in order to **keep their transmission power levels to the lowest possible for reducing interference to the minimum.**
  - **Power Control increases the complexity of the system**.

Summary of the various Multiple Division Techniques

Technique	FDMA	TDMA	CDMA
Concept	Divide the frequency band into disjoint subbands	Divide the time into non-overlapping time slots	Spread the signal with orthogonal codes
Active terminals	All terminals active on their specified frequencies	Terminals are active in their specified slot on same frequency	All terminals active on same frequency
Signal separation	Filtering in frequency	Synchronization in time	Code separation
Handoff	Hard handoff	Hard handoff	Soft handoff
Advantages	Simple and robust	Flexible	Flexible
Disadvantages	Inflexible, available frequencies are fixed, requires guard bands	Requires guard space, synchronization problem	Complex receivers, requires power control to avoid near-far problem
Current applications	Radio, TV, and analog cellular	GSM and PDC	2.5G and 3G

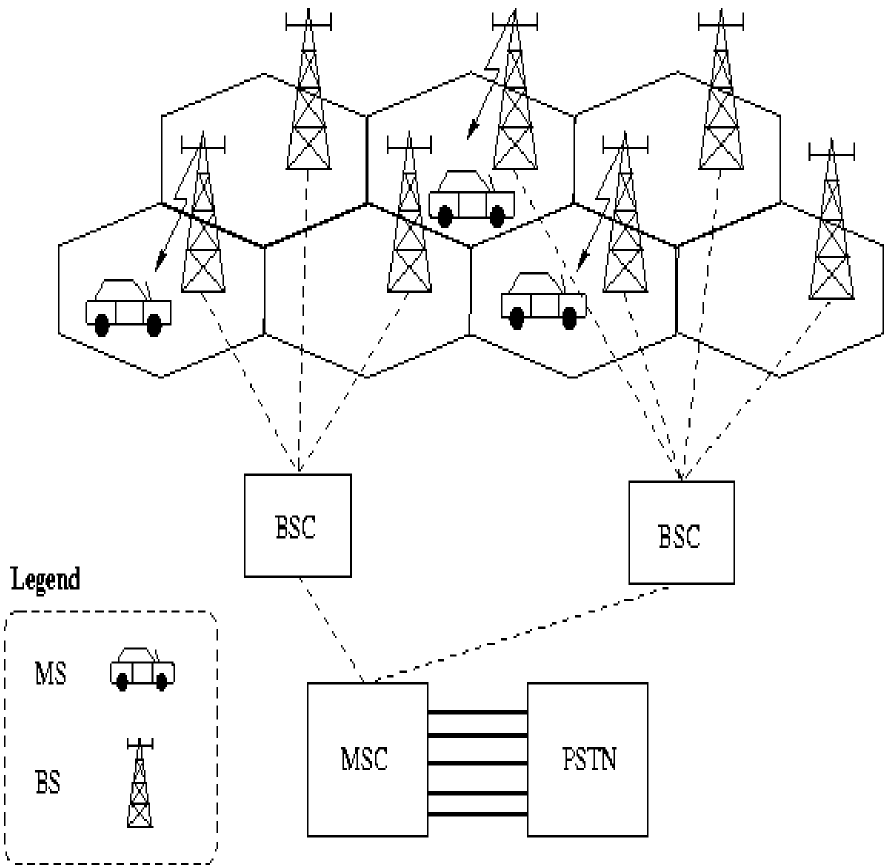
Cellular Network

- In a **Cellular Network** a **geographical area** is **split into smaller land areas** called **Cells,** each served by a fixed **Base Station (BS)**.
- A **Mobile Station (MS)** located in the Cell's area **is attached to the Network** through the **Base Station**.



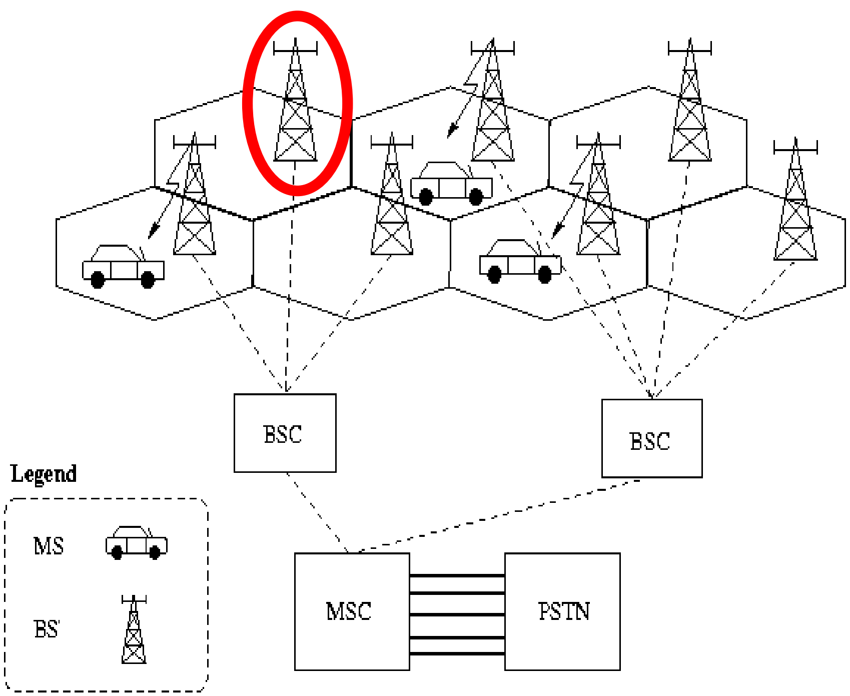
Cellular Network

- **When joined together**, these cells **provide radio coverage** over a **wide geographic area**.
- **Continues service coverage** within this area is achieved by **handoff (or handover)**, which is the **seamless transfer** of a **call** from one Base Station to the other as the **Mobile Station (MS)** crosses Cell boundaries.



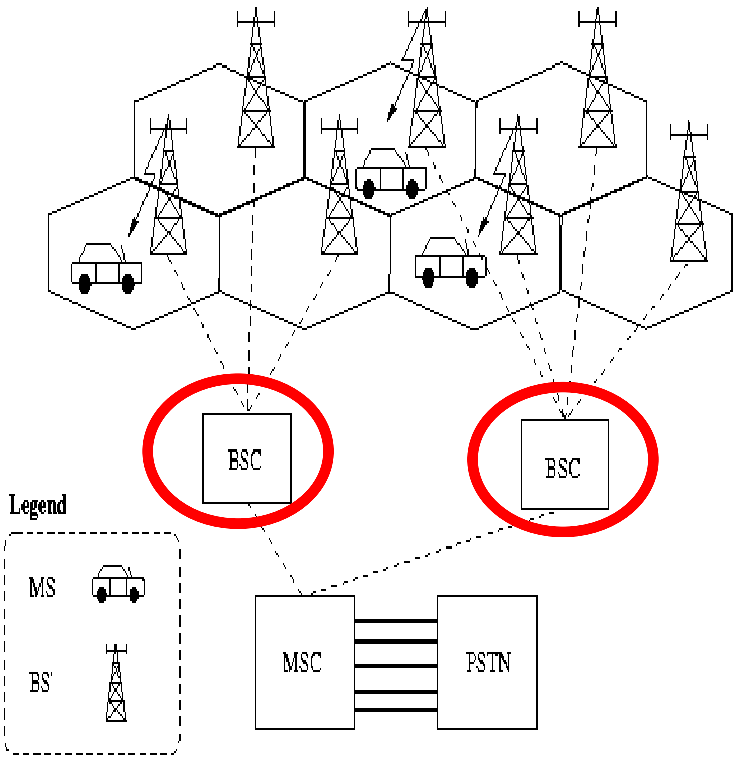
Cellular Network: Main Components
Base Station (BS)

- Also known as **Base Transceiver Station (BTS)** or **NodeB (in 3G)**
- Is a piece of network equipment that **facilitates wireless communication** (i.e., is the interface) between a **Mobile Station (MS)** and the **Core Network.**
- **Mainly Responsible for establishing the physical channels (using electromagnetic waves) and relay messages** between the **MSs** and the **Network. Performs:**
  - Encoding/Decoding, Encrypting/Decrypting, Multiplexing, Modulating, Demodulating and feeding the RF signals to the antenna.



Cellular Network: Main Components
Base Station Controller (BSC)

- **Provides** the **Intelligence behind** the **Base Stations. Known as Radio Network Controller (RNC) in 3G.**
- Typically a **BSC has tens or even hundreds** of **BSs under its control**
- **The BSC mainly handles/controls:**
  - **Radio Resource (Frequency) Control: Controls** and **Reserves** the **radio frequencies** that will be **used by each BS** that is **under its control.**
  - **Allocation and Deallocation of Radio channels for the MSs (e.g., frequency bands, time slots, spreading Codes)**
  - **Transmission Power of the BSs and MSs**



Cellular Network: Main Components Base Station Controller (BSC)

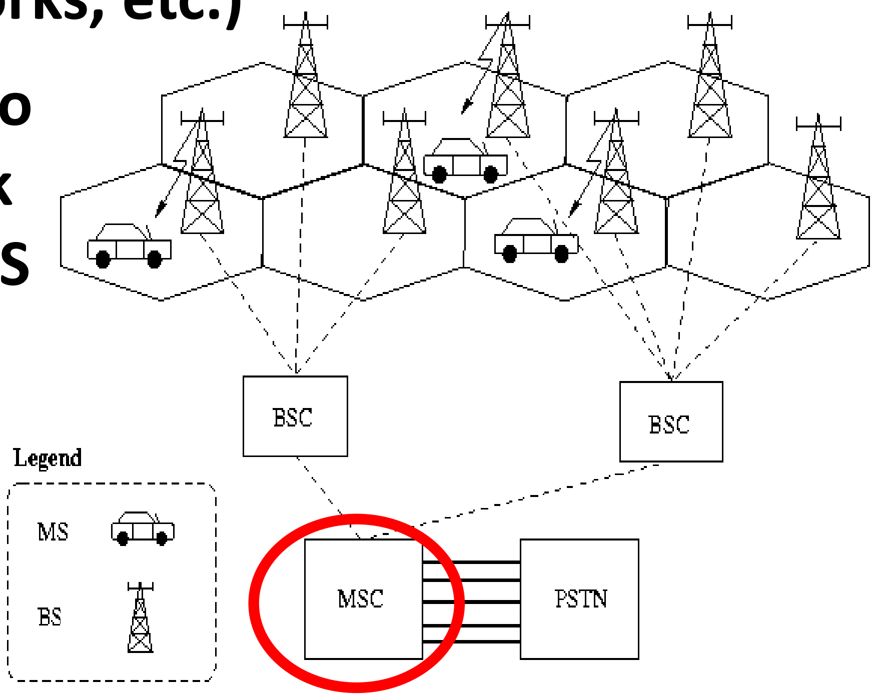
- **Paging Control** to **locate a MS based on its reported location** (done in cooperation with the MSC – the **MSs' "approximate" location** is **stored** in the **VLR located in the MSC**)
- **Call Setup (allocation of needed network (RN and CN) resources) between the calling and the called MSs** (done in **co-operation** with the Mobile Switching Center (MSC))
- **Controls Handovers of MSs moving between BSs** that **are under its control**
  - Note: In the case of an **inter-BSC handover (i.e., handover between two BSs controlled by different BSCs),** handover control is part of the responsibility of the **anchor MSC**

Cellular Network: Main Components Mobile Switching Center (MSC)

- Provides the **link (connection):**
  - **Between the MSs supported by the Network's Base Stations.**
  - **To other external Networks, e.g., other PSTNs (Public Switched Telephone Networks, etc.)**

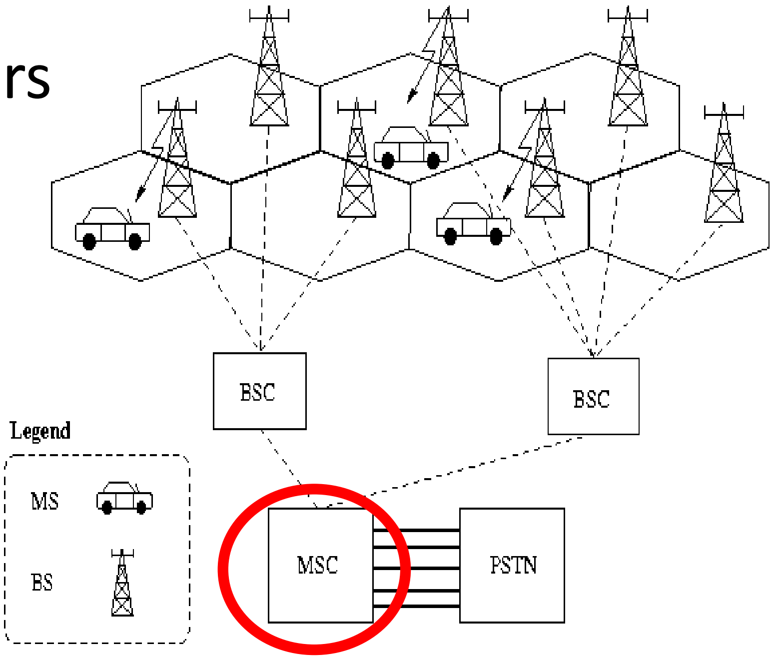
All Communications between two MSs within the Cellular Network or between a MS and another MS in another Network, travel through the MSC.

MSC has a number of BSCs under its control.

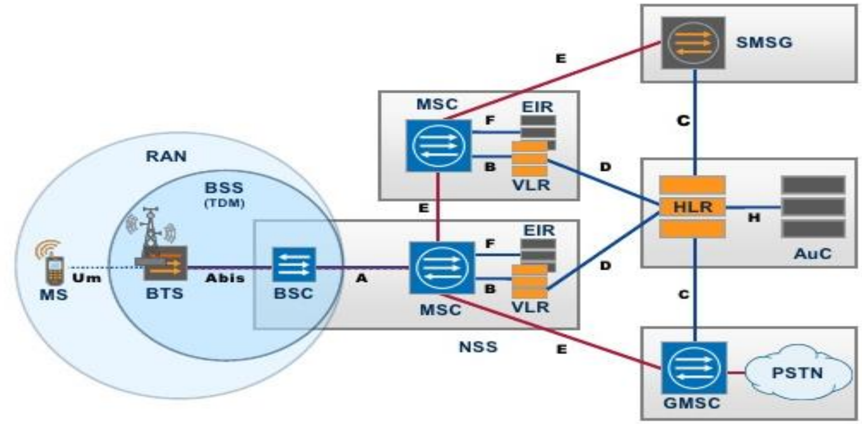


Cellular Network: Main Components Mobile Switching Center (MSC)

- Performs **functions**, such as **Call Set-up/Release** and **Routing of data** **(in association with the BSCs) to MSs**.
- **Controls Handovers of MSs moving** between cells (BSs) controlled by different BSCs (known as **inter-BSC handovers**)
- **Authenticates** and **validates** Users
- **Charge** **users' accounts**.

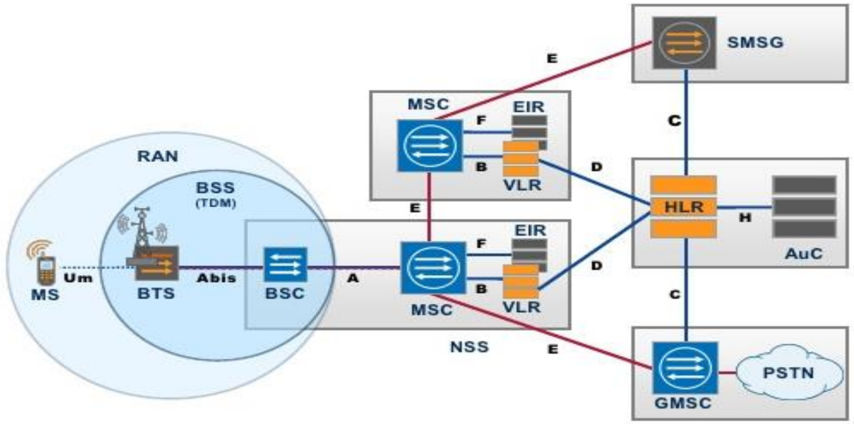


Cellular Network: MSC – HLR/VLR



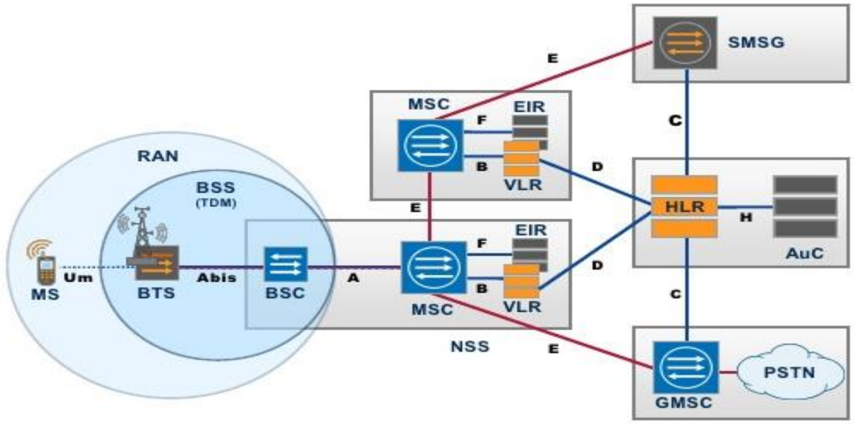
- As **Mobile Stations move, it is important for the** **MSC** **to be able to** **determine** **their** **"location"** **(i.e., at least the Cell ID that the MS is within)** **in the coverage area,** to **effectively facilitate** **routing of communications** between them.
- For this task, the Network maintains a **large database** known as the **Home Location Register (HLR),** which stores **relevant** **Location** for each **Mobile Station** and **other** **permanent information,** **(i.e., IMSI, Name, Identity, services supported for the customer, etc.) regarding the** Cellular Network's **subscribers**.
  - **IMSI** (**International Mobile Subscriber Identity**) **uniquely identifies the user** of the Cellular Network. Identifies also the **Country** and the **Network Operator** the User is subscribed. Stored in the **Subscriber Identity Module (SIM) card** and serves as the **primary key for each HLR record.**

Cellular Network: MSC – HLR/VLR



- Because **accessing the HLR** consumes **MSC's processing resources** **(heavy queries will have to be performed due to the great amount of subscribers records included)**, most operators employ a **Visitor Location Register (VLR)** **database in the MSCs.**
- A **VLR** is a database that **contains information** **only for the subscribers currently "active" and roaming** within the **geographical area that is supported by the MSC**.

Cellular Network: MSC – HLR/VLR



- The **MSC obtains** **information about a user currently roaming** within its coverage area, by **signaling the HLR** **where the user is subscribed,** and creates and maintains a **temporary record** **in the** **VLR** **while the user is within its coverage area.**
  - Note that the kind of **data stored in a VLR** is **similar to that stored in the HLR**, but are **not permanent.**
  - In case the user is **subscribed to another Cellular Network**, it signals the **Gateway-MSC/HLR** of that network **using the** **IMSI** **of the user.**
  - ***Recall:*** *The* ***user is uniquely "Internationally" identified by the*** ***IMSI.***

Cellular Network: Main Components MSC – HLR/VLR

- The **VLR contains the** “location” of all mobile phone subscribers **currently roaming** in the **service area of the MSC**. This information is **necessary to** route a call to the right Base Station.
- The **database entry of the subscriber** is deleted from the VLR when the subscriber leaves **the MSC’s service area**.
- The primary role of the VLR is to **minimize the number of queries that MSCs have to make** to the **Home Location Register (HLR)** (which holds the full list of all the users subscribed at the MSC – i.e., all the subscribers of the Cellular Network).

Cellular Network Advantages

Question: **Why** mobile network providers install several thousands of Base Stations throughout the country (**which is quite expensive**) and do not use powerful transmitters with huge cells?

Cellular Network Advantages

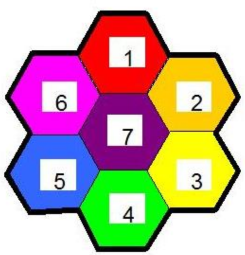
Answer: Because Cellular Network provides:

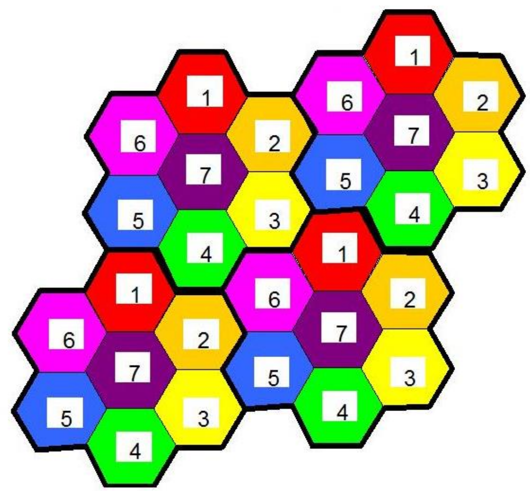
- **Higher Capacity since smaller cells are used and the frequency reuse concept is applied**
- **Less Transmission Power is required by the MS to reach the BS, and vice versa, in shorter distances → Thus less the energy consumption (improves battery life for the MSs, lower power emissions thus positive health impacts, etc.)**
- **Interference is Reduced as less transmission power is required for the signal to cover shorter distances, thus less intra- and inter- cell interference.**
- **More Robustness to the network as if one BS fails, only one small part of the network will be affected.**

Cellular Network Advantages Higher Capacity

- Higher capacity comes from the fact that the **same radio frequencies can be reused in different smaller areas** for a **completely different transmission**
  - **"Frequency Reuse" concept:** The **same frequency band** can be **assigned to two or more cells** that are **far enough apart** such that the **radio Co-Channel Interference between them is within a tolerable limit**.

7 cell cluster. The available Bandwidth (F) is divided between these 7 cells in the cluster.





The cluster is repeated until the selected service area is covered.

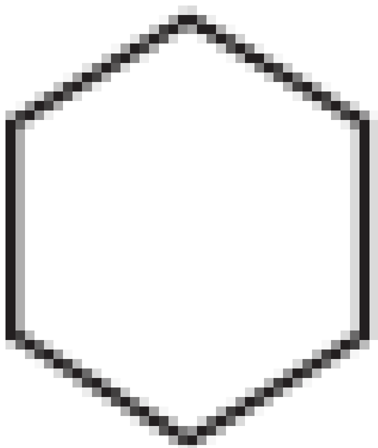
Cellular Network Advantages
Higher Capacity

- **Each Network Operator is given** a **specific amount of frequencies (Bandwidth)** that a BS can use to **establish the channels** that will be assigned to the users under its control → The **amount of channels**, and thus the number of **concurrent users** within a cell, **is limited**.
- When a **certain amount of frequencies**, **from the given BS's bandwidth,** **is assigned to a certain user**, this **frequency band** is **blocked for other users within the same cell**.
- Thus, **huge cells do not allow for more users!!!** On the contrary, they are **limited to less possible users per km^2**!!!

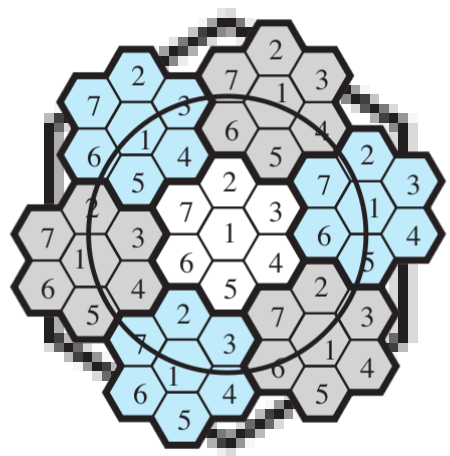
Cellular Network Advantages
Higher Capacity

- Using the **Frequency Reuse concept** and a **number of smaller cells** to cover an area, **much more users can be supported per Km^2**.
- This is also the reason for **using very small cells in cities** where many **more people use mobile phones**.

Cellular Network Advantages
Higher Capacity



Only one BS supporting a large coverage area using a specific range of frequencies (F)



Frequency Reuse Concept: A number of smaller cells are used to cover the same coverage area. In this example the same cluster of cells is repeated 7 times → The same range of Frequencies (F) is reused 7 times → Can accommodate seven times more users.

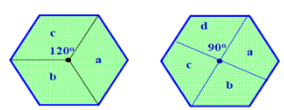
- **The number of times a cluster is re-used, is the number of times the entire spectrum (F) can be re-used → and thus the number of times the capacity is increased (more users can be supported)**

Cellular Network Advantages
Less Transmission Power Required

- While **transmission power aspects** are **not a big problem for Base Stations**, they are in fact a **very serious problem for Mobile Devices** which are **powered by batteries.**
- A **Mobile Device far away from** the **Base Station** would **need much more transmission power** for its signal to reach the Base Station.
- Thus, **with small cells** the **amount of transmission power required by the Mobile Device** to reach the BS **is reduced**,
  - So **Mobile Devices can last longer between battery charges** and **batteries can be smaller**.
- Moreover, **lower power emissions** help in **addressing health concerns**.

Cellular Network Advantages
Reduced Interference

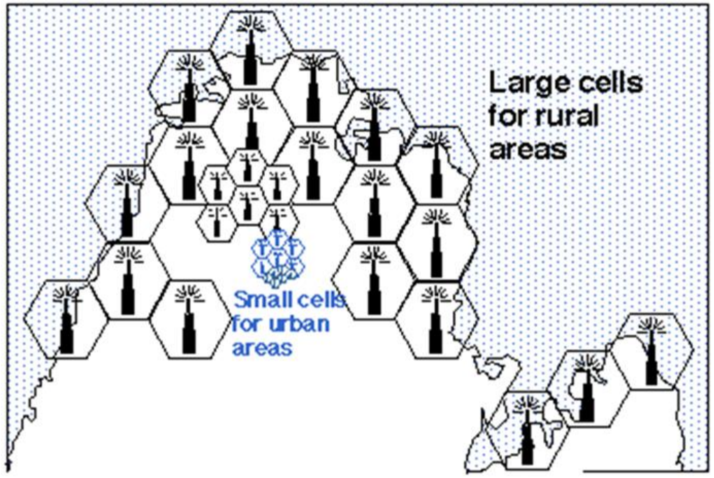
- Having **long distances between a MS** and **a BS** results in even **more interference problems** **(Longer Distance → Higher Transmission power required → more interference in the Radio Access Network)**.
- With **small cells** and the **use of "frequency reuse" concept**, the problems of **adjacent channel** and **co-channel interference** can be **greatly reduced.**
- The **interference is reduced even further** with the use of **Sectorized antennas**.



  - In Sectoring, the **cell coverage remains the same**, however **is divided into several sectors by using Directional antennas** at the Base Station instead of a single omnidirectional antenna.

Cellular Network Advantages Robustness

- Cellular systems **are decentralized (i.e., uses a number of smaller cells, distributed in a large geographical area, to cover the area)** and so, **more robust against the failure of simple components**.
  - If one **antenna fails** this **influences communication only within a small area of the whole coverage**.



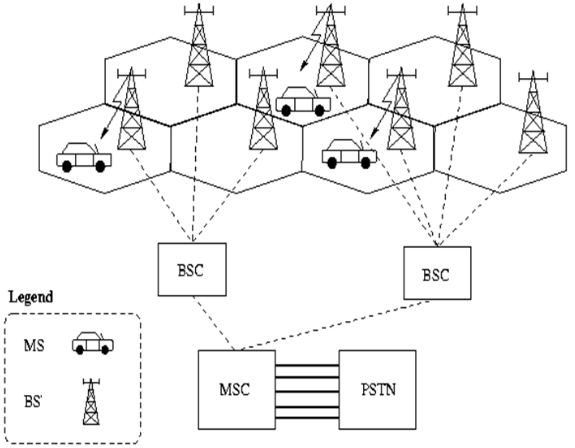
Cellular Network Problems Encountered

- The cellular solution **resolves the basic problems of radio systems in terms of radio system capacity constraints**, but raise new problems, such as:
  - **Infrastructure Needed:** Cellular systems need a **complex infrastructure** to **connect all Base Stations**.
    - This includes **many antennas**, **switches for call forwarding**, **Location registers** to find a Mobile Device in the Network, etc., which makes the whole system **quite expensive**.

Cellular Network
Problems Encountered

- **Problems due to Mobility:** The Mobile Device has **to perform a handover** when **changing from one cell to another → Handover Control (and also more complex Mobility Management functions) is needed!**
    - **Depending on the cell size** and the **speed** of movement, this **can happen quite often** (i.e., the **smaller the size of the cell** or the **higher the speed** of the user, **the more frequent the handovers**)

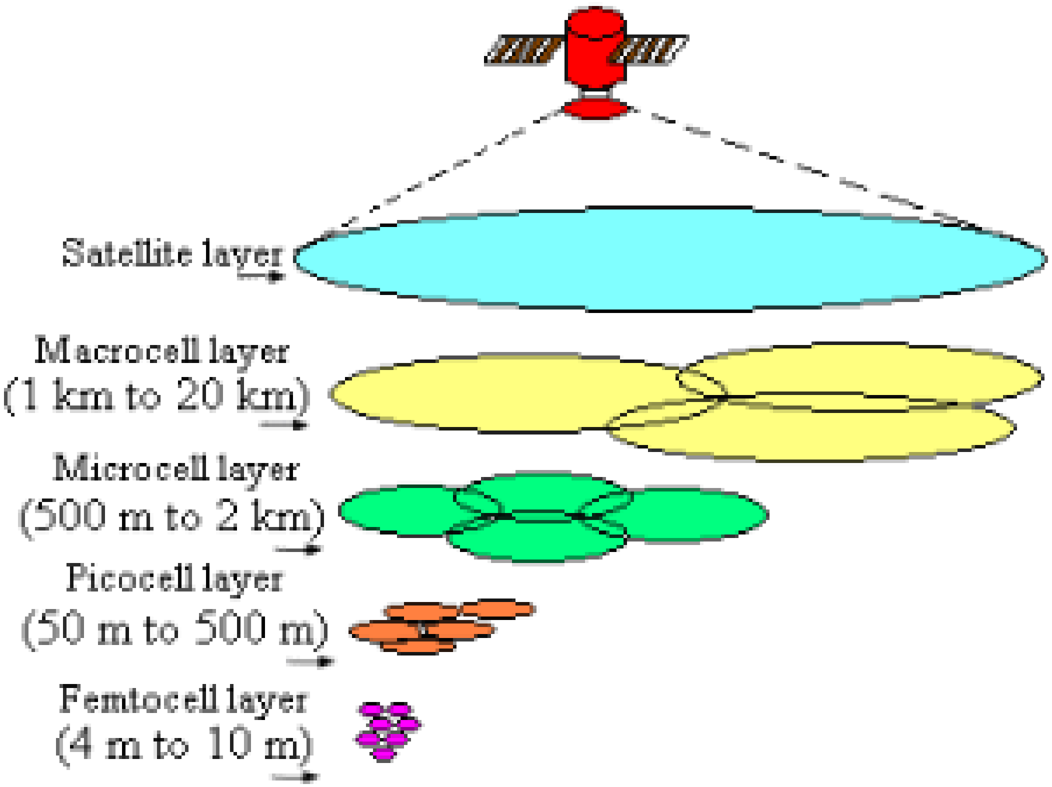
How Does Cellular System Work
Location Management

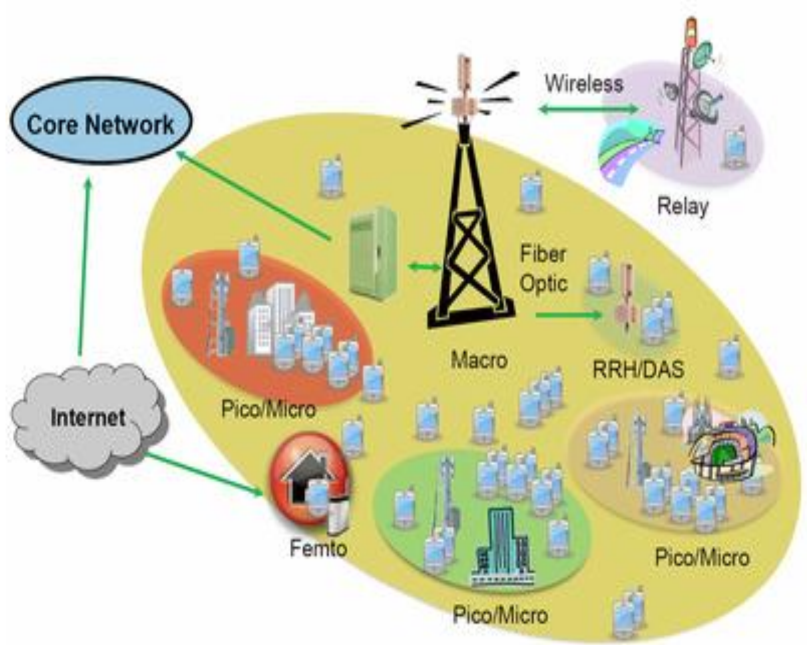


- **Aim: Track the MS in order to deliver data to it.**
  - The MS **Periodically sends Location Updates** to the MSC (these are registered in the **VLR** and updated in the **HLR**)
  - **MSC locates the MS** by **Paging** the MS **in a group of cells (BSs)** the **MS may be located in.**
    - To **avoid signaling overhead** and **MS battery consumption**, the **Location Updates are Periodic** and **Not continuous**. Therefore we **may not know the exact BS of the MS.** → **That is why the paging message is sent to a group of cells**

Cell Sizes

- **Depending on their size**, cells can be categorized as **Macro**, **Micro**, **Pico** and **Femto Cells**





Cell Sizes

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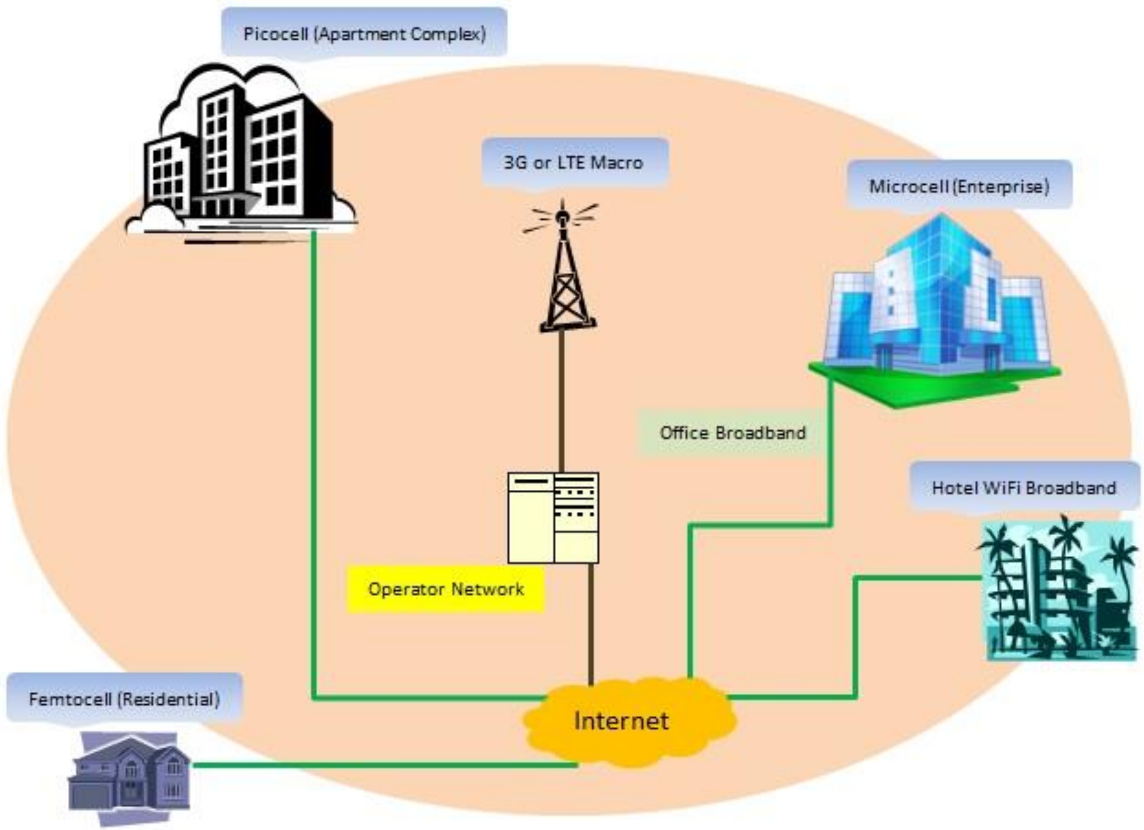
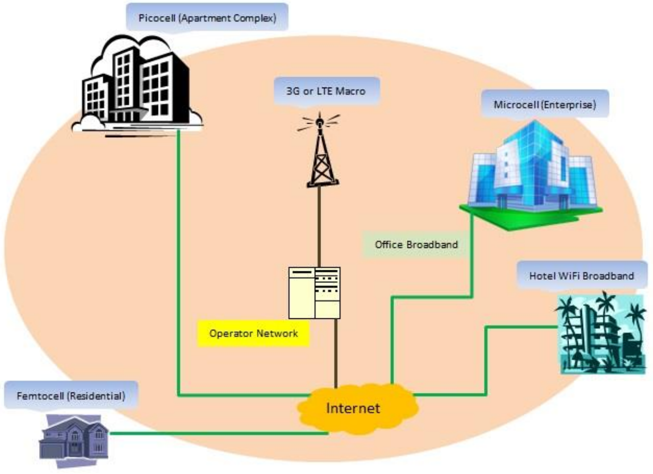


Wireless Network with Small Cells

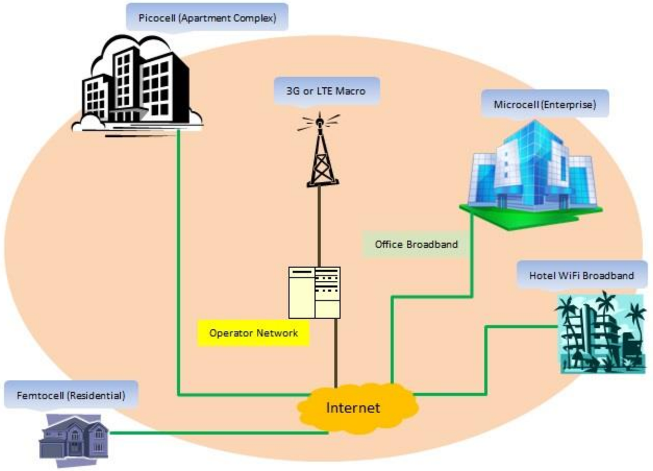
Cell Sizes – Macro Cell



Wireless Network with Small Cells

- **1 to 20 Km radius (and more…)**
- A **macro cell** provides the **largest coverage area within a mobile network** – perhaps an entire metropolitan area (e.g., area of Nicosia).
- The antennas for macro cells are placed at a **height that provides a clear view over the surrounding buildings and terrain**.
- Provides radio coverage served by a **high power (typically tens of watts) cellular BS** (tower).
- Macrocells are mainly found in **rural areas (αγροτικές περιοχές)** or **along highways**.

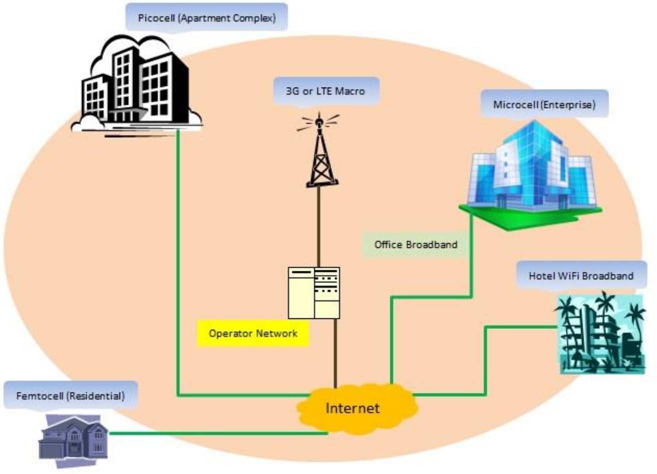
Cell Sizes – Micro Cell



Wireless Network with Small Cells

- **500 meters – 2 Km radius**
- A micro cell is a cell served by a **low power cellular BS (some watts)**, **covering a limited area.**
- Micro cells are **usually used** to **add network capacity in areas** with **very dense phone usage**, such as **train/metro stations, hot spot areas, etc.**
- Micro cells are also **often deployed temporarily during sporting events** and **other occasions** in **which extra capacity is known to be needed** at a **specific location** in advance.

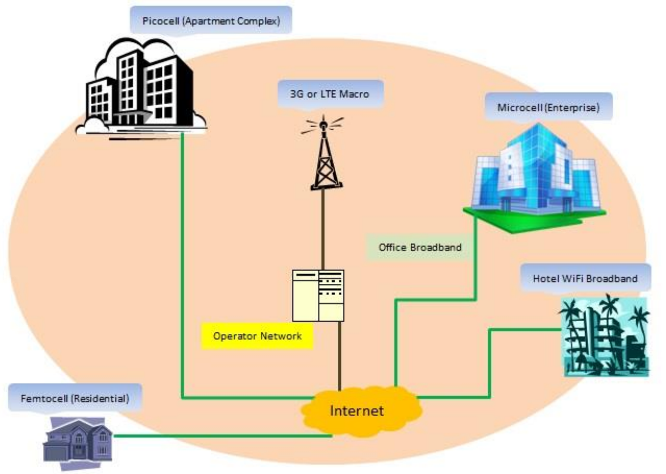
Cell Sizes – Pico Cell



Wireless Network with Small Cells

- **50 - 500 meters radius**
- **Most commonly used** for **covering a small area**, such as a **street corner**, **in-building** (offices, shopping malls, etc.), or more **recently** an **airplane cabin**.
- Typically used to **extend cellular coverage to indoor areas** where **outdoor signals do not reach well (e.g., underground metro stations)**, or si**milarly to micro cells**, to **add network capacity in areas with very dense phone usage**, such as train stations or stadiums.

Cell Sizes – Femto Cell

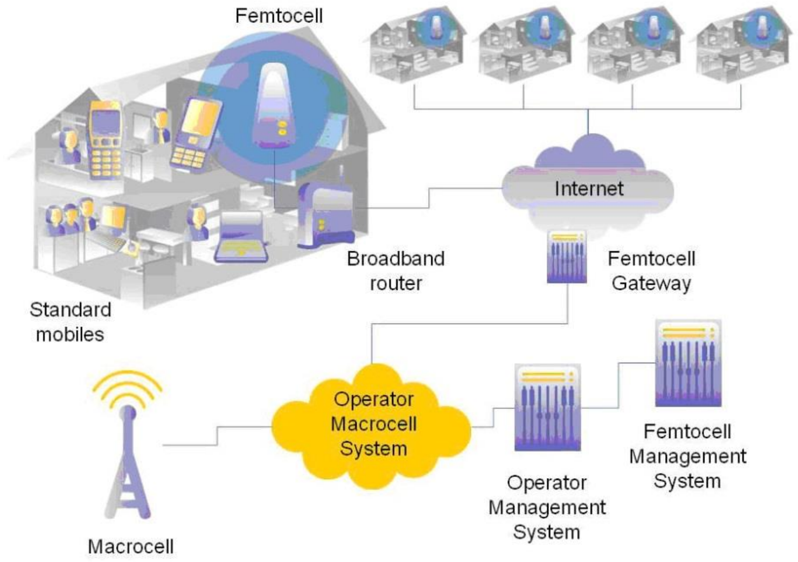


Wireless Network with Small Cells

- **4 – 10 meters radius**
- Currently, the **smallest area of coverage** that is proposed to be implemented is with **a femto cell**.
- A **femto cell** is a **small**, low-power cellular BS, typically **designed for use** in a **home** or **small business**.
- These are perhaps the **most exciting products** and **challenging technology emerging in the communications market today**.

Cell Sizes – Femto Cell

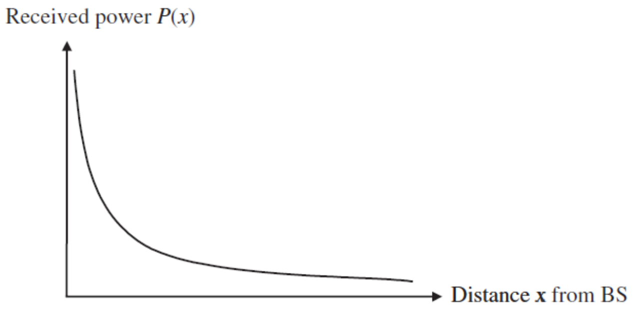
- Current designs typically support **2 to 4 active mobile phones** in a **residential setting**, and **8 to 16** active mobile phones in **enterprise settings**
- **3G/4G Connections are established between the BS of the femto cell and the MSs.**
- A Femto cell **connects the MSs** to the **service provider's network via broadband internet connection.**



Cell Sizes

- The **sizes of cells** can be different **depending on the environment and the purpose that will be used**.
- Cells designed to cover **suburban/rural areas (προαστιακές ή αγροτικές περιοχές) (where we have few users) or long highways (where the Users move with Vehicular Speeds)** have antennas **on tall towers** and **cover a large area** (**Macro cells**).
- In **urban areas (αστικές περιοχές)** antennas are usually located **low in height** and their **transmitting powers are also low**. Therefore the coverage areas are **small for two reasons**:
  - Since the **population density is high, more smaller Cells are needed so as to support more users per km^2**
  - **Buildings may block radio wave transmission**, therefore **more cells (BSs) may needed to cover an area in a city.**

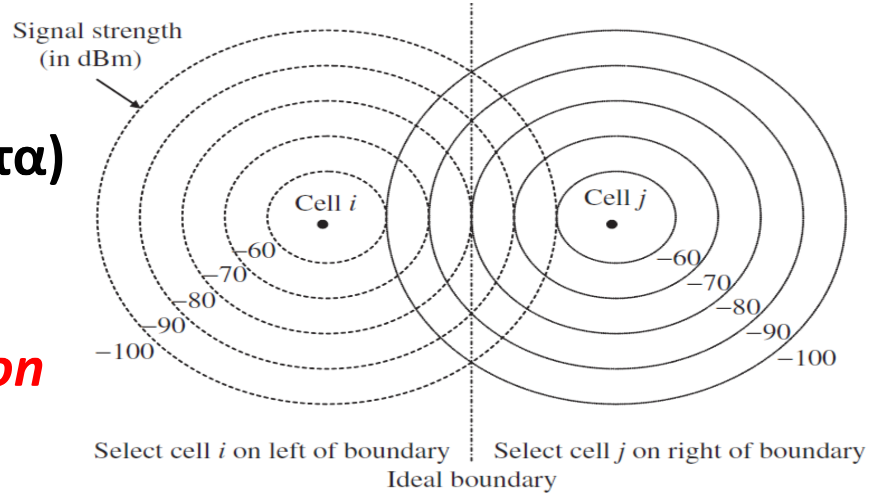
Signal Strength



- The **strength of a signal** transmitted from a BS **attenuates as it propagates longer distances** → **The longer the distance of the MS from the BS, the weaker the signal strength will become**.
- Thus, **as the MS moves away from the BS of the cell**, **the signal strength weakens,** and **at some point** a phenomenon known as **Handover,** **occurs**.
  - This implies a **radio connection to another adjacent cell**.

Signal Strength contours (περιγράμματα) around two adjacent cells

Ideal Case (Not feasible due to the different propagation effects caused on the signal)

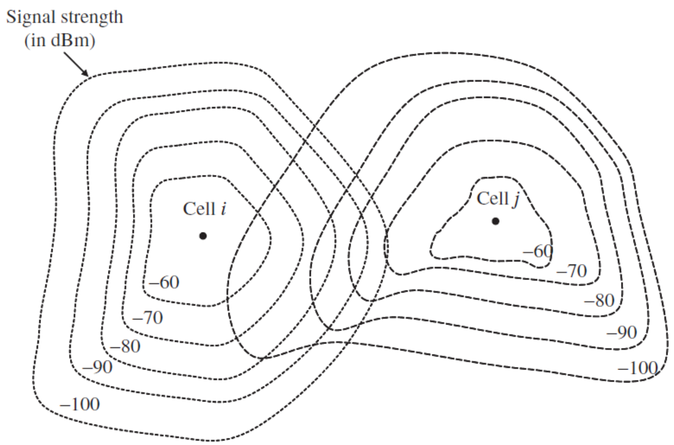


Signal Strength

- However, the **distance** is **not the only factor affecting signal strength → Environmental factors and multipath propagation affects the signal strength, too**.
- The **signal strength contours** may **not be concentric circles as signal strength** can be **distorted by a lot of factors**:
  - Atmospheric conditions, presence of obstacles, terrain, interference, noise, multipath propagation, etc.

Signal Strength contours (περιγράμματα) around two adjacent cells

Actual Case



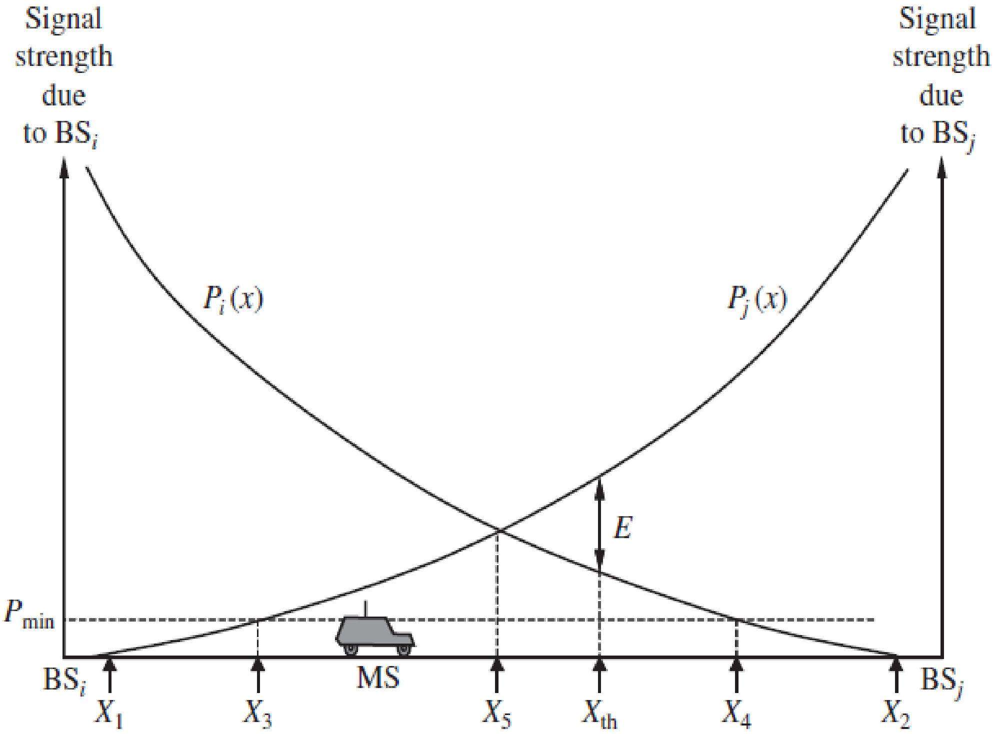
Handover Control

- **During a call**, a Mobile Station (MS) may **move out of coverage area of a cell** and **move into the coverage area of a different cell**
- The **Base Station Controller** (BSC; or sometimes the Mobile Switching Center (MSC)) **must identify the new BS that will handle the call.**
  - The BSC must **seamlessly transfer** the **control** of the call to **the new BS** and **assign to the call a new channel** from the available **channels of the new BS.**

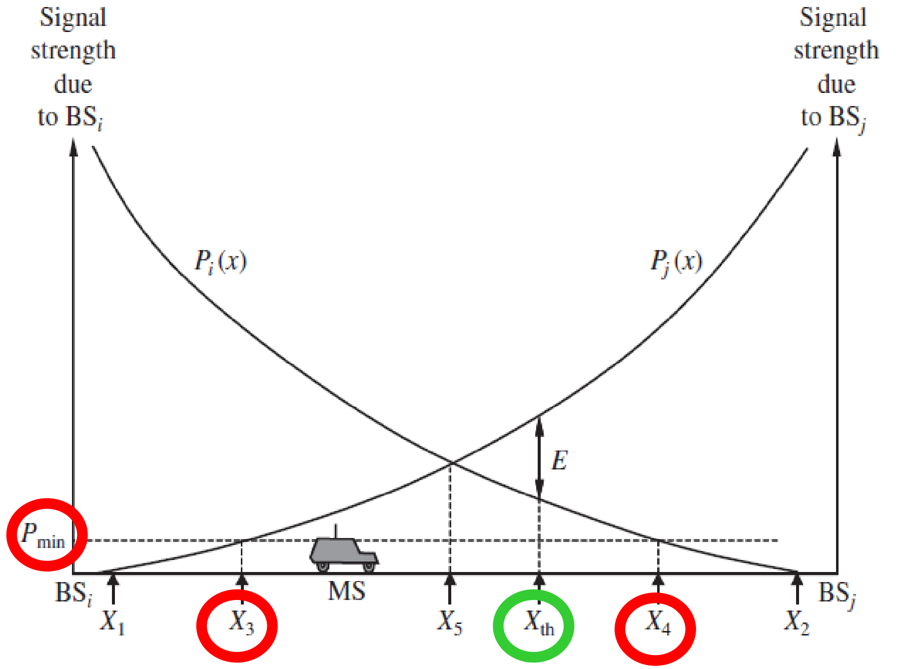
Handover Control

Handover algorithm: The Handover from *BS_i* *(**the Old or Current Cell**) to BS_j (**the New or Target Cell**) is triggered when the CPICH Signal Strength received* from *BS_j* (***$RSSI_{j\_NEW}$***) *exceeds the CPICH Signal Strength received from BS_i* (***$RSSI_{i\_OLD}$***) *by a pre-defined threshold* ***E*** ***(e.g., $RSSI_{j\_NEW}$ - $RSSI_{i\_OLD} \geq E$)***.

RSSI: Received Signal Strength Indicator

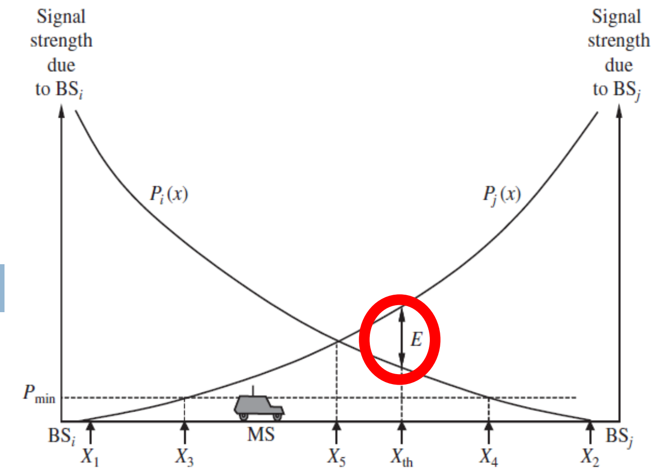


Handover Control



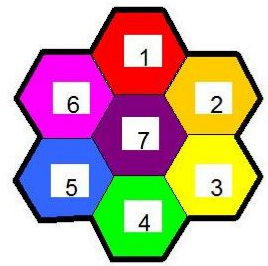
- **P_{min}** denotes the **minimum power level (i.e., the minimum RSSI received from CPICH) that the signal should have** at the MS so **as to receive and interpret the signal correctly.**
- Thus, in the **region between** the points **X_3** and **X_4** the MS **can be served by both *BS_i and BS_j***
- Therefore, we **have to determine the optimum point (X_{th}) between X_3 and X_4 regions,** that the **handover must be triggered.**

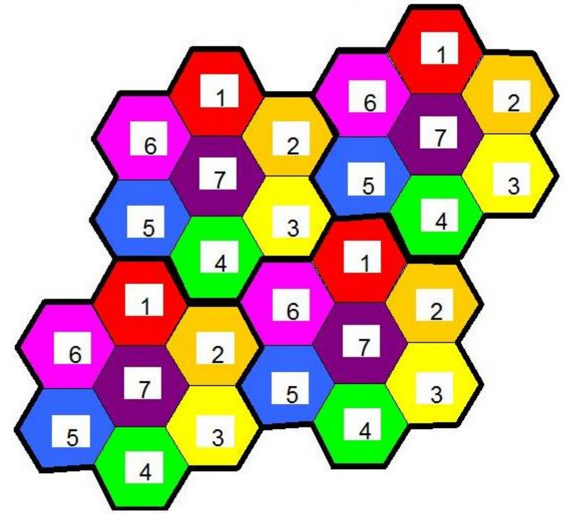
Handover Control



- **Important handover parameter determining the point of Handover Triggering is the pre-defined threshold E**:
  - **When $RSSI_{j\_NEW}$ - $RSSI_{i\_OLD}$ ≥ E → Handover is Triggered**
  - If **E too small**, **unnecessary handovers will occur** if the Mobile Station is very close to point X_5 (i.e., the **$RSSI_{j\_NEW}$ ≈ $RSSI_{i\_OLD}$**) and **moves back and forth** (Referred to as the Ping-Pong Effect).
  - If **E too large**,
    - The **$RSSI_{i\_OLD}$** may become **too weak and the signal will be lost**
    - **The downlink transmission power used by the old Cell will be "unnecessarily" increased to reach the MS in greater distance.**
  - **Thus the threshold E should be selected with care so as to avoid the aforesaid inefficiencies**

Frequency Reuse



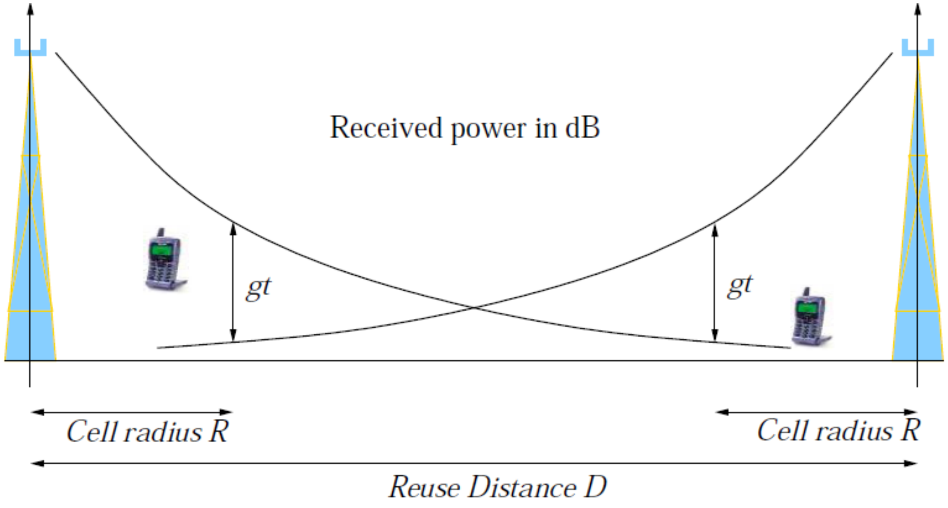


- **"Frequency Reuse" Concept:** The **same frequency band** can be **assigned to two or more cells** that are **far enough apart** such that the **radio co-channel interference between them is within a tolerable limit**.

- With this concept, **higher capacity** (i.e., more users can be served by the network) can be achieved as the **same radio frequency band** can be **reused in different smaller areas** for a **completely different transmission.**

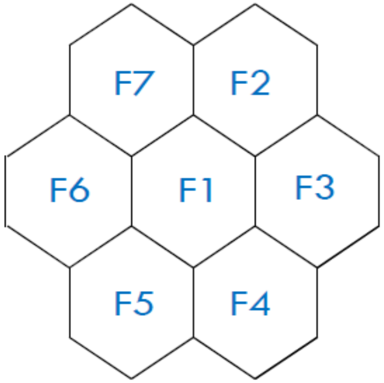
Frequency Reuse

- **Frequency reuse** is **possible thanks to the propagation properties of radio waves** (i.e., radio waves **attenuate as they travel longer distances**)
- Thus, the **BSs using the same frequency band** should be **located in a distance** (**Reuse Distance D**) **far enough apart between them** so that to keep **Co-Channel Interference (CCI) levels within a tolerable limit**.
- **The Issue is to determine how many cells must intervene, between two cells that will use the same frequency band.**



Frequency Reuse Main Steps

- Given a **Service Area (A)** and total **amount of frequencies (S; i.e., total available bandwidth)**, we mainly do the following:
  - We **form a cluster of cells**, i.e., with size **N** **cells.**
  - The **total amount of frequencies (S)**, are divided into **N groups** of **k amount of frequencies** each, where **S = k x N**.
    - **Each cell of the cluster** is **assigned one** of the N groups (**F_N**) each including **k** amount of frequencies (**k = S/N**).
    - All the frequencies within the cluster are **orthogonal** (i.e., **No interference between cells of the same cluster**)

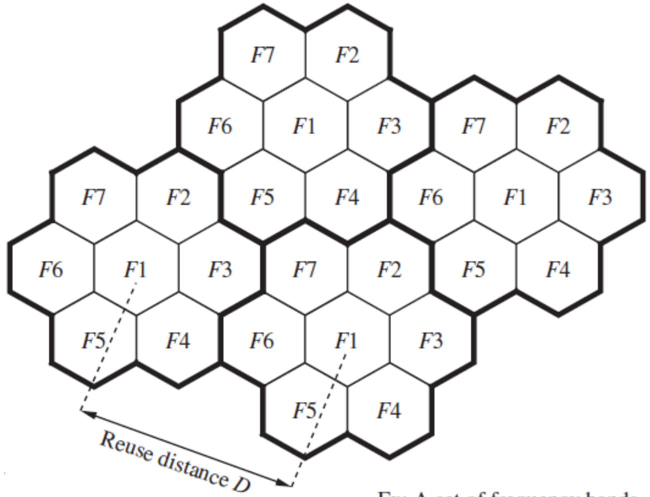


Example of a cluster with 7 cells (N = 7)

S = F1 + F2 + F3 + F4 + F5 + F6 + F7

Frequency Reuse Main Steps

- We **repeat the cluster M times** over the remaining service area **until all area A is covered.**
  - The **same group of frequencies** can **be reused by two different cells** provided that they are **sufficiently far apart (Reuse Distance D – The distance between two cells using the same Frequency Group (or channels))**.
  - The **total number of system channels (C)** is used as a **measure of capacity** of the system.
  - Given that **F** channels can be supported with **S** amount of frequencies, if the **cluster of cells is repeated M times → C = *M* x *F***

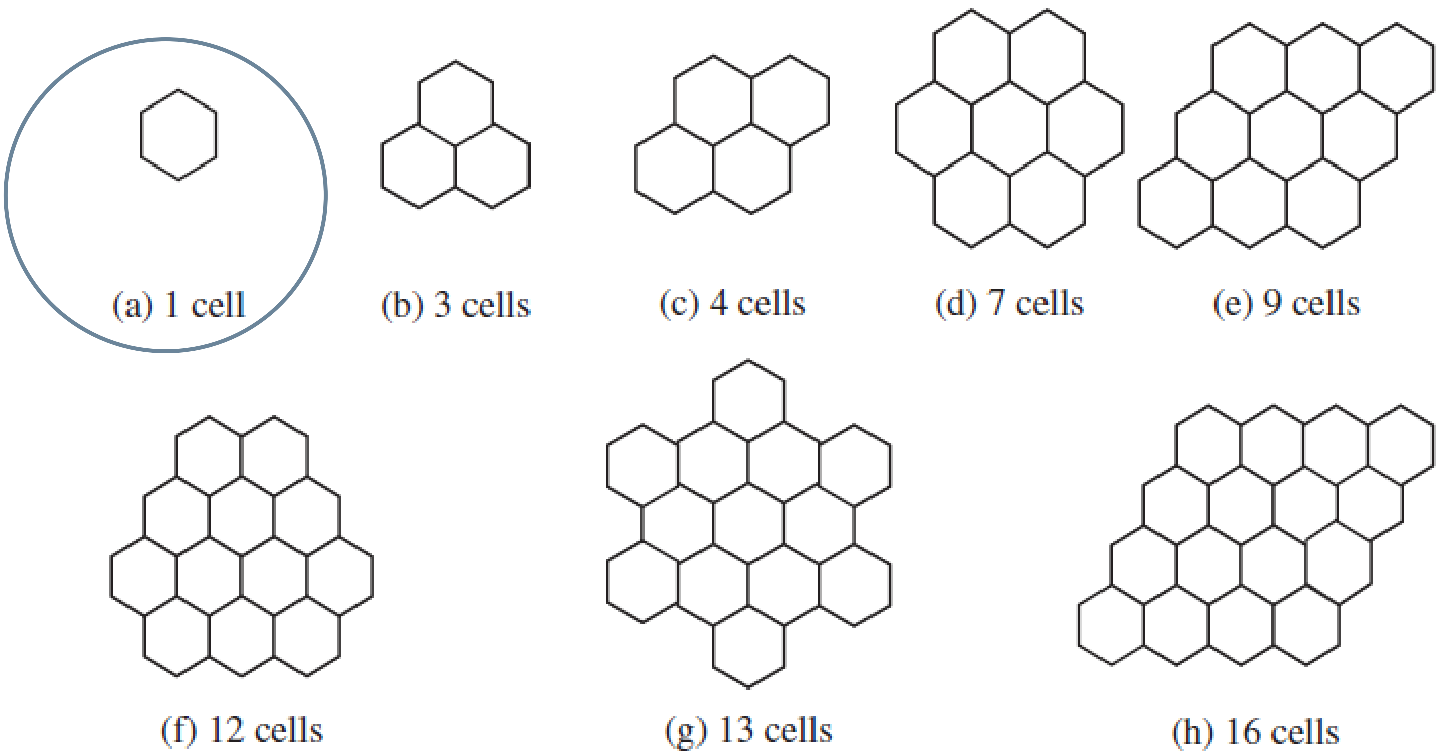


Fx: A set of frequency bands

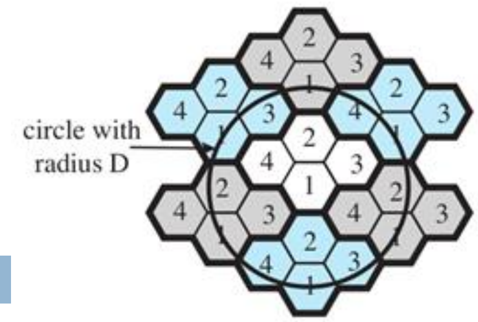
Frequency Reuse Main Steps

- **We can have different cluster sizes.**
- **Most popular is 4 cell and 7 cell clusters.**

1 cell cluster is used with CDMA (3G Networks)



Frequency Reuse – Capacity Enhancement



(a) Frequency reuse pattern for $N = 4$

Example 1: Assume we have a bandwidth (S) that can be used for 36 voice channels, and using this bandwidth we have to cover a 200 square km area.

- If we divide the area into **28 cells**, and **form clusters of 4 cells each (i.e., each group of 4 cells** can use the **entire frequency spectrum (S)**), then the **bandwidth will be used 7 times** → **With a cluster of 4 cells, the available spectrum (S) will be divided to four group of frequencies (F1, F2, F3, F4), and each group will be allocated to one cell of the cluster.**
- **Each time the entire spectrum is used**, **36 users can be supported**.
  - All together 36 x 7 = 252 users will be supported. It's a **7 time increase** of the **capacity**.

Frequency Reuse – Capacity Enhancement

Example 2: We have a **total bandwidth of 25 MHz** and **each user** requires **30 KHz** for voice communication. We need to cover the Strovolos area.

- **Scenario 1**: Only one high power antenna is used.
  - We can support **833 simultaneous users (25MHz/30KHz)**
- **Scenario 2**: 20 low power antennas are used.
  - We **divide the area into 20 cells and form clusters of 4 cells each** → We divide the **entire frequency band into 4 sub-bands** and **assign one to each cell**,
  - **Each cell will have a bandwidth** of **25MHz/4** = **6.25MHz.**

Frequency Reuse – Capacity Enhancement

Example 2 (Scenario 2 Continue….):

- The **number of simultaneous users supported by each cell** is **6.25MHz/30KHz = 208**.
- In this example, **4 cells form a cluster**. Since there are total of **20 cells, the town is covered by 5 clusters** (20/4=5).
- **Each cluster will use the entire frequency band**, so the **number of users per cluster is 833**, as calculated earlier, and **the total number of simultaneous users for 5 clusters** is **833 x 5 = 4,165** → **5 five times increased in the capacity than with** a single antenna.

Some Capacity Expansion Techniques

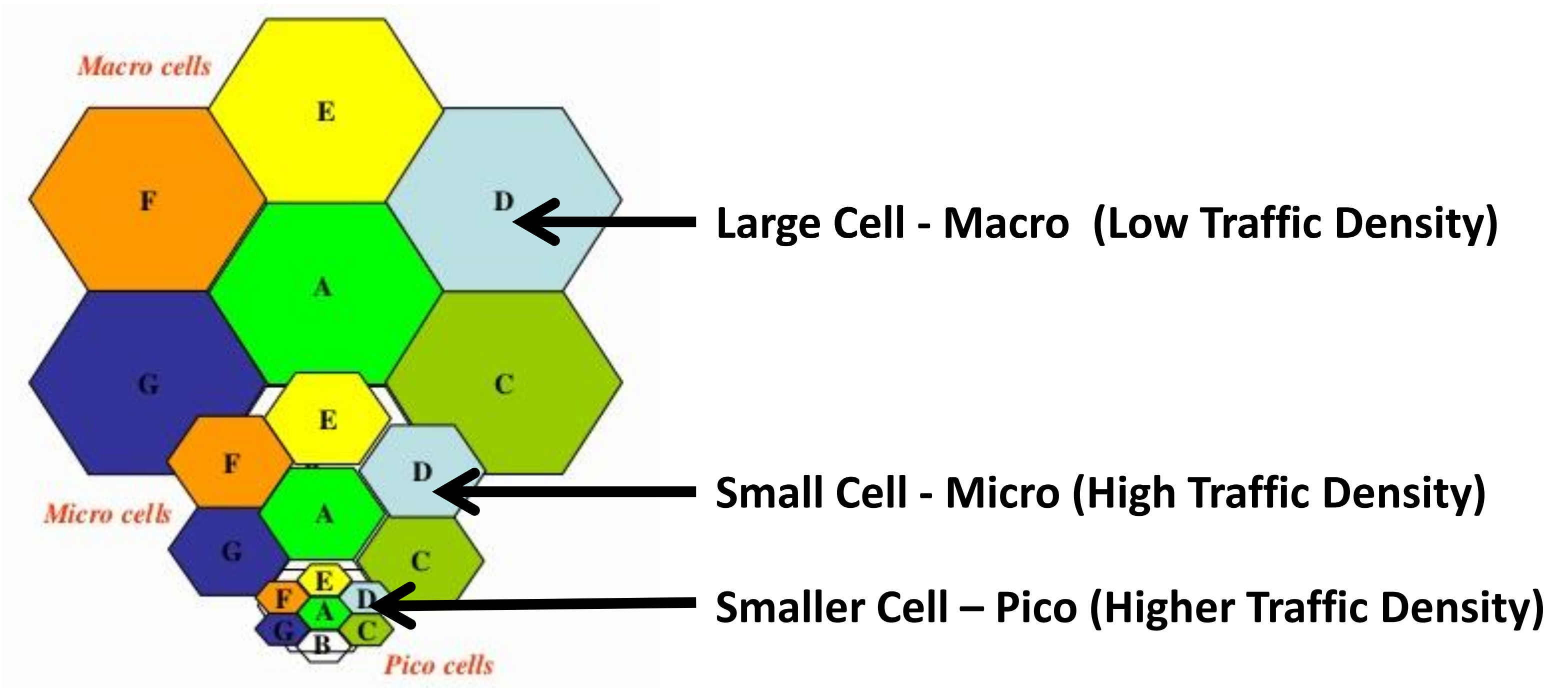
- **Frequency Borrowing:** In the simplest case, **congested cells** can **take ("borrow") frequencies from their adjacent cells**. The **frequencies** can also be **assigned to cells dynamically**.
- **Cell Splitting:** In practice, the **distribution of traffic** and **topographic features** **(i.e., the way the users are distributed in the geographical area) is** **not uniform**, and this presents opportunities of capacity increase. **Cells in areas of high usage** **can be** **split into smaller cells**.
- **Cell Sectoring:** With cell sectoring, a **cell is divided** **into a** **number of Slice shaped sectors**, each **with its own set of channels**, typically **3 or 6 sectors per cell**. Each sector is **assigned a separate subset of the cell's channels**, and **directional antennas** at the Base Station are used to **focus on each sector.**

Cell Splitting

- Until now we have been **considering the same size cell across the board**. **This implies** that **the BSs** of **all cells transmit information at the same power level** so that the **net coverage area for each cell is the same**.
- **Some times**, this **is Not Feasible, due to the terrain environment of the geographical area; e.g., high buildings, mountains, open area, etc.)**,
- And in general, this **may Not Be Desirable → Service providers** would like to **service users** in a **Cost-Effective way**, and **resource demand may depend** on the **concentration of users (i.e., traffic density)** in a **given area**.

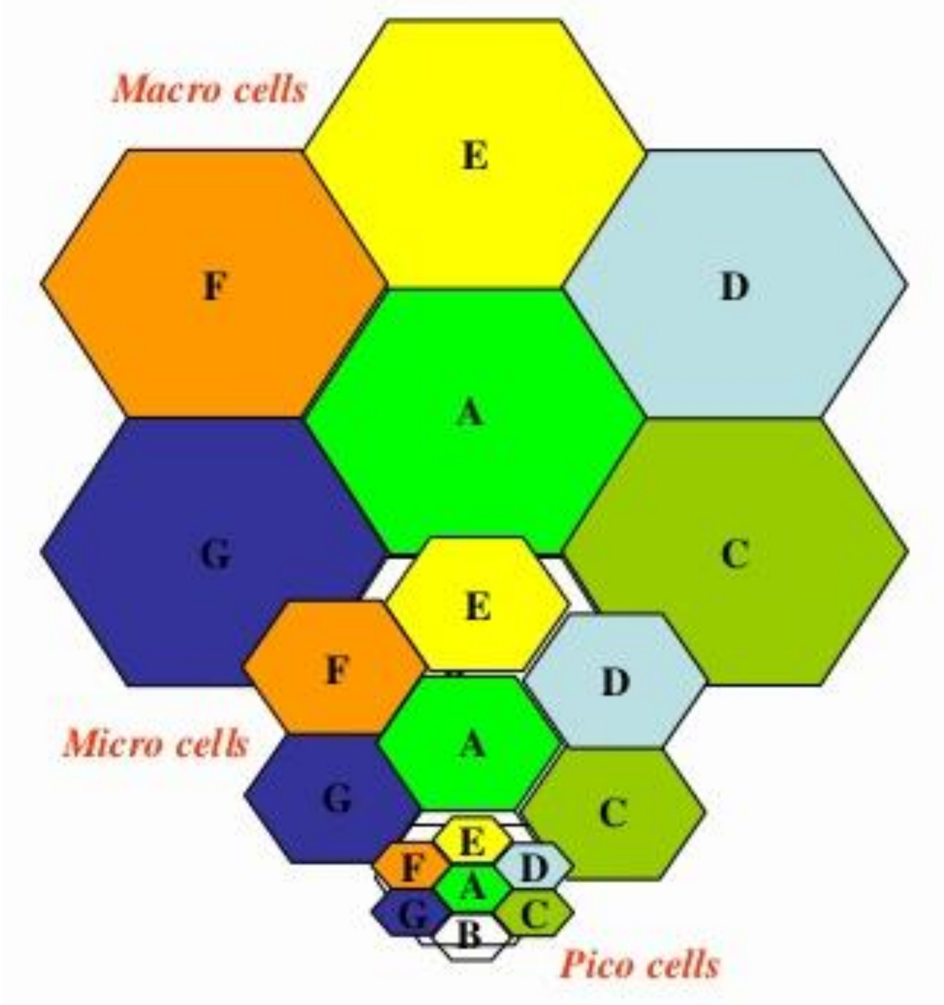
Cell Splitting

- One way to cope with **different terrain environments** and **increased traffic** is to **split a cell into several smaller cells.**

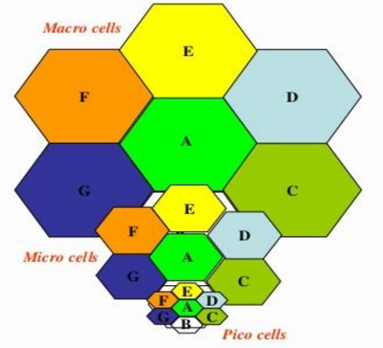


Cell Splitting – Example

- We start with macro cells to support Rural Areas – i.e., Low Traffic Density
- We split macro cells into micro cells for more crowded areas – i.e., sub urban or medium traffic Density in Urban Areas.
- Micro cells are further split into Pico cells to support high crowded areas (hot spot areas).

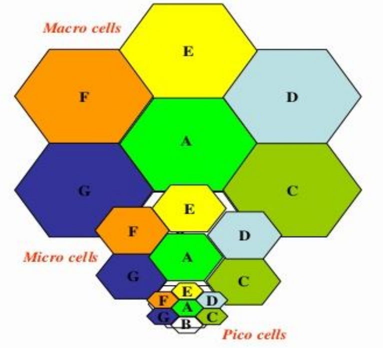


Cell Splitting



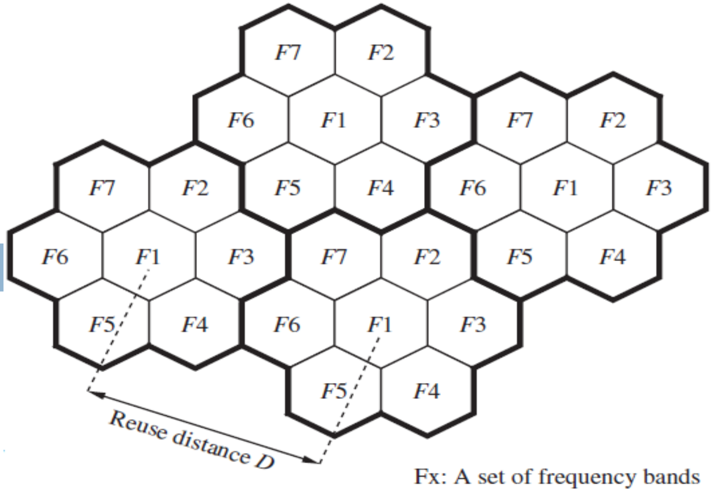
- This implies that **additional BSs need to be installed** at the **center of each new cell that has been added** so that the **higher density areas** can be **handled effectively**.
- As the **coverage area of new split cells is smaller**, the **transmitting power levels are lower**, and this helps in **reducing Co-Channel Interference**.
- **Also cell splitting increases the capacity** of cellular system since it **increases** the **number of times the channels are reused, increasing thus the additional number of channels per unit area.**

Cell Splitting



- Also, **depending on** **traffic patterns**, the **smaller cells** may be **dynamically activated** **or** **deactivated** in **cases where extra capacity is known to be needed** (e.g., at a stadium during a football match).
- **Weakness of cell splitting**:
  - **Reduced capacity of the bigger cell** (that is because **the frequencies allocated by the smaller cells** **cannot be used** **by the bigger cell**)
  - **Increased handovers** (this is because with smaller cells, the BSs are closer to each other and thus MSs' handovers can occur more frequently).

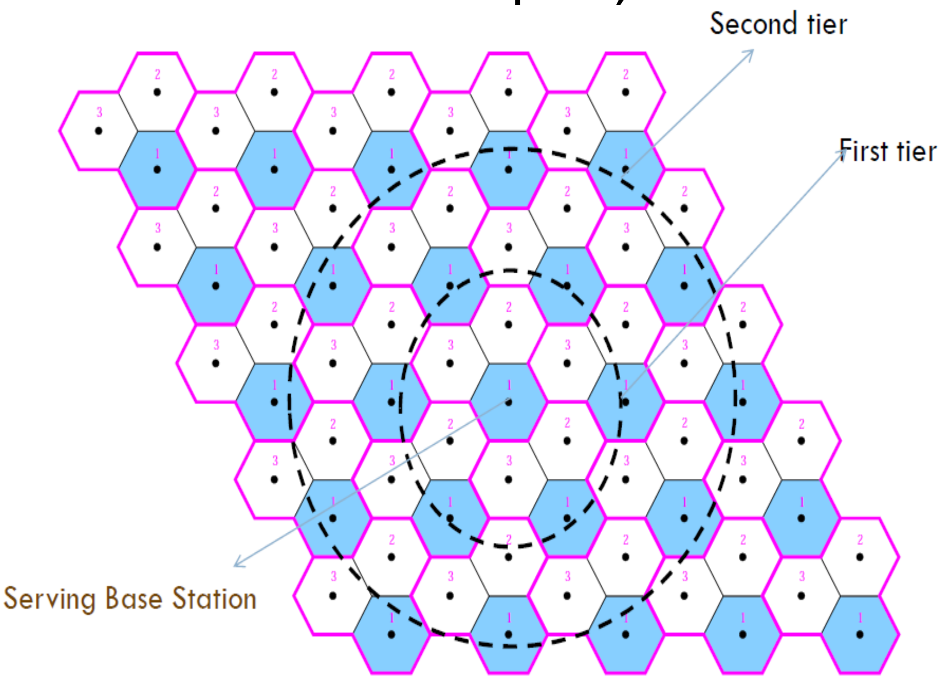
Co-Channel Interference (CCI)

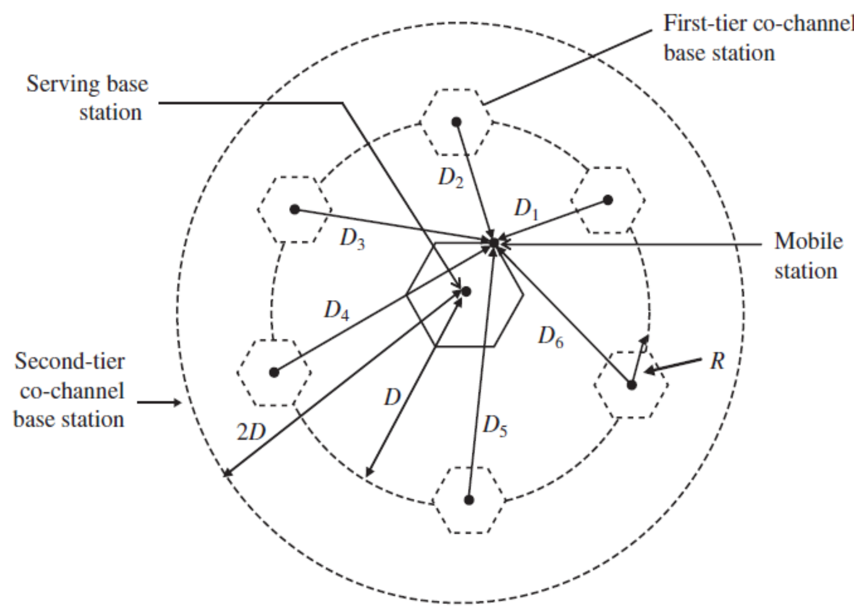


- When using the **Frequency Reuse pattern**, all the **cells using the same channels (i.e., the same frequency range)** are **physically located apart** by at least a **Reuse Distance**.
- **Even though the power level is controlled carefully,** so that such "co-channels" do not create a problem for each other, **still some degree of interference remains**.
  - Called **Co-Channel Interference (CCI)**
  - **CCI increases** as the **cluster size N becomes smaller**

Co-Channel Interference (CCI)

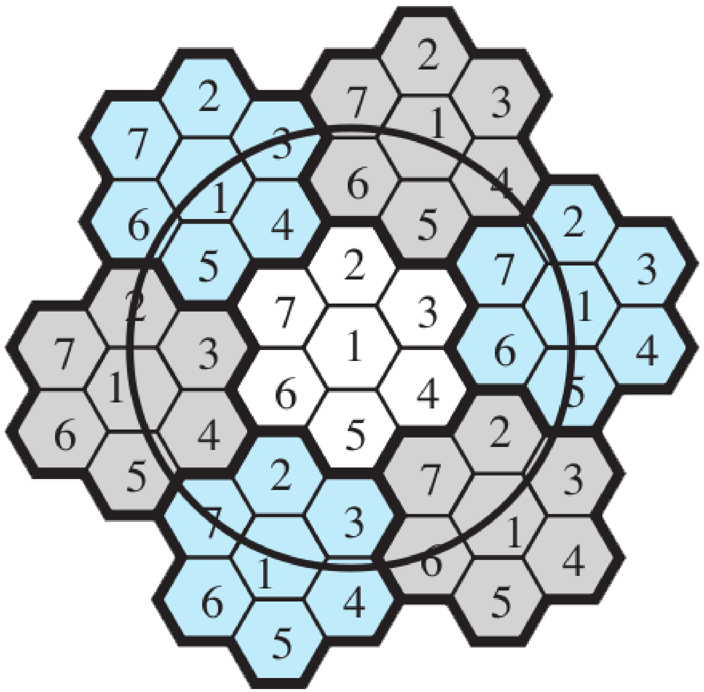
- In a **cellular system**, with a **cluster of three, four, seven, … cells**, there will be **six cells using co-channels** at the **Reuse Distance (D)**.
  - **Most Co-Channel Interference (CCI)** comes **from the First-tier**.
  - The **Second-tier co-channels**, are at **two times** the **Reuse Distance** apart, and their **effect on the serving BS is negligible**.

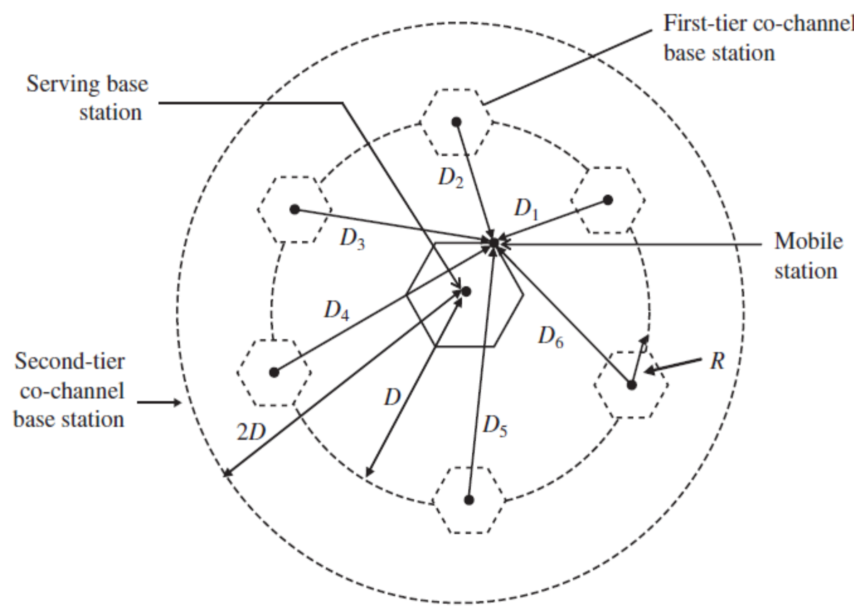




Co-Channel Interference (CCI)

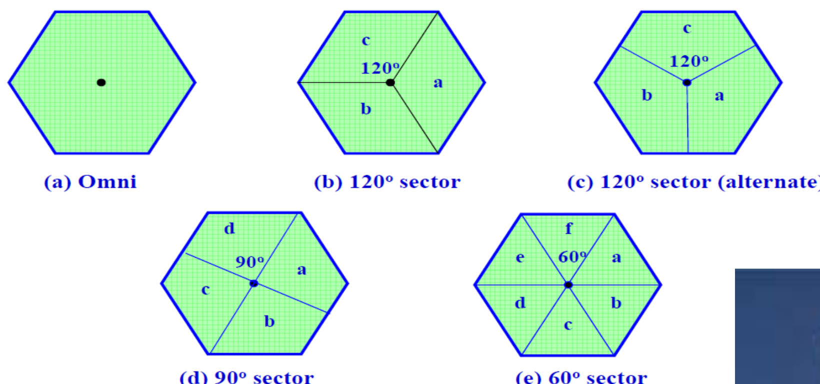
- Using Omni-Directional Antennas





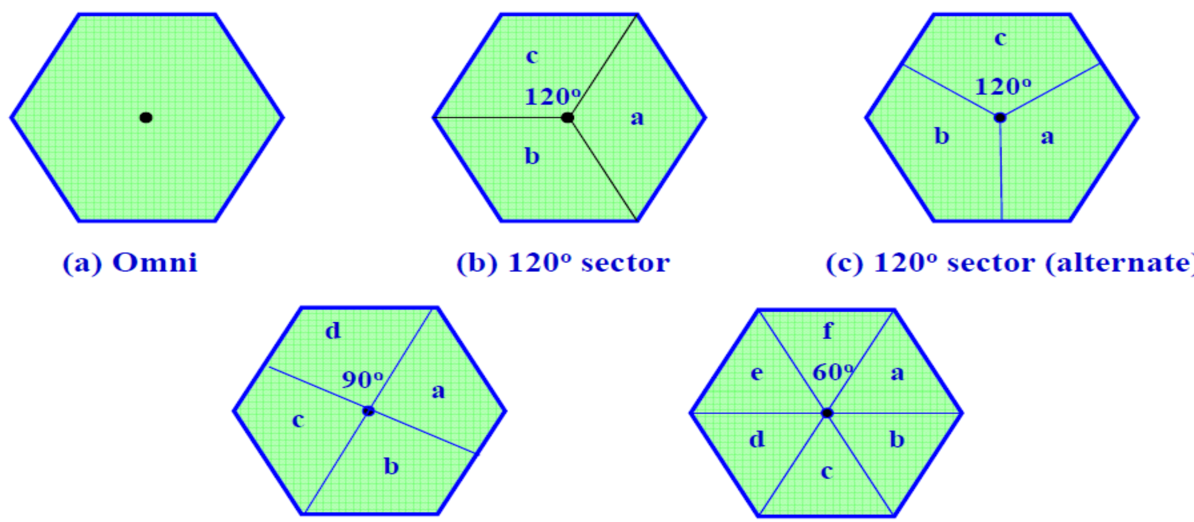
Cell Sectoring

- With cell sectoring, a **cell is** **divided** **into a** **number of wedge shaped sectors**, typically **3 or 6 sectors per cell**.
  - **Replacing a single** **Omni-directional** **antenna by several** **Directional** **antennas** **each radiating within a specified sector.**



Cell Sectoring

- **Each sector** is **assigned a** **separate subset of the cell's frequencies (i.e., channels)**, and **directional antennas** at the Base Station are used to **focus radiation on each sector.**
- **With cell sectoring and the use of directional antennas** **the Co-Channel Interference (CCI) is decreased** while the **cell radius R remains unchanged.**



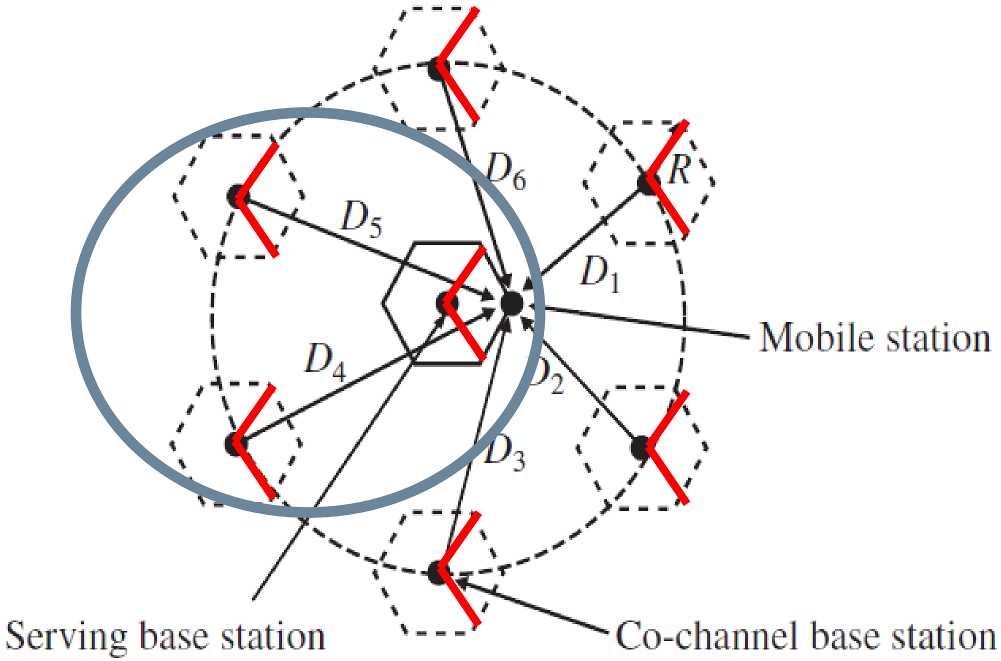
(a) Omni (b) 120° sector (c) 120° sector (alternate)

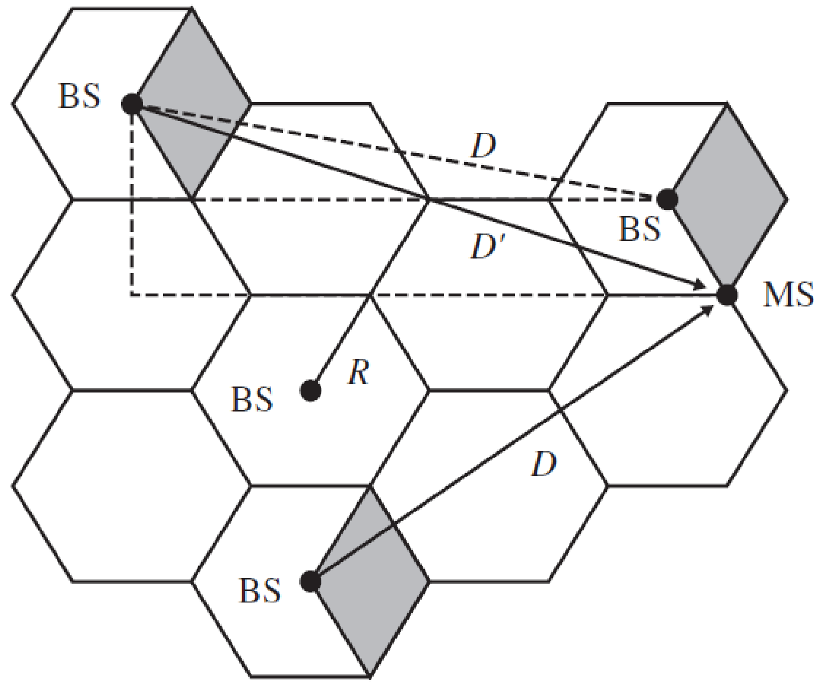
(d) 90° sector (e) 60° sector

Cell Sectoring

- The **advantages** of sectoring (besides **easy borrowing of channels as these are controlled by the same BS**) are that:
  - It **requires coverage of a smaller area** by **each antenna** and **hence lower power** is **required** in **transmitting radio signals** which also **helps in decreasing interference between co-channels cells (i.e., cells that uses the same range of frequencies).**
  - The **spectrum efficiency** and the **overall system capacity is enhanced (as it allows for smaller cluster sizes)**.
    - Since the **co-channel interference is decreased** this **allows to reuse the same frequencies in closer distances (i.e., allows the use of smaller cluster sizes providing for better capacity and thus more users can be supported**)

Cell Sectoring
CCI for 3 sector Directional Antennas



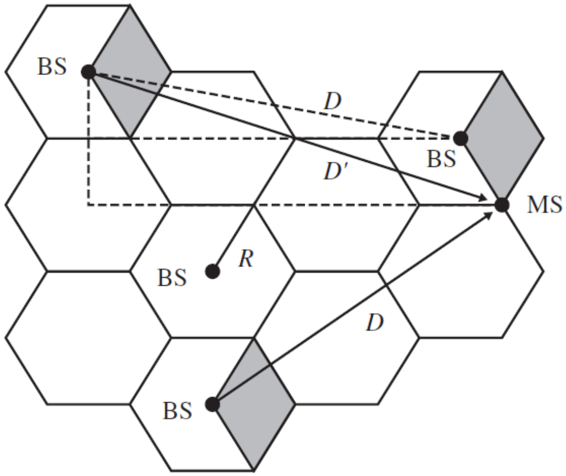


Cell Sectoring
CCI for 3 sector Directional Antennas

- Worst case for the **three-sector directional antenna is shown in the figure at the right.**
  - **No of interferers = 2 per sector (K_I = 2; instead of 6)**

$$\frac{C}{I}=\frac{1}{\sum_{k=1}^{K_I}\left(\frac{D_k}{R}\right)^{-\gamma}}=\frac{1}{\sum_{k=1}^{K_I}(q_k)^{-\gamma}}$$

$$\frac{C}{I}=\frac{1}{q^{-\gamma}+(q+0.7)^{-\gamma}}$$



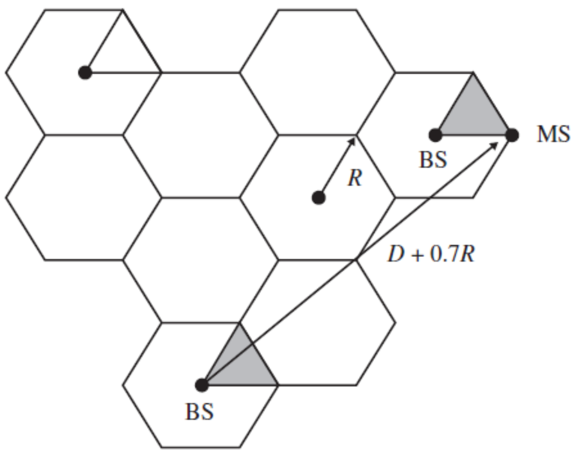
$$D=\sqrt{\left(\frac{9}{2}R\right)^2+\left(\frac{\sqrt{3}}{2}R\right)^2}=\sqrt{21}R\simeq 4.58R$$

$$D'=\sqrt{(5R)^2+(\sqrt{3}R)^2}=\sqrt{28}R\simeq 5.29R=D+0.7R.$$

- ***Where***
  - ***q** (=$\frac{D}{R}$) is the **frequency reuse factor***
  - ***γ** is the is the **propagation path loss slope** and varies between 2 and 5 depending on the propagation environment*

Cell Sectoring
CCI for 6 sector Directional Antennas

- Worst case for the **six-sector directional antennas is shown in the figure at the right.**
  - **No of interferers = 1 per sector** (K_I = 1)



$$\frac{C}{I} = \frac{1}{\sum_{k=1}^{K_I}\left(\frac{D_k}{R}\right)^{-\gamma}} = \frac{1}{\sum_{k=1}^{K_I}(q_k)^{-\gamma}}$$

$$\frac{C}{I} = \frac{1}{(q+0.7)^{-\gamma}} = (q+0.7)^4$$

Thus, the use of directional antennas (Cell Sectoring) is helpful in reducing co-channel interference.

- ***Where***
  - ***q** (= $\frac{D}{R}$) is the **frequency reuse factor***
  - *Assuming **γ = 4***, as the **propagation path loss slope**

Cell Sectoring

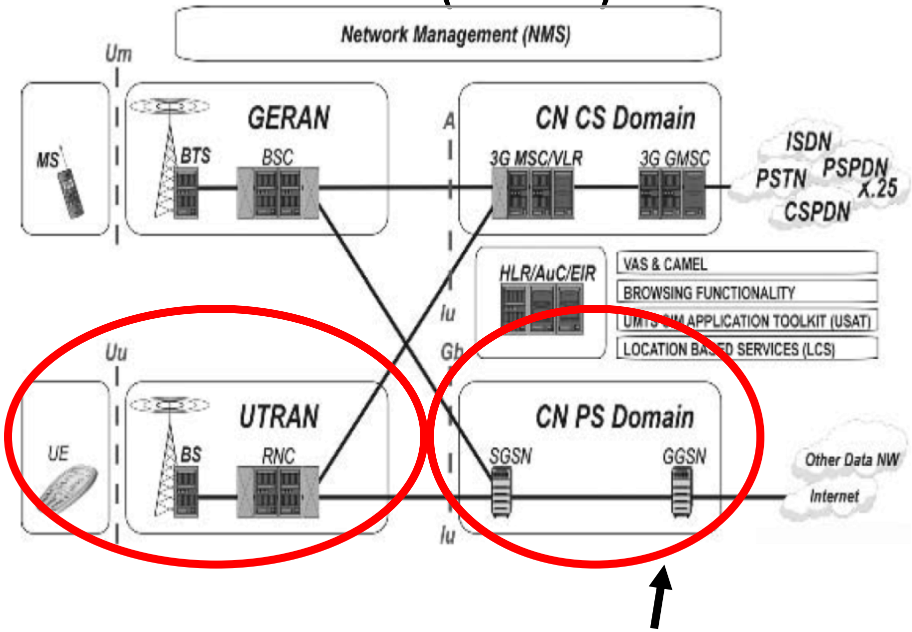
- By using **Directional Antennas** (Cell Sectoring), the **interference can be reduced** and **thus a lower frequency reuse factor (q) can be used**.
  - Thus we can reuse the same frequencies in closer distances (i.e., smaller cluster sizes) → Better Capacity → The Network can support more users.
- Using **three- or six- sector cells, the frequency reuse pattern** can be **reduced** from **7 to 4 or even 3 cells per cluster**, resulting in a **capacity increase** of **1.67** and **2.3**, **respectively**.

Universal Mobile Telecommunications System (UMTS) Network

- The **Universal Mobile Telecommunication System (UMTS)** is a **3rd Generation (3G)** wireless system that **utilizes a higher bandwidth** (i.e., 5 MHz Bandwidth) **than previous generation networks** to deliver **packet data** and **voice services** to mobile users and also **provide access to the web, with high data rates**.
- **Frequency bands indented for use on a worldwide basis** for UMTS are **around to 2 GHz**
  - Uplink: 1885-2025 MHz , Downlink: 2110-2200 MHz
  - In the US, 1710–1755 MHz and 2110–2155 MHz will be used instead, as the 1900 MHz band was already used.

Universal Mobile Telecommunications System (UMTS) Network

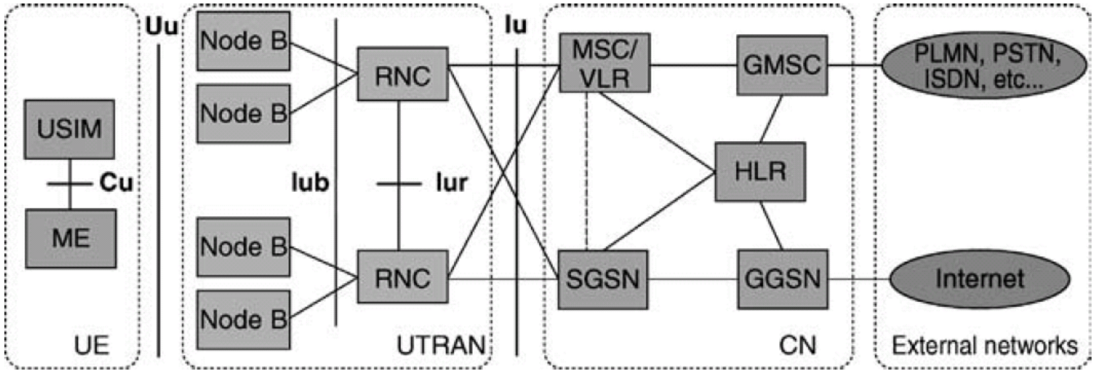
- UMTS **evolved from Global Systems for Mobile communications** (**GSM**) and it has an **Internet Protocol (IP) Core Network** based on General Packet Radio Service (**GPRS**).
- **3G Networks radio access equipment** as such, are **not compatible** with **GSM equipment.**
- **A new part that will maintain the 3G connections (i.e., the W-CDMA connections) in the radio interface is required (UMTS Terrestrial Radio Access Network (UTRAN))**



Internet Protocol (IP) Core Network based on GPRS

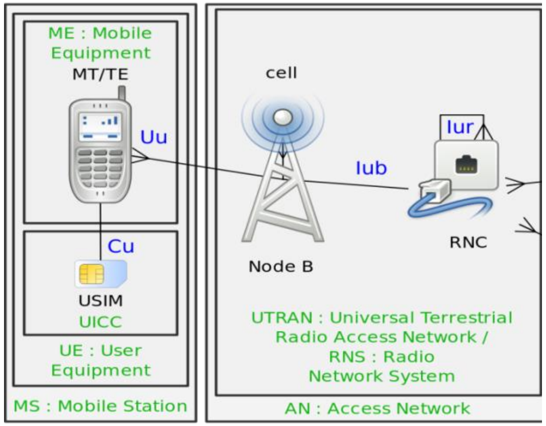
UMTS Network Architecture

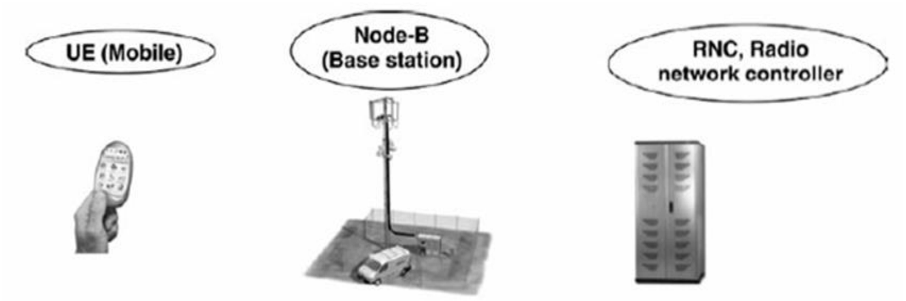
- **The main components of a UMTS system are:**
  - The **Core Network (CN)**, which is responsible for **switching and routing calls** to the users, as well as **data connections** to other **external networks (all calls go through the CN).**
  - The **UMTS Terrestrial Radio Access Network (UTRAN)** that **handles all radio-related functionality (e.g., Radio Resource Management)**
  - The **User Equipment (UE)** that is the **interface** between the **user** and the **Network (through the Node-B)**.



Radio Resource Management

- The **Radio Resource Management (RRM)** is a **responsibility solely taken care of by the UTRAN**.
- **RRM** is located in the **Node-B** and the **RNC** inside the UTRAN but also in the **UE**.
- The **control protocol** used for this purpose (e.g., to exchanged signalling) is the **Radio Resource Control (RRC)** protocol.



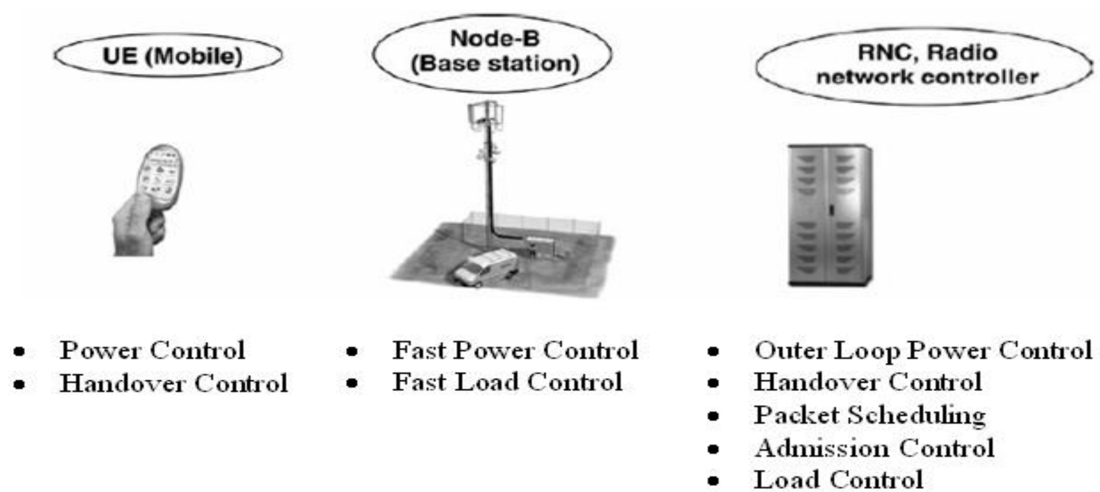


Radio Resource Management

- **More specifically RRM contains a set of algorithms devoted to:**
  - Achieve **optimal usage** of the **radio interface resources**
  - **Guarantee** Quality of Service (**QoS**)
  - **Maintain** the **planned coverage area**
  - To **increase** the **Network capacity**

Radio Resource Management

- **The family of RRM algorithms can be divided into:**
  - **Power Control**
  - **Handover Control**
  - Admission Control
  - Load Control
  - Packet Scheduling



Radio Resource Management

- **Connection based functions:**
  - **Power Control (PC)**
    - **Controls the transmission power used** by the **UE** and the **BS** in order to **keep the interference levels at minimum** in the air interface.
  - **Handover Control (HC)**
    - **Provide continuity of mobile services** to a user traveling **over cell boundaries in a cellular infrastructure**.

Radio Resource Management

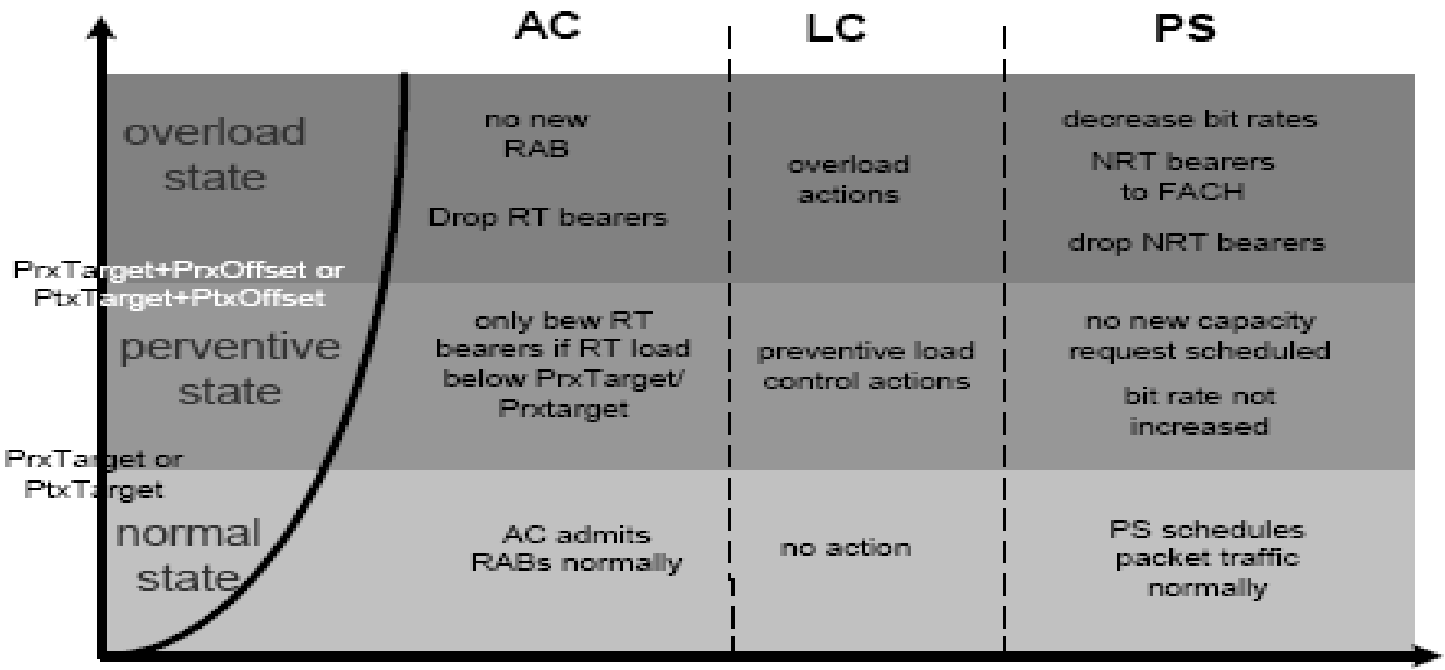
- **Network based functions:**
  - **Admission control (AC)**
    - **Handles all new connections requests** by **checking whether a new connection can be admitted** to the system.
    - Has the function to **provide resources for new call requests** or **regulate resources** for **already ongoing calls** (e.g., in case of congestion)
    - Occurs **when a new call is set up**, and also **during handovers (**as a new connection will be required in the new cell**)**.

Radio Resource Management

- **Load Control (LC)**
  - The main objective of Load Control is to **ensure that the network is not overloaded** and **remains in a stable state**.
  - **Manages situation** when **system load exceeds the threshold** and some **counter measures** have to be taken to **get system back to a feasible load**.
- **Packet Scheduling (PS)**
  - The main objective of Packet Scheduling is to **control the traffic in the network** by **regulating how much bit rate an application is allowed**, by **giving priority to packets** according to the **type of service**, mainly by controlling **Non Real Time (NRT) traffic (e.g., provides the appropriate radio resources**, etc.**)**

Radio Resource Management

- **Packet Scheduling, Admission Control** and **Load Control** algorithms **work together** in order **to prevent the Radio Network from congestion (Συμφόρηση)** and **maintain the requested QoS**.



RT: Real Time

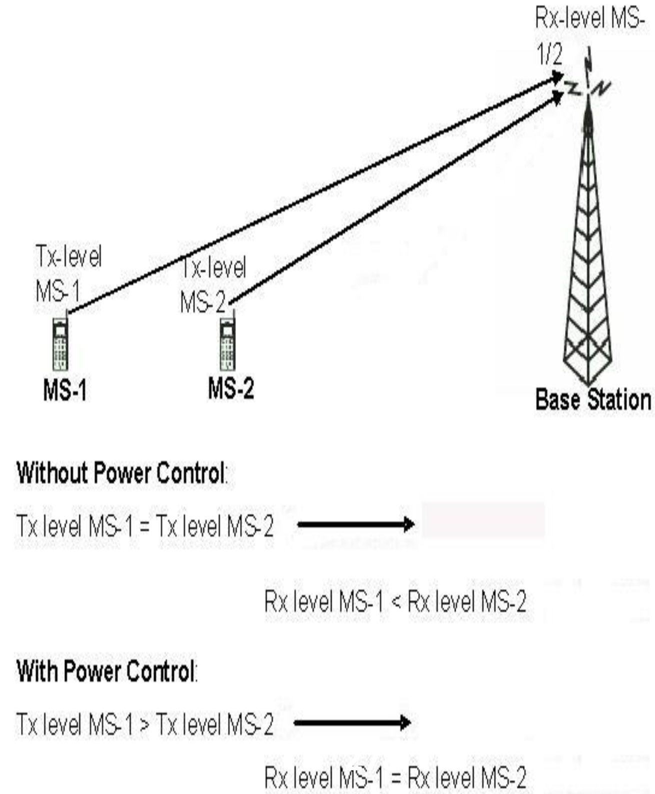
NRT: Non Real Time

Power Control (PC)

- **Power Control is one of the most important functions in WCDMA**, especially in the **Uplink**
  - Without it, a **single overpowered Mobile Station** could **block a whole Cell.**
- **The main reasons for implementing Power Control are**:
  - The **Near-Far problem**
  - The **interference depended capacity** of **W-CDMA**
  - The **limited power source of the UE** (**Battery**)

Power Control (PC)
The Near-Far Problem

- MS-1 and MS-2 **operate within the same frequency**, **separable at the Base Station** only by their **respective Spreading Codes**.
- **MS-1** at the **cell edge** suffers a **path loss, say 70 dB** above that of MS-2 which is near the Base Station.
- **If there were no mechanism for MS-1 and MS-2 to be Power Controlled to the same level at the Base Station, MS-2 could easily overshout MS-1 and thus block a large part of the cell**
  - The optimum strategy in the sense of **maximizing capacity** is to **equalize the received power per bit** of **all Mobile Stations** at all times (**Target SIR**).



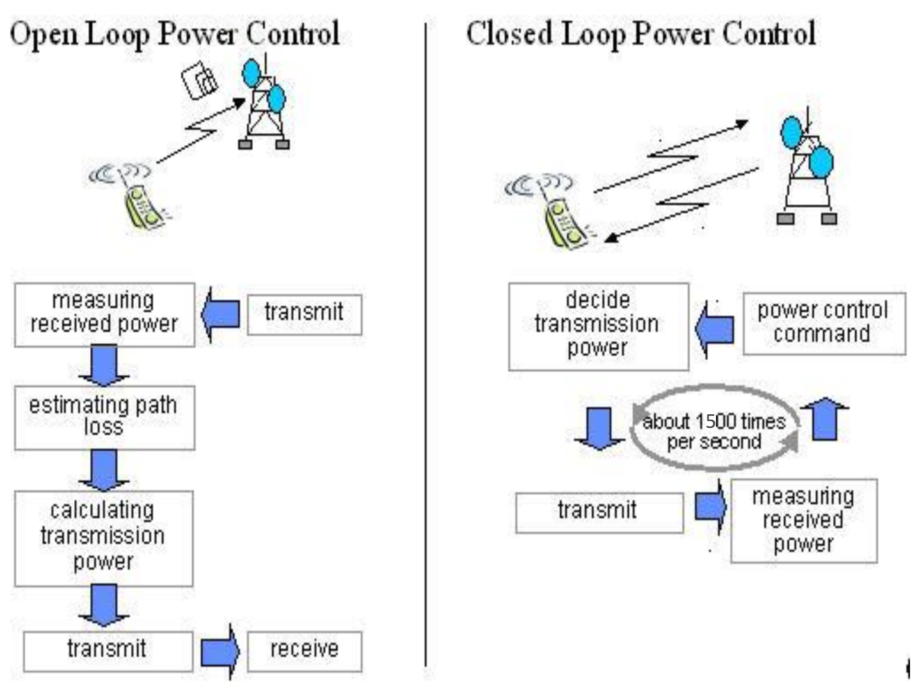
Power Control (PC)

- **Power Control is employed** in both in the **Uplink** (UL) & in the **Downlink** (DL)
  - **Uplink Power Control:** The Power Control Algorithm running in the **BS determines** the **Uplink transmission power of the UE**
  - **Downlink Power Control:** The Power Control Algorithm running in the **UE determines** the **Downlink transmission power of the BS**

Power Control (PC)

- To **efficiently manage** the power control in WCDMA, the system uses **two different defined Power Control mechanisms**:
  - **Open Loop Power Control (OLPC)**
  - **Closed L**

OLPC: Performed only once and this is when the UE is requesting Access to the Network. Then CLPC takes place.



CLPC: Performed continuously, once the connection of the UE with the Base Station is established.

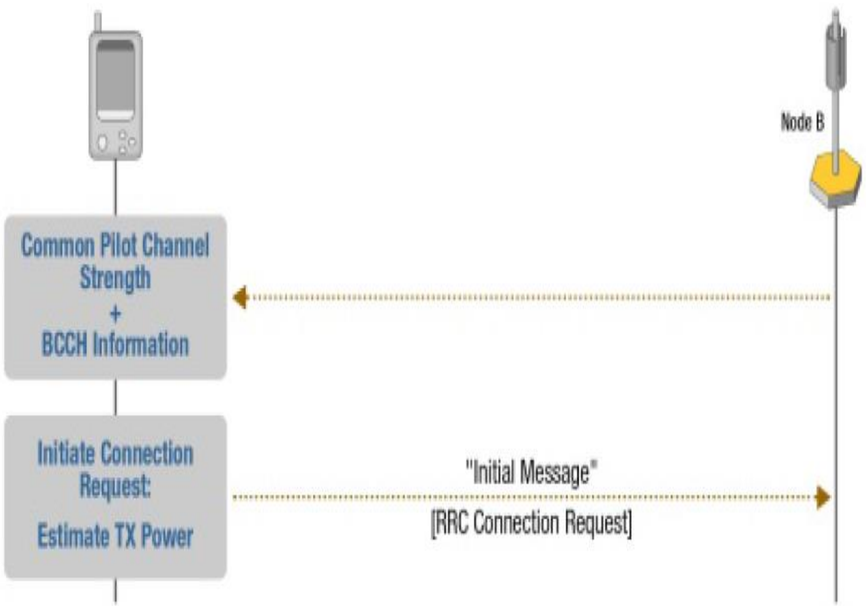
Open Loop Power Control

- ***CPICH (Common Pilot Channel)***
  - *This (downlink) channel is received by all the UEs within the cell.* ***Used for synchronization purposes,*** *between the MS and the BS. It is also used by the UE for* ***channel signal quality estimation reference. In order for all the UEs to be able to decode this channel,*** *a* ***Pre-defined bit sequence*** *(i.e., using a Pre-Defined* ***Spreading Code****) with a* ***fixed length*** *(****Spreading Factor (SF) = 256****) is used.*
- ***Target SNIR***
  - *Defines the* ***minimum level that the signal power should have*** *over the noise and interference so as for the receiver to be able to decode the signal correctly.*

Open Loop Power Control (OLPC)

- This kind of Power Control is useful for **determining the initial value** of the **transmitted power that will be used when a UE is requesting access (i.e., connection) to the Network.**

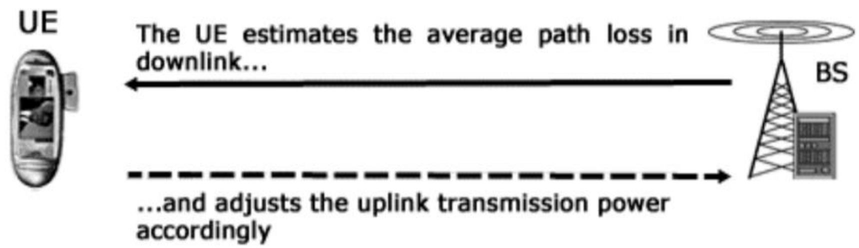
1. *The UE **measures the (Downlink) CPICH Signal Strength** and **roughly estimates** the **Uplink Channel Conditions** (i.e., estimates **the path loss** that the signal will experience during propagation in the uplink)*
2. *Based on this assessment and some other info received from the Network (broadcasted in the BCCH), the UE **roughly estimates the initial transmission power that will be required** to send "Connection Request" to the Node B*



Open Loop Power Control (OLPC)

- **Open Loop Power Control** mechanisms attempt to **make a rough estimation of** the **Uplink Channel Conditions (i.e., the path loss that the signal will experience in the uplink)** by **measurements performed on the Downlink CPICH Signal Strength.**

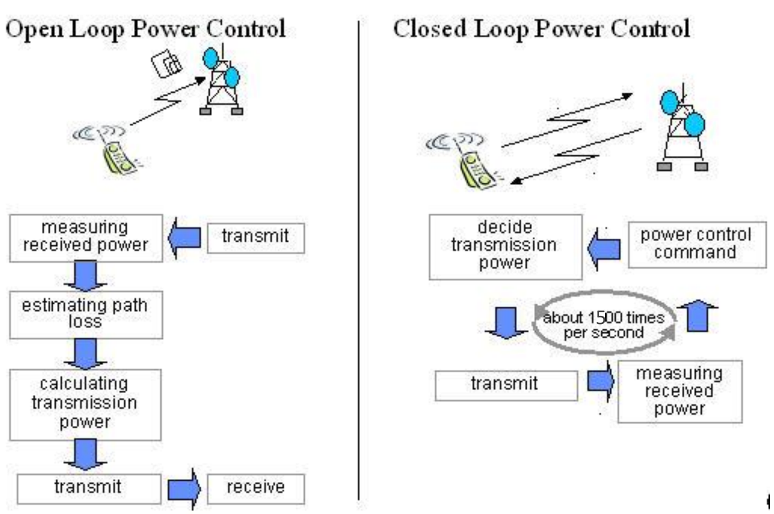
- **Based on this estimation, the UE adjusts its uplink transmission power accordingly.**

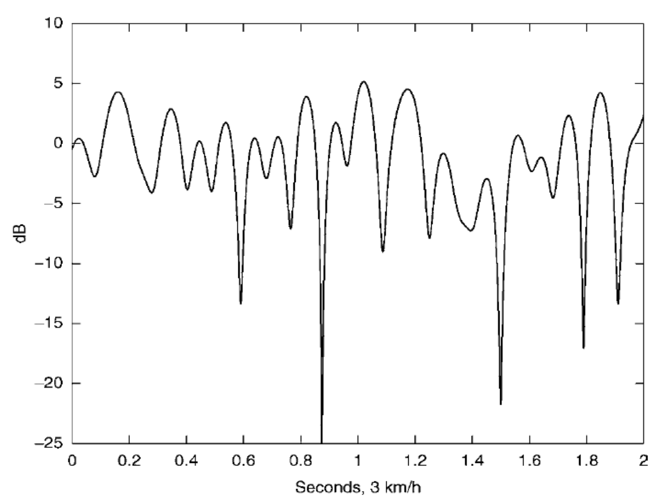


- Such a method would be **far too inaccurate**.
- The **prime reason** for this, is that the pathloss experienced on the signal is **essentially uncorrelated between Uplink** (1920 – 1980 MHz) **and Downlink** (2110 – 2170 MHz), due to the **large frequency separation** of **uplink** and **downlink bands** of WCDMA FDD mode.

Open Loop Power Control (OLPC)

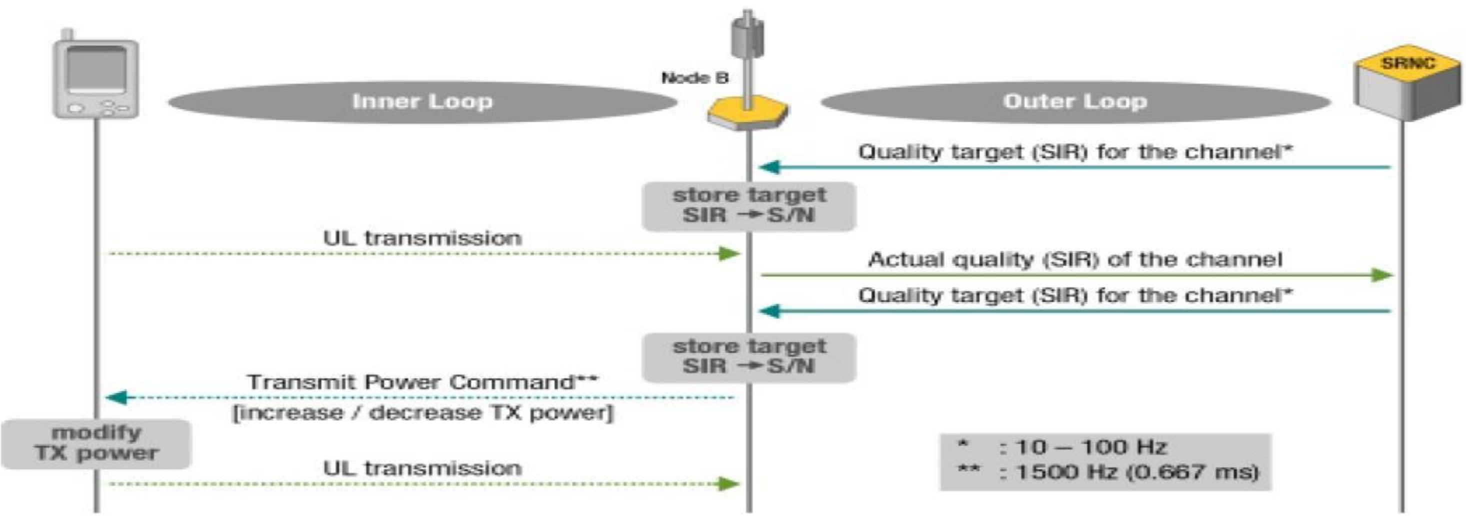
- Thus, **Open Loop Power Control alone** is **neither adequate nor accurate** for **adjusting the UE transmission power during the connection**.
- In order to **more efficiency** and **more accurately compensate the rapid changes in the signal strength (caused at the receiver, mainly due to Fast fading), once the connection is established, Close Loop Power Control is essential**.





Closed Loop Power Control (CLPC)

- **Once the connection is established,** the **CLPC takes place in order to determine the Uplink and Downlink transmission power** used **during the connection**.
  - **Closed Loop Power Control** includes:
    - **Inner Loop Power Control** (or Fast Power Control)
    - **Outer Loop Power Control** (or Slow Power Control)



Uplink case:
BS adjusts the transmission power of UE

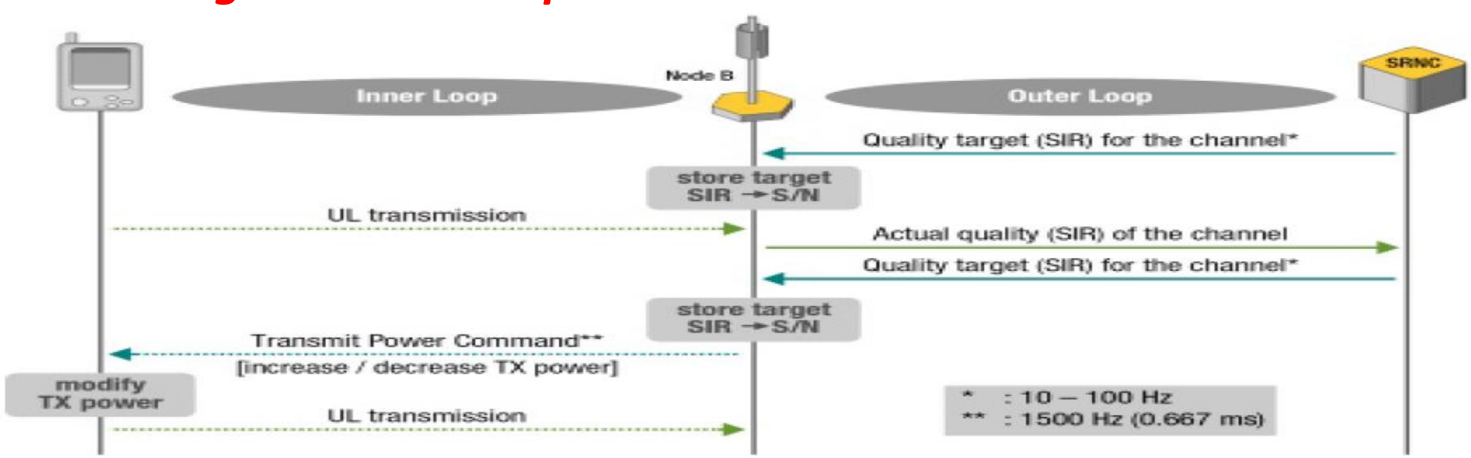
Closed Loop Power Control (CLPC)

- **The Inner and Outer Loop Power Control work together**, in order to **keep the Target SIR** in a **minimum but always acceptable level and thus:**
  - **Reduce Bit Error Rate**
  - **Reduce transmission power levels required by the MS and the BS to the minimum**
  - **Increase the Terminal's** (UE) **Battery-life**
  - **Increase the overall system capacity** (by **minimizing the uplink** and **downlink interference caused**)

Closed Loop Power Control (CLPC)

Uplink Closed Loop Power Control Example:

- ***Inner Loop*** → *Runs **between** the **UE** and the **Node-B**. The Node-B **compares** the **signal quality (measured SIR) receive from the UE** with the **Target SIR** and **commands the UE** to **increase or decrease** its **transmission power accordingly***
- ***Outer Loop*** → *Runs **between** the **Node-B** and the **RNC**. **Every time a frame is received by the NodeB (from the UE)**, this frame is **forwarded to the RNC**. The RNC **checks the quality of that frame** (i.e., if it is **received correctly or not**) and **sets the new Target SIR**. This **new Target SIR** is **provided to the Node-B** to be **considered during the Inner Loop Power Control**.*



Closed Loop Power Control (CLPC)

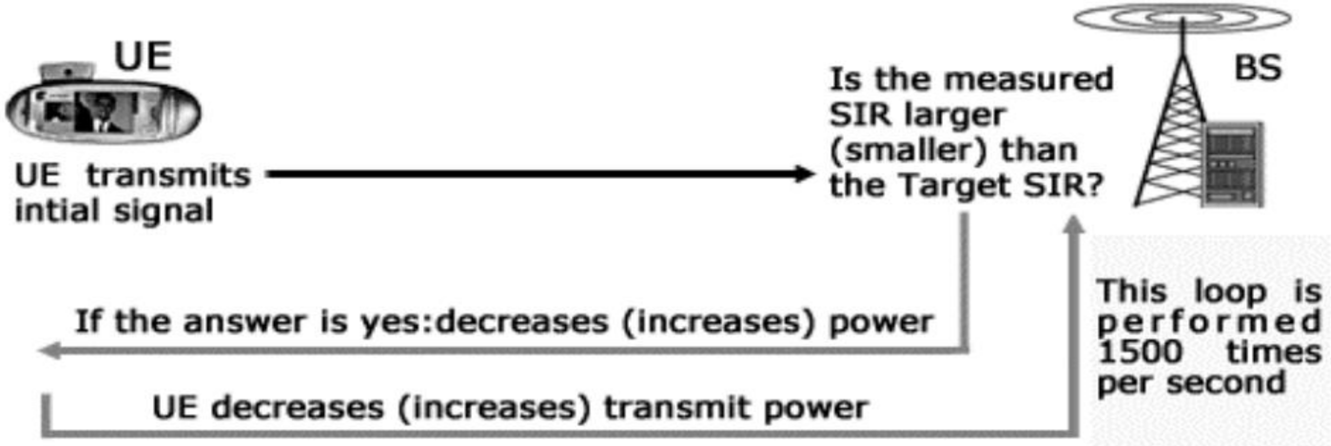
- **Inner Loop Power Control**
  - **Adjusts the transmission power used by the UE (in the Uplink) and the Base Station (Downlink) based on a Target SIR* value.**
  - **Performed with a frequency of 1500Hz** (1500 times per sec)

- **Outer Loop Power Control**
  - **Sets the Target SIR for the Inner loop Power Control**
  - **Performed with a frequency** of **10–100Hz** (10-100 times per sec)

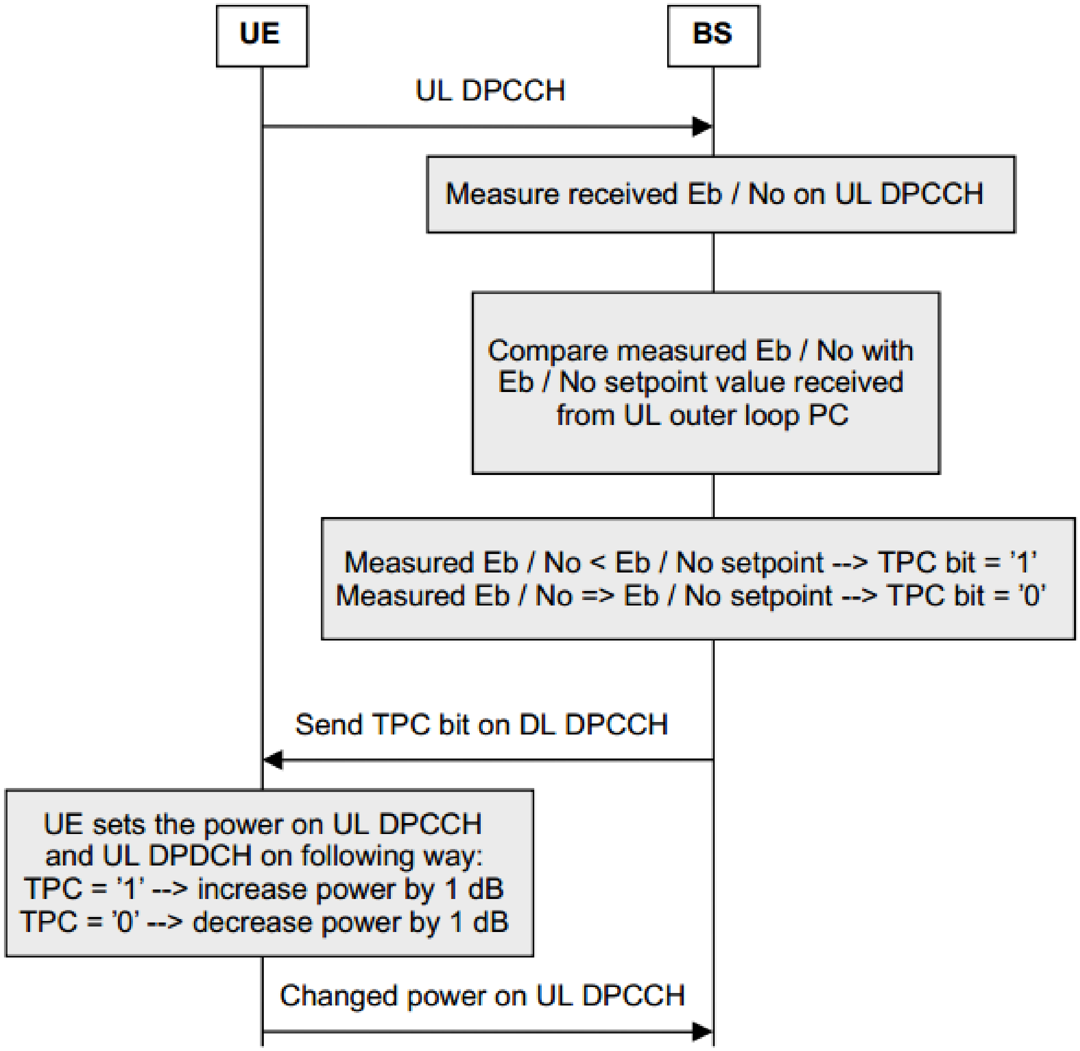
**** Target SIR defines the minimum level that the signal power should have over the noise and interference so as for the receiver to be able to decode the signal correctly.***

Inner Loop Power Control Uplink

- **The Base Station measures the Signal-to-Interference Ratio (SIR) of the signal received from the UE** and **compares** it to the **Target SIR (this value is set by the Outer Loop Power Control)**.
  - If the **measured SIR** is **higher than** the **Target SIR**, the Base Station will **send a Transmission Power Command (TPC)** to the Mobile Station **to reduce its transmission power**
  - If the **measured SIR** is **lower than** the **Target SIR** it will command the Mobile Station to **increase its transmission power**.



Inner Loop Power Control Uplink

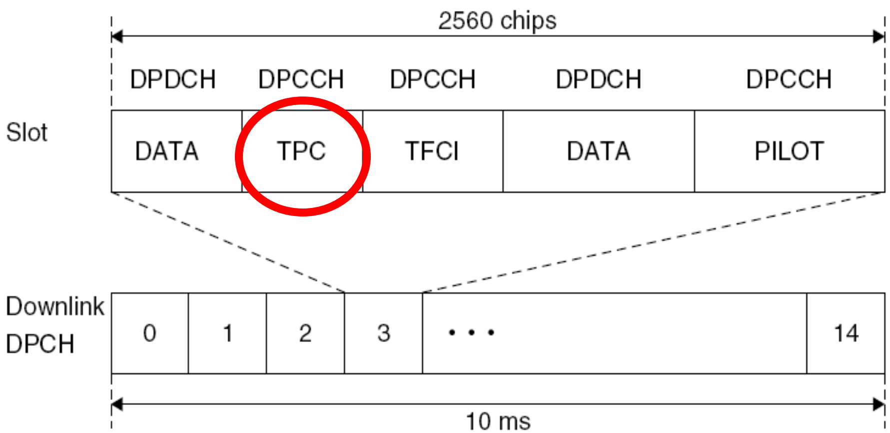


Inner Loop Power Control Downlink

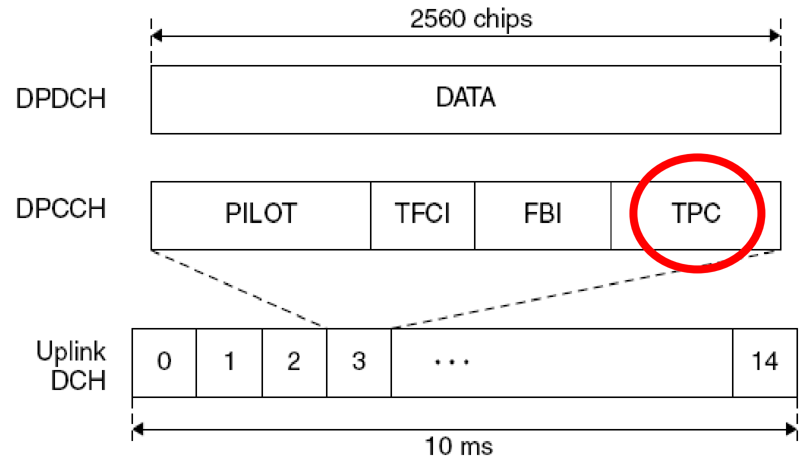
- In the **Downlink**, the **roles** of the **BS** and the **UE** are **interchanged**.
  - The **UE measures the received Signal-to-Interference Ratio (SIR) of the signal received from the BS** and **compares** it with the **Target SIR** and sends the **Transmission Power Command (TPC)** to the BS to adjust its transmission power accordingly.
  - On the **Downlink** though, the **motivation is different**:
    - On the downlink there is **No Near–Far problem,** due to the **One-to-Many scenario**. **All the signals within one cell originate from one Base Station to all mobiles**.
    - It is, however, desirable to **provide additional power to Mobile Stations at the cell edge**, as they **suffer from increased other-cell interference**.
    - Also is used for **enhancing weak signals caused by Fast Fading**.

Inner Loop Power Control

- **Inner Loop Power Control** is executed with a cycle of **1.5 kHz (1500 times per second – One per slot)** **for each Mobile Station (1dB to 2dB increase/decrease step for every TPC command)**
- **Open Loop Power Control** is executed with a cycle of **10-100 Hz** (**10-100 times per second – E.g., one per frame**) for each Mobile Station. **The size of the WCDMA frame is equal to 10ms**.



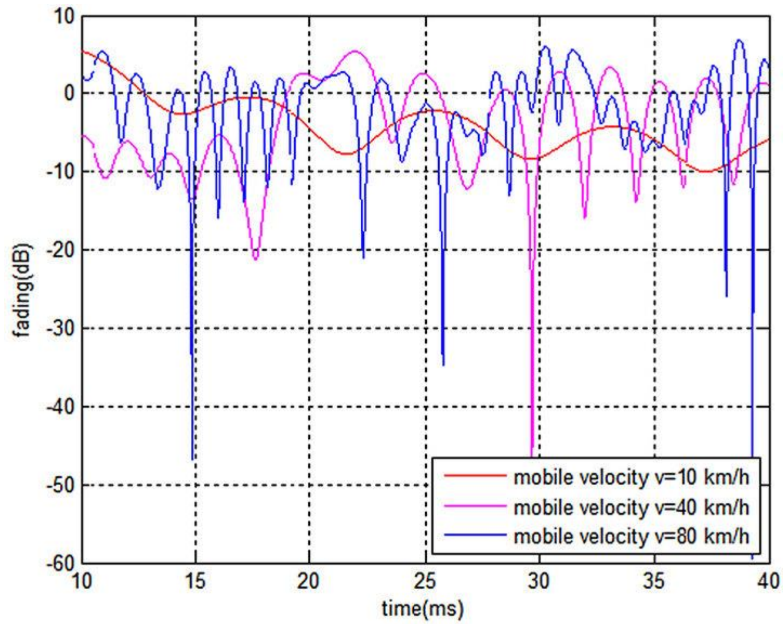
Downlink Dedicated Physical Channel (Downlink DPCH) control/data multiplexing



Uplink dedicated channel structure

Inner Loop Power Control

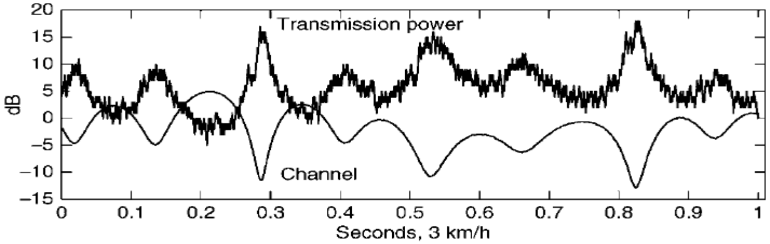
- **Inner Loop Power Control operates every 0.666 ms** (once every slot; **10ms frame/15 slots per frame**)
  - **Faster than any significant change of path loss could possibly occur on the signal at the Receiver,** and
  - **Faster than** the **speed of Fast Fading** for **low to moderate mobile velocity**.
- Thus **with Inner Loop Power Control**, only **very little residual fading is left** and the **channel becomes an essentially non-fading channel as seen from the Receiver** (**Base Station or the UE**).



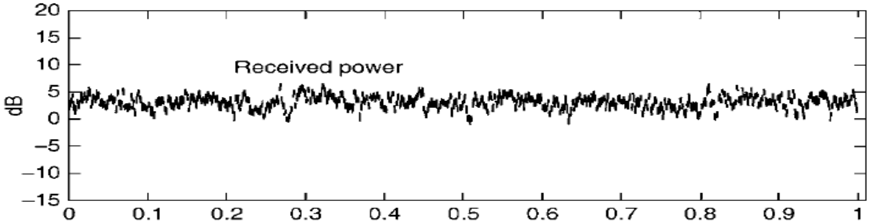
Inner Loop Power Control

- While this **fading removal is highly desirable** from the **Receiver point of view**, it **comes at the expense of increased average transmit power at the Transmitting end**.
- This means for example that for a channel **in a deep fade**, **will require the Transmitter (i.e., the Mobile Station) to use a large transmission power** to send its signal to the Base Station (so as the **signal to be received with the Target SIR required** at the Receiver), and thus it **will cause increased interference to other cells**.

In deep fades (experienced at the Receiver)
Transmitter needs to use a large transmission power



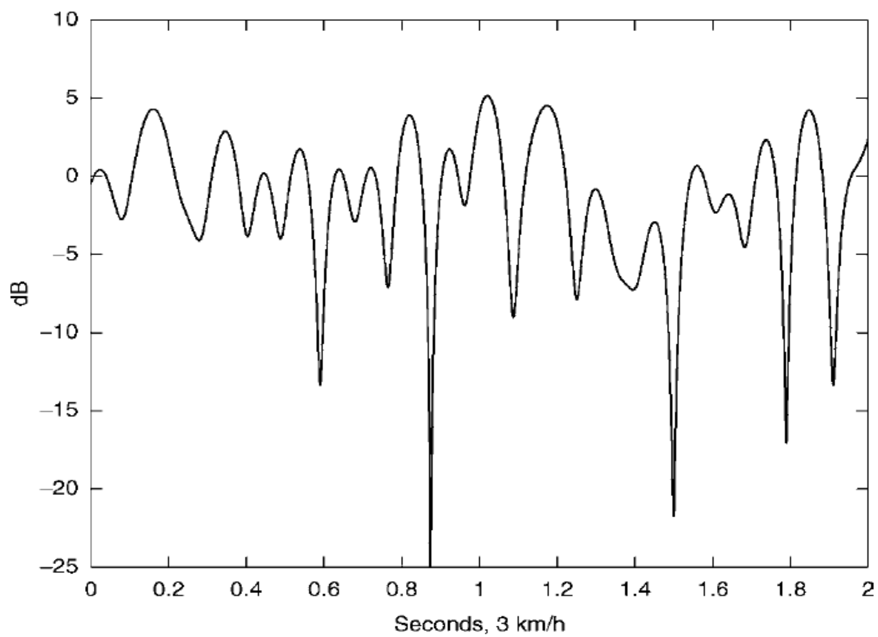
Fading is removed at the Receiver.
Received Signal Strength ≈Target SIR



Inner Loop Power Control

- **Fast Fading**
  - The following figure shows a **typical** **fast fading pattern** as would **be discerned for the arriving signal energy** at a **particular delay position** as the **receiver moves**.

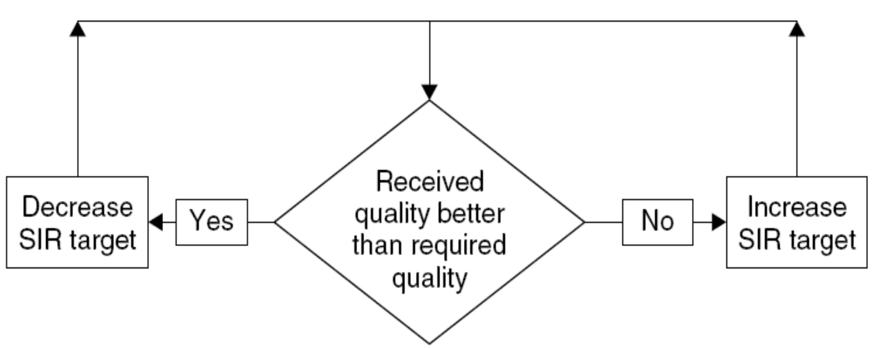
- We see that the **received signal power** can **drop considerably (by 20–30 dB)** **when phase cancellation of multipath reflections occurs**



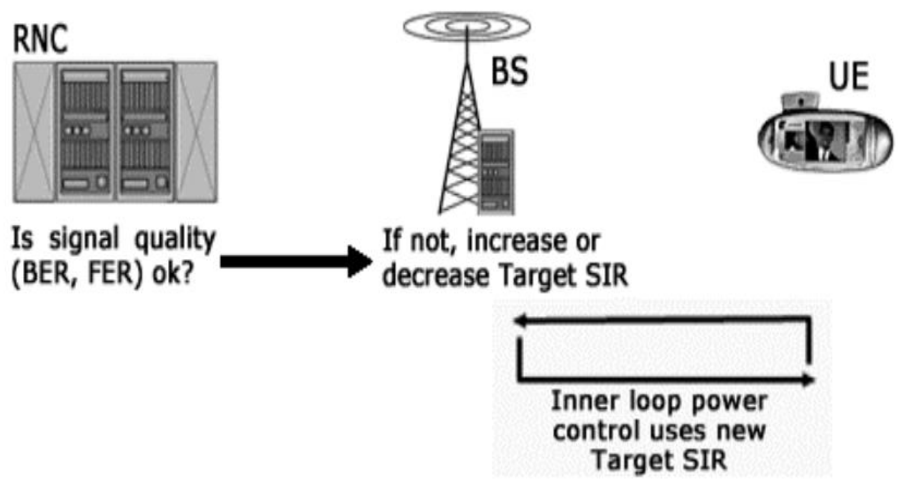
Fast Rayleigh fading as caused by multipath propagation

Outer Loop Power Control

- The **Outer Loop Power Control** is needed to **keep the quality of the communication at the required level** by **setting the Target SIR** for the **Inner Loop Power Control**.

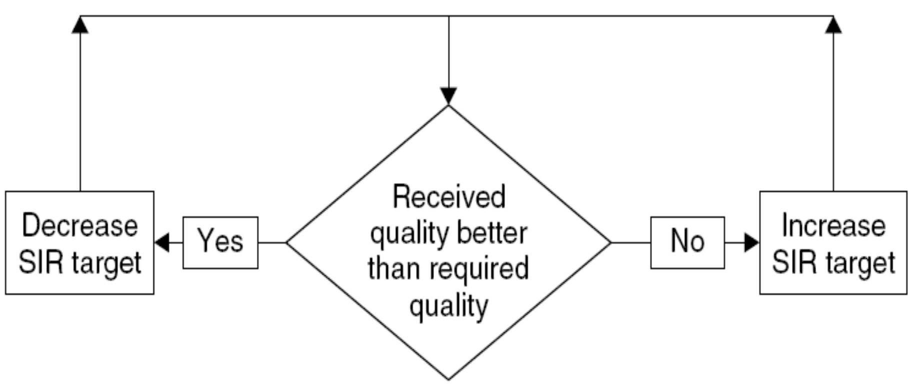


General outer loop power control algorithm

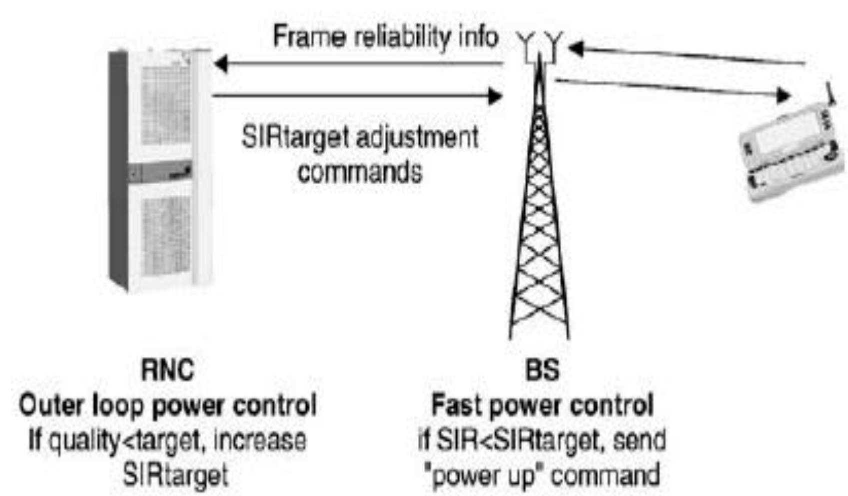


Outer Loop Power Control

- **In the Uplink, the Base Station tag each data frame received by the UE** with a **Frame Reliability Indicator and forwards the frame to the RNC.**
  - The **Frame Reliability Indicator value** is **estimated based on the Cyclic Redundancy Check (CRC) result obtained during decoding of that particular user data frame**.

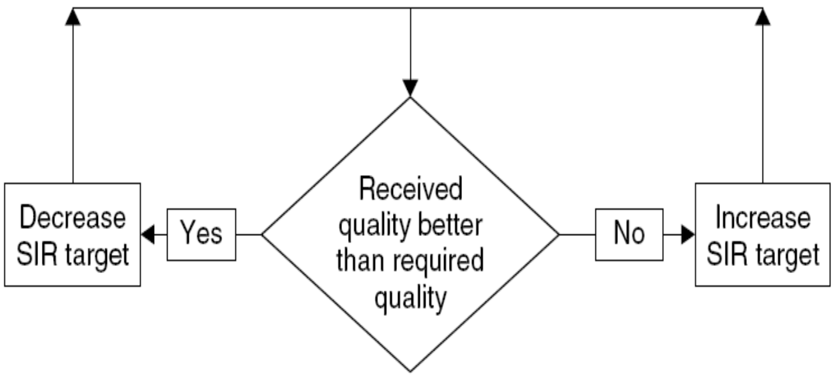


General outer loop power control algorithm



Outer Loop Power Control

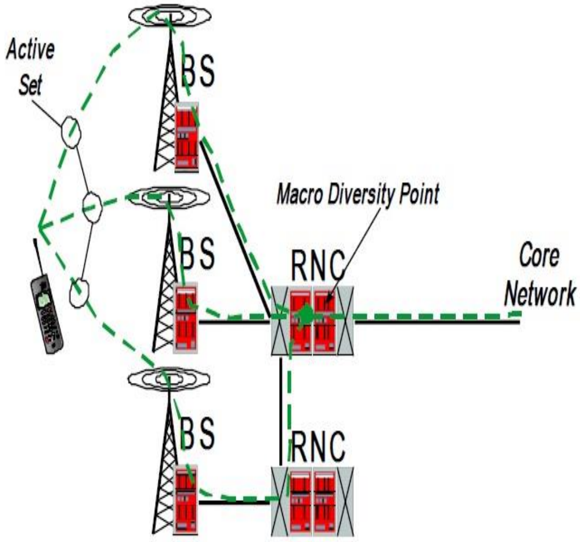
- If the **Frame Reliability Indicator value** indicates to the Radio Network Controller (RNC) that:
  - **The transmission quality is ok (i.e., there are not any errors in the frame received), the RNC** in turn **will command the Node-B to decrease the Target SIR by a certain amount.**
- **The transmission quality is below the one required (i.e., there are errors in the frame received), the RNC** in turn **will command the Node-B to increase the Target SIR by a certain amount.**



General outer loop power control algorithm

Outer Loop Power Control

- **In the Uplink**, the reason for having Outer Loop Power Control **reside in the RNC** and **not in the Node-B** is that **this function might be performed after a possible Soft Handover (which allows concurrent connection with more than one Base Station)**.
- In the **Downlink** the Outer Loop Power Control **performed in the UE follows the same concept**.
  - However, **in the Downlink both Inner and Outer Loop Power Control runs in the UE,** since during Soft Handover, **all the frames received by the concurrent connections are received from one unit (the UE)**



Gain of Outer Loop Power Control

- **As illustrated in the figure below, the average SIR Target** value **is not fixed** but **depends on the environment used:**
  - The **lowest average Target SIR** (or Eb/No Target) is **needed in the Non-fading channel** and
  - The **highest average Target SIR** is needed in the ITU Pedestrian A channel with **high UE speed (120Km/h)**.

Average SIR targets in different environments

Multipath	UE speed (km/h)	Average E_b/N_0 target (dB)
Non-fading	—	5.3
ITU Pedestrian A	3	5.9
ITU Pedestrian A	20	6.8
ITU Pedestrian A	50	6.8
ITU Pedestrian A	120	7.1
3-path equal powers	3	6.0
3-path equal powers	20	6.4
3-path equal powers	50	6.4
3-path equal powers	120	6.9

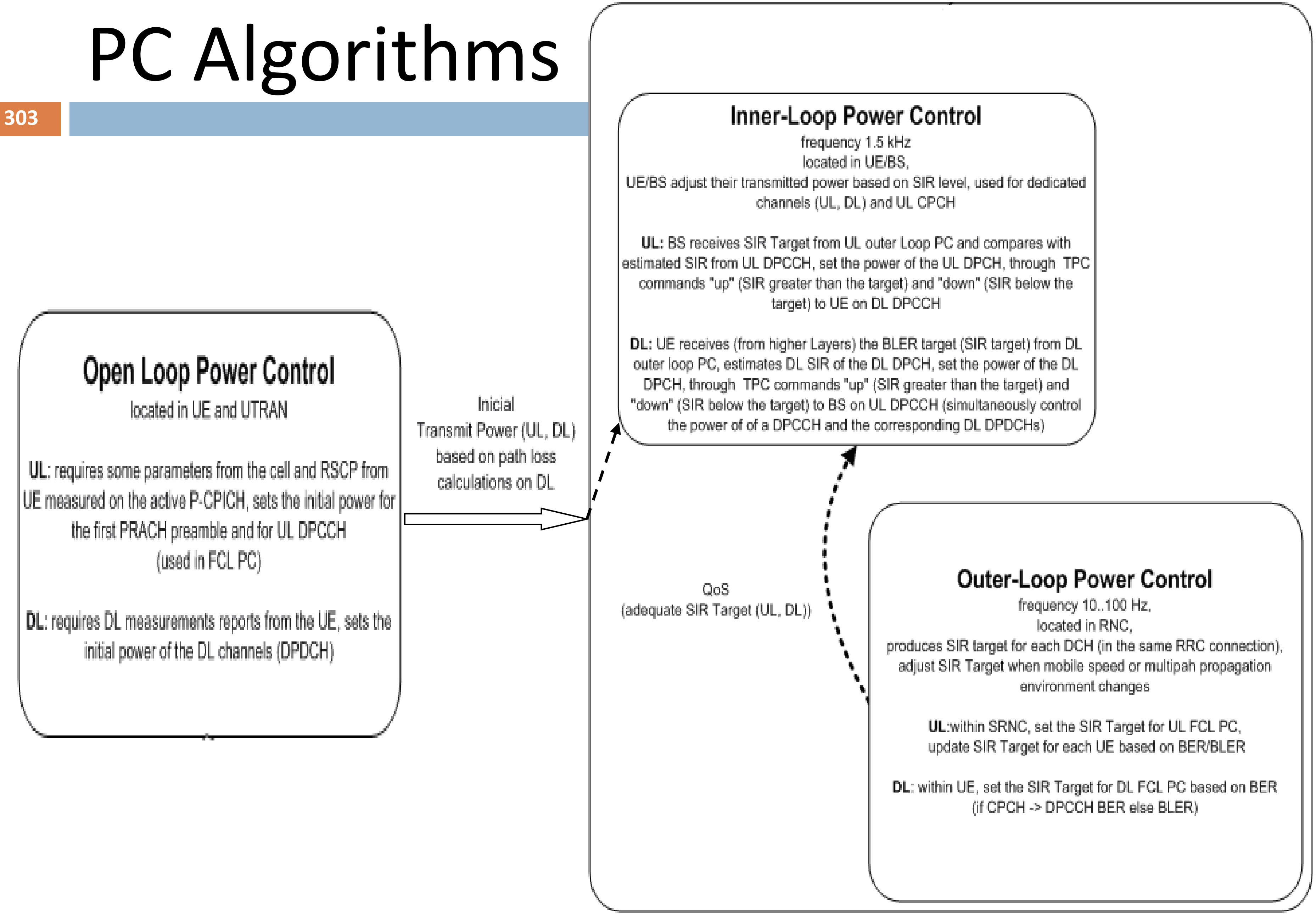
Gain of Outer Loop Power Control

- Why should there be a **need for changing the Target SIR set-point during time**?
- **The Target SIR required for receiving the signal correctly** depends on:
  - **UE velocity (i.e., pedestrian, vehicular, high vehicular)**
  - **Multipath Profile (based on the propagation environment)**

Gain of Outer Loop Power Control

- **Setting the Target SIR for the worst case** (i.e., high mobile speeds and areas with a lot of high buildings, etc.) one would **waste much transmission power** for **those connections with better channel conditions in the same cell (i.e., at low mobile speeds** and **open space area)**.
- On the other hand, **setting the Target SIR for the best case**, this would mean **bad quality of those connections with worse channel conditions in the cell (i.e.,** at **high mobile speeds** and areas with **high buildings**)
- Thus, the **best strategy** is to **let the Target SIR set-point float around** the **minimum value** that **just fulfils the required Target quality** *(i.e., the signal should have the minimum power required to be received by the receiver for decoding the signal correctly)*

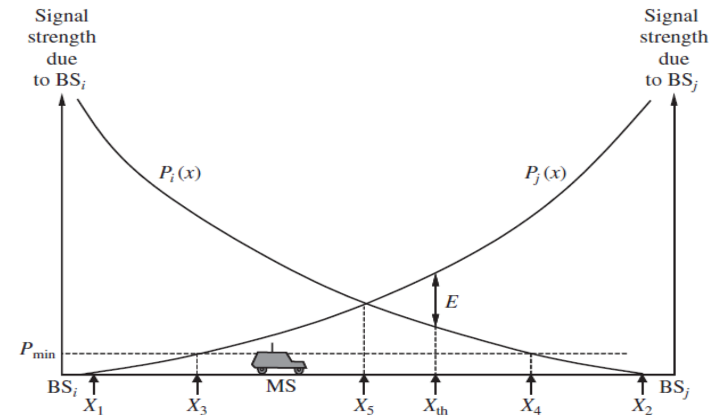
Interaction between Open and Close PC Algorithms



Handover Control

- **Handover Control** aims to **provide continuity of mobile services** to a **user traveling over cell boundaries** in a **cellular infrastructure**.
- For a **user having an ongoing communication** and **crossing the Cell's edge**, it is **more favorable to use the radio resources in the new cell** (Target cell), because **the quality of the signal strength perceived in the "old" cell** (Current cell) **is decreasing as the user moves towards the Target cell**.
- **The whole process** of **tearing down the existing connection in the Current cell** and **establishing a new connection in the Target cell** is called **"Handover".**

Handover Reasons



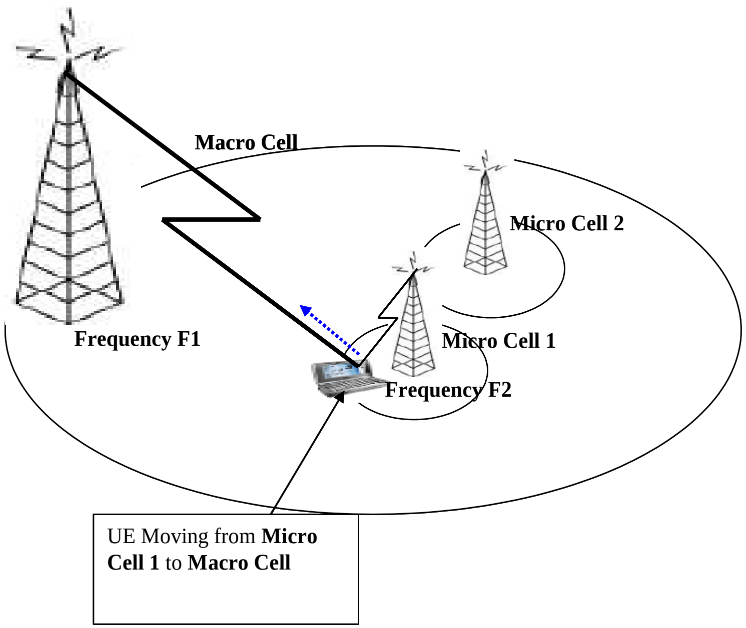
- The **basic reason behind a Handover** is that **the connection does not fulfil the desired QoS criteria set anymore** and **thus either the UE or the UTRAN initiates actions in order to improve the connection**.
- **Overall, the reasons behind a Handover can be due to**:
  - **Signal Quality Received by the UE (Main Reason)**
    - **The UE continually measures the signal strength received from its Serving Cell (as well as the signal quality of its Neighbouring cells)** aiming to **detect any signal deterioration**.
    - When the **quality or the strength of the radio signal falls below certain parameters set by the RNC**, a **Handover is initiated (by the UE)**.

Handover Reasons

- **Traffic level in a cell**
  - A **Handover is initiated (by the Network) when the intra-cell traffic** is **approaching the maximum cell capacity** or a **maximum threshold**.
  - This **sort of Handover helps to distribute the system load more uniformly within the network**.
  - Usually, the **UEs that are handover** to Neighbouring (less loaded cells) are **those that are located at the edge** of **the high loaded cell**.

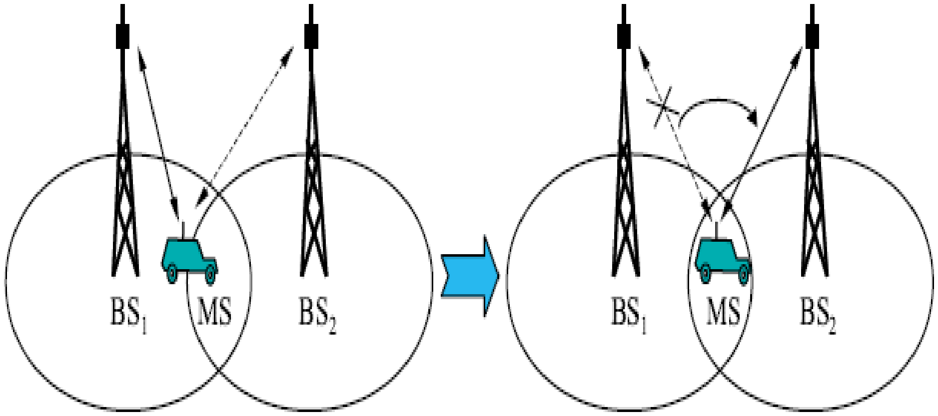
Handover Reasons

- **User Speed**
  - The **frequency of Handovers** is **proportional** to the **UE's speed** and the **size of the cell**.
  - To **avoid frequent and unnecessary Handovers**, UEs with **high motion speed** may be **handed over from micro cells** to **macro cells.**
  - In the same way, **UEs moving slowly or not at all**, can be **handed over from macro cells to micro cells**.



Handover Types
Hard Handover

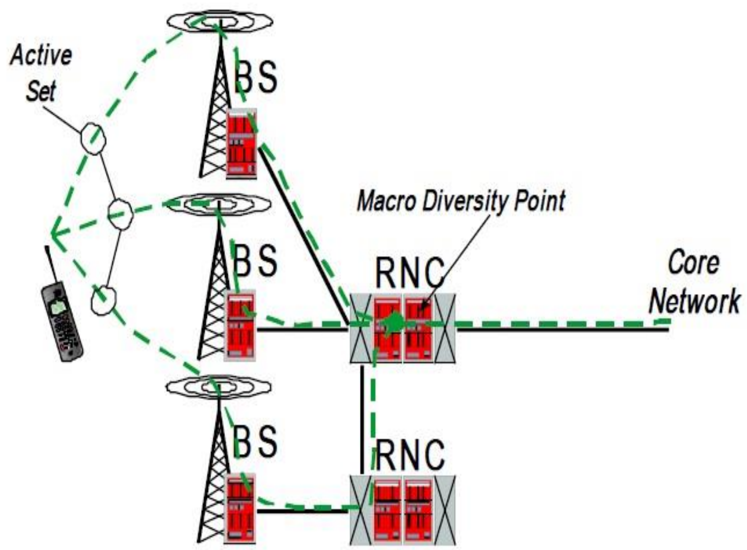
- **During a Hard Handover, the old connection with the old Cell is released before the new connection with the new Cell is established ("break-before-make" connection).**



Handover Types
Soft Handover (and Macro-Diversity)

- **Soft Handover** refers to the process that **allows a Mobile Station** to be **served simultaneously by several cells (BSs).**
- This feature is **possible in WDMA** because **all Cells** **use the same frequencies** → Note that the channels in WCDMA are separated only by the use of **Spreading Codes**.

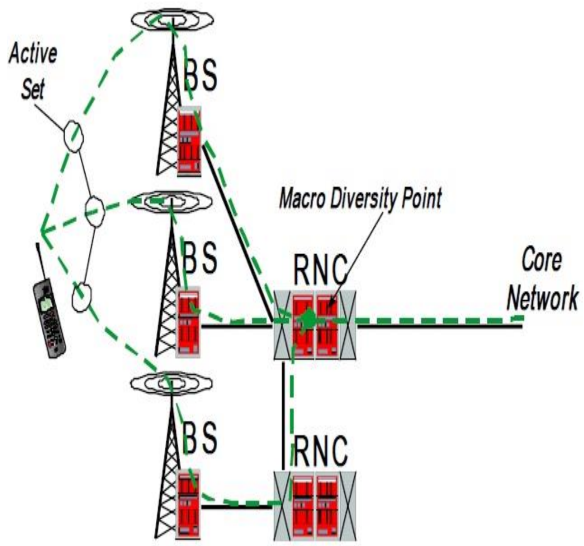
- **With Soft Handover several radio links are active at the same time providing a "Macro-diversity" gain on the received signal (or frame).**



Handover Types

Soft Handover in the Downlink (Soft Combining)

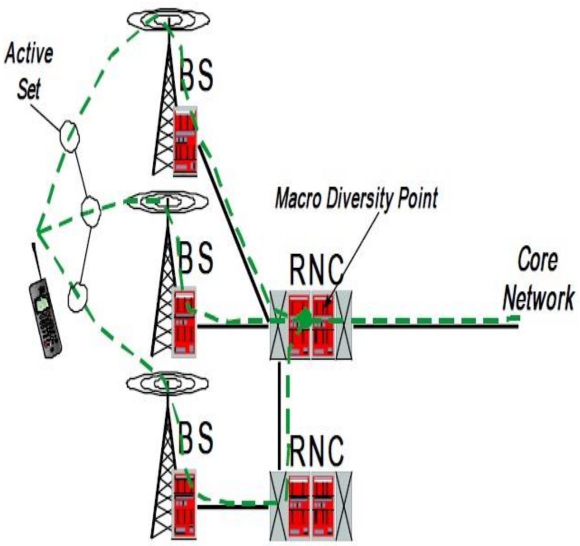
- **In the Downlink, the MS can combine the different received (de-spreaded) signals to increase the reliability of demodulation → This is termed as Soft Combining Gain.**
  - **By combining the signals from different links, a stronger signal can be generated thus Increasing the Received SIR, which reduces the transmit power requirements** *(even when compared to the power required over the best link only)*



Handover Types

Soft Handover in the Uplink (Selective Combining)

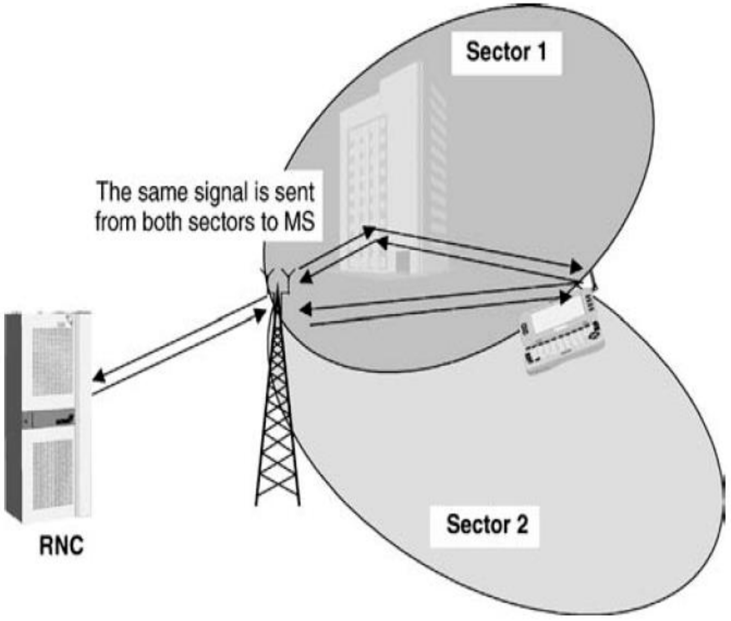
- **On the Uplink**, since the **Cells in the Soft Handover do not belong to the same Node-B, it is Not possible to combine the signals before they are demodulated.**
- **Instead, all the frames are sent to the RNC, which decides which one to use** (i.e., **the first frame which is received correctly is chosen**).



- This process **still provides a gain compared to a single link, since it increases the probability of having at least one link without error → This is termed as "Selective Combining" Gain**

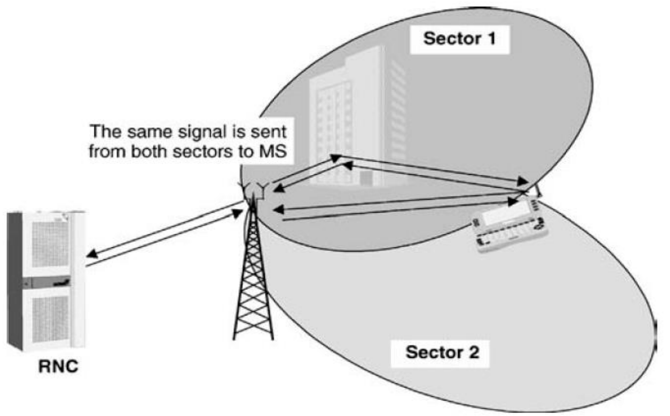
Handover Types
Softer Handover

- **Softer Handover** is a **special case of Soft Handover** where the **radio links** that **are added and removed belong to the same Node-B (Base Station)**.
- During Softer Handover, a **UE is in the overlapping cell coverage area** of **two adjacent sectors of the same Node-B.**
- The **communication between** the **UE** and the **Node-B usually takes place concurrently via two connections, one for each sector separately** → From the **UE's point of view** this is **just another Soft Handover case.**



Handover Types
Softer Handover

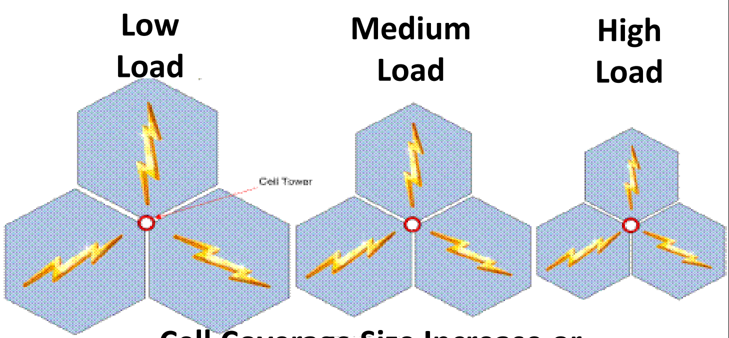
- The **different of Softer and Soft Handover** is **only meaningful to the Network (i.e., in the Uplink)**, as a **Softer Handover** is an **internal procedure for a Node-B.**
- **The uplink Softer Handover branches can be combined within the Node-B, similarly to the case of the UE, resulting in a stronger signal and thus increasing the reliability of demodulation → "Soft Combining" Gain can be achieved at the Node-B**



Admission Control

- **If the air interface loading (i.e., the active connections) is not controlled and allowed to increase excessively:**
  - The **Coverage area of the cell will be reduced below the planned values (due to the high interference that will be caused – causing the cell breathing phenomenon), and thus**
  - The **Quality of Service of the existing connections will not be guaranteed, especially for those located on the cell's edge.**
- **Before admitting a new UE, Admission Control needs to check that the admittance will not sacrifice the planned coverage area** or the **Quality of the existing connections.**

Cell Breathing



Cell Coverage Size Increase or Decrease with air interface load

Admission Control

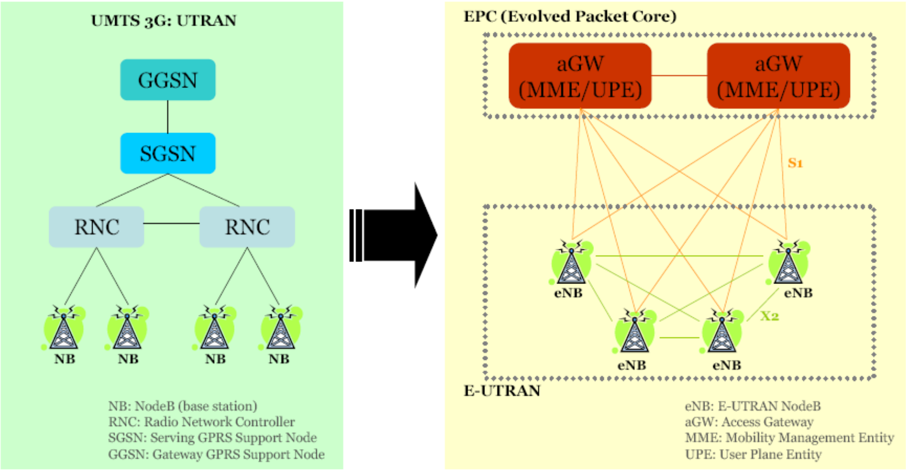
- **Admission Control accepts** or **rejects a request to establish a new connection** in the **Radio Access Network**.
- **It** is **executed when a new connection is set up or an existing connection needs to be modified/regulated (in case of cell overloading), or during a handover**.
- The **Admission Control functionality** is **located in the RNC where the load information from several cells can be obtained**.

Admission Control

- The Admission Control algorithm **estimates the load increase that the establishment of the new connection would cause in the Radio Network**.
  - This is **estimated separately** for the **uplink** and **Downlink directions**.
- The **new connection can be admitted only if both uplink and downlink Admission Control admit it**, **otherwise it is rejected because** of the **excessive interference that it would produce in the network**.
  - The **threshold limits for Admission Control are set by the Network Operator during Radio Network Planning.**

Long Term Evolution (LTE)

- **Despite constant evolution, 3G (UMTS) was approaching a number** of **inherent design limitations** in a manner similar to what GSM and GPRS did a decade ago.
- Therefore, the **3GPP decided to once again redesign both the Radio Network and the Core Network.**
- The result is commonly referred to as **'Long-Term Evolution'** or **LTE** for short.



Mobility Management Entity (MME)

User Plane Entity (UPE)

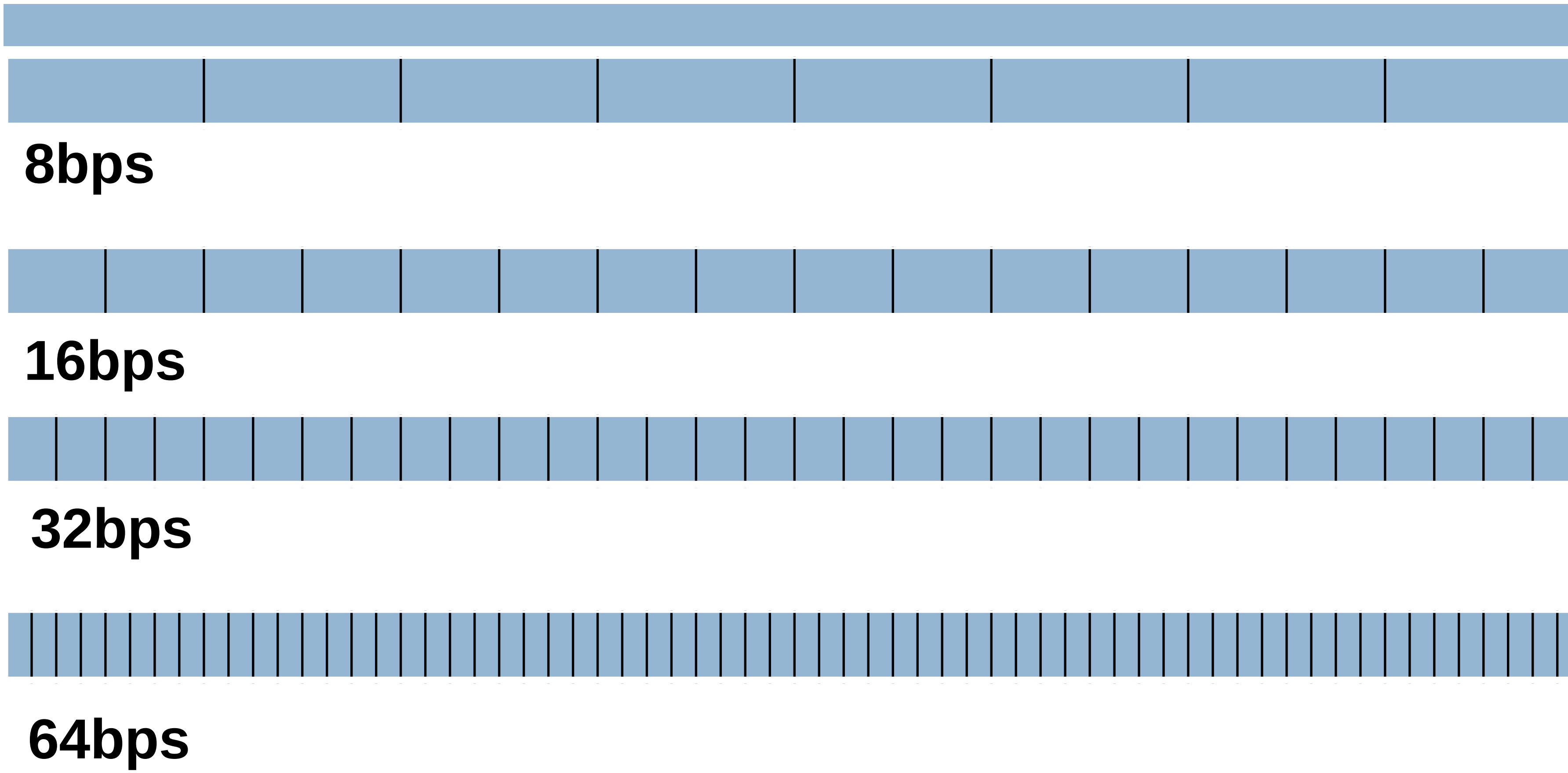
Long Term Evolution (LTE)

- **When UMTS (3G) was designed, WCDMA with** a **Carrier Bandwidth of 5 MHz was specified for the radio interface**.
- However, even if higher bandwidth is used, WCDMA is **not ideal for the higher data rate channels demanded for 4G Networks (i.e., up to 100 Mbits/s – 1 Gbits/sec)**.
  - **The main reason is that WCDMA** is a **Single Carrier Transmission scheme**

Long Term Evolution (LTE)

- With **single Carrier Transmission** schemes, even if the carrier bandwidth is increased to achieve higher data rates, **the time between subsequent symbols need to become shorter** to **take advantage of the additional bandwidth** (as more bits have to be sent at the same amount of time).
- **That is by increasing the Data Rate, the time between subsequent symbols is decreased**, causing the **negative effect** of the **InterSymbol Interference (ISI)**

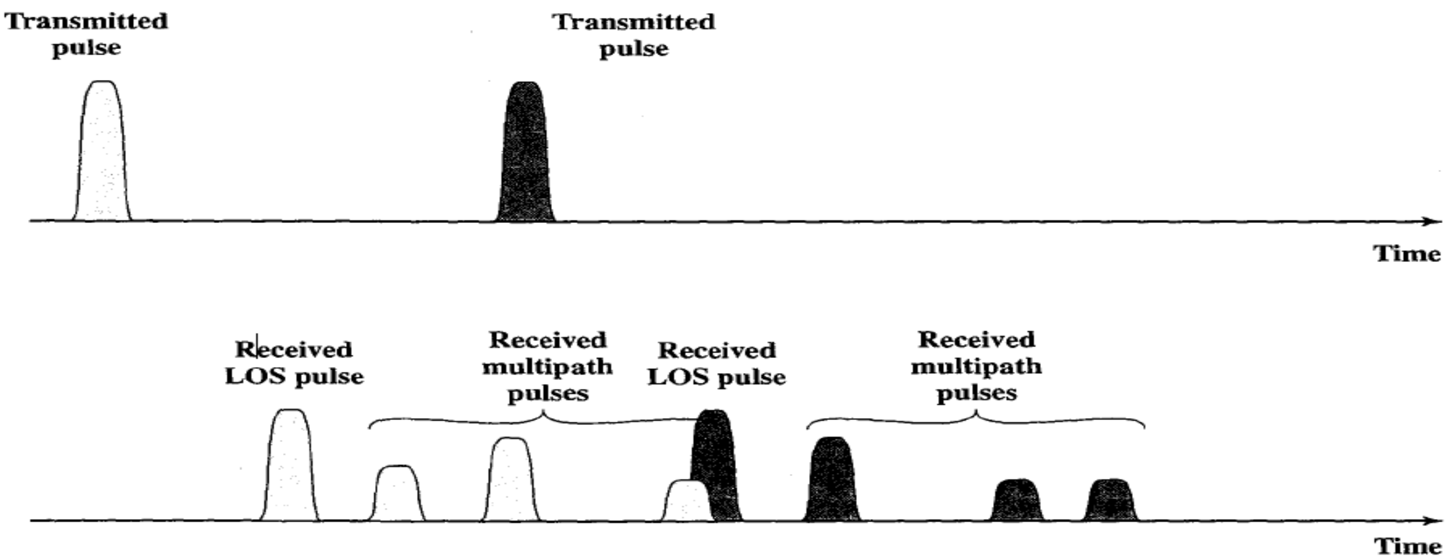
Long Term Evolution (LTE)



Single Carrier Scheme (Assuming 1 bit per symbol)

Inter-Symbol Interference (ISI)

- The **shorter the time between subsequent Symbols**, the **greater the impact** of **InterSymbol Interference (ISI)**, which degrades the quality of the signal considerably.



Long Term Evolution (LTE)

- To **mitigate the problems of InterSymbol Interference (ISI)** to some degree, **Multicarrier Transmission** is needed.

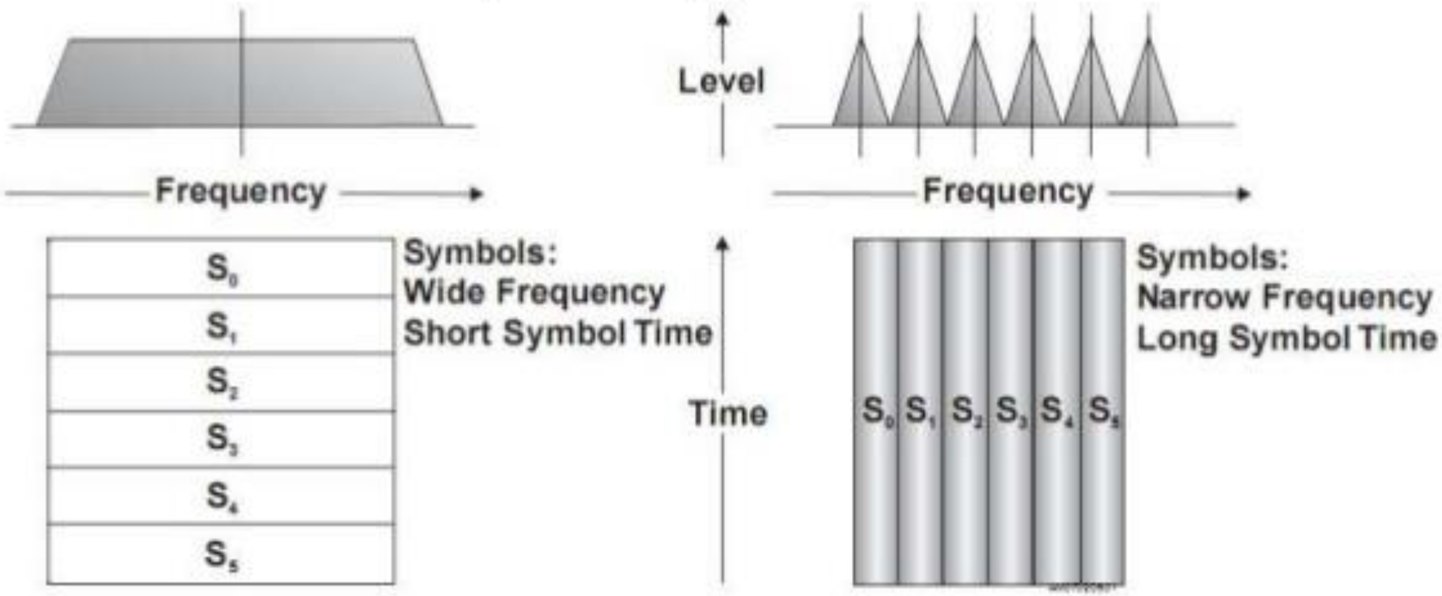
- **Therefore, with LTE**, the **first major change** was the **completely different air interface (based on OFDM; Orthogonal Frequency Division Multiplexing) specified to significantly increase the data rates in the air interface**.

Long Term Evolution (LTE)

- **Instead of transmitting the data over a single carrier, LTE uses Orthogonal Frequency Division Multiplexing (OFDM)** that **transmits the data over many narrowband carriers.**
  - A high data rate **data stream is split into many slower data streams** that are **transmitted simultaneously, using many different narrowband carriers (180KHz each)**.
  - As a consequence, the **achievable data rate compared to 3G can be much greater even in the same bandwidth, since** the **ISI effect can be greatly reduced**.
  - ***If the time between consecutive symbols is kept greater than the Delay Spread then the ISI is mitigated.***

Long Term Evolution (LTE)

OFDM Concept: Single-Carrier Vs. OFDM



Single-Carrier Mode:

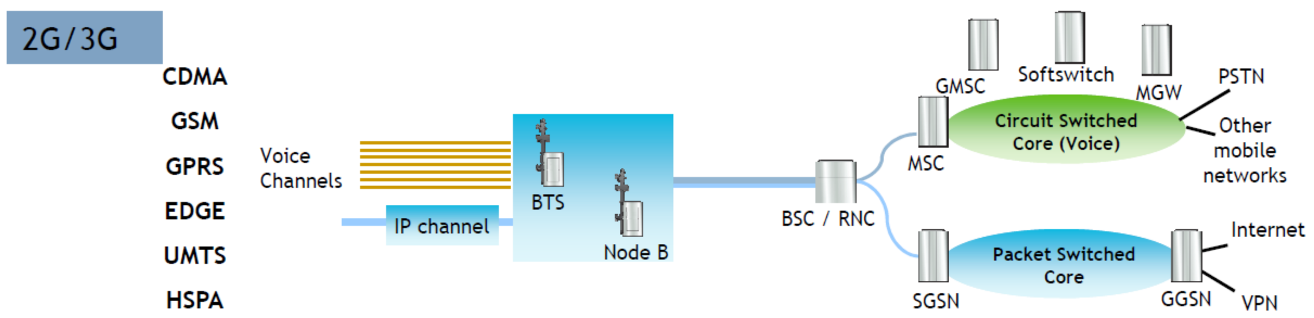
- Serial Symbol Stream Used to Modulate a Single Wideband Carrier
- Serial Datastream Converted to Symbols (Each Symbol Can Represented 1 or More Data Bits)

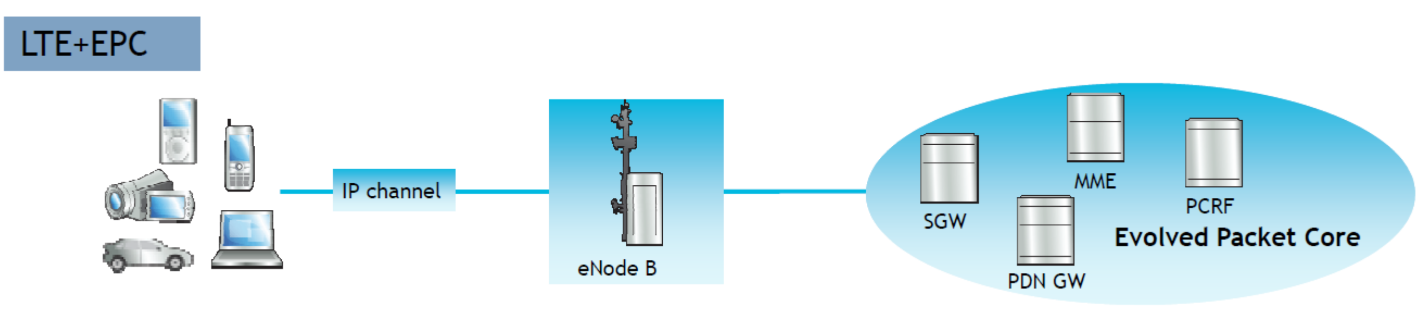
OFDM Mode:

- Each Symbol Used to Modulate a Separate Sub-Carrier

Long Term Evolution (LTE)

- The **second major change** of **LTE compared to previous systems** is the **Adoption of an All-IP approach**.
  - While **2G/3G Networks used a traditional Circuit-Switched packet core** mainly for **voice services**, **LTE solely relies on all IP Network Architecture!**



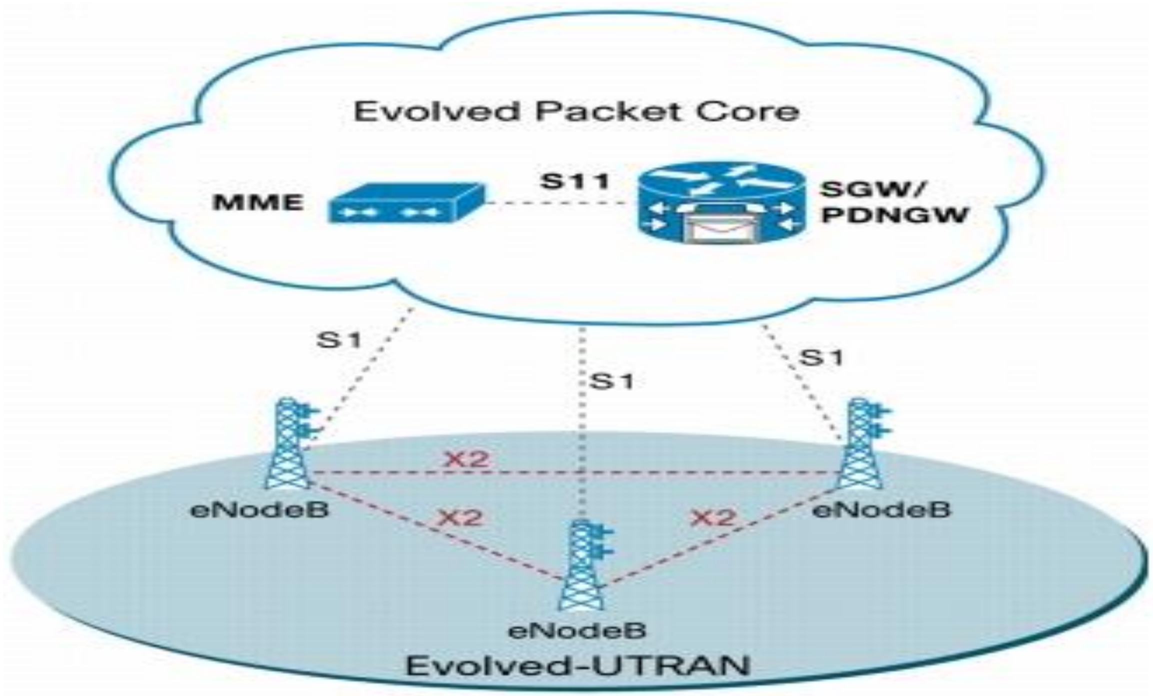


An All IP-based Core Network

Evolved Packet Core (EPC)

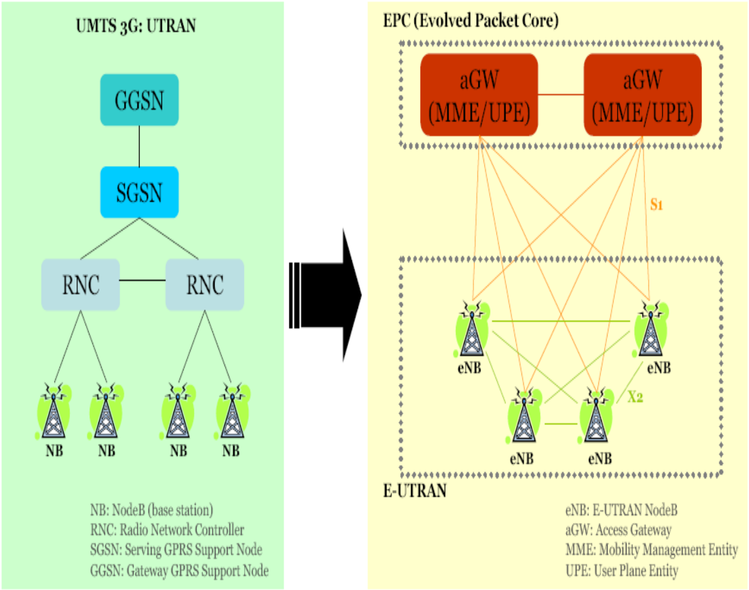
Long Term Evolution (LTE)

- An **All-IP network architecture greatly** **simplifies** **the design and implementation** of both the **Radio Network** and the **Core Network**.

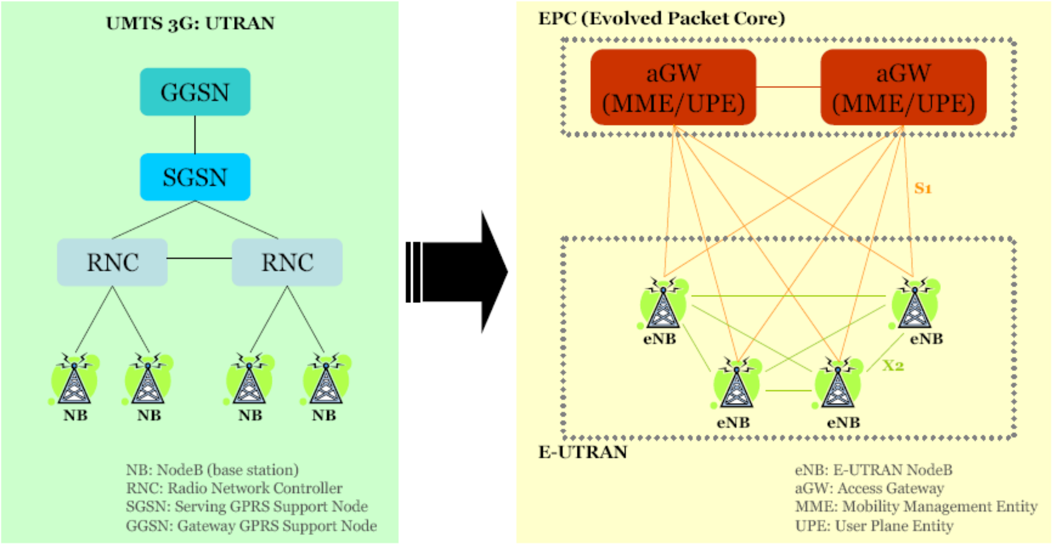


Long Term Evolution (LTE)

- To further **simplify the network architecture** and to **reduce user data delay**, **fewer logical and physical network components** have been defined in LTE → **The RNC is removed and its functionality is spitted between the eNodeBs and the MME.**
  - In practice, this has **resulted in data delay times** of **less than 25–30 milliseconds** **(used to be 150 ms for UMTS).**



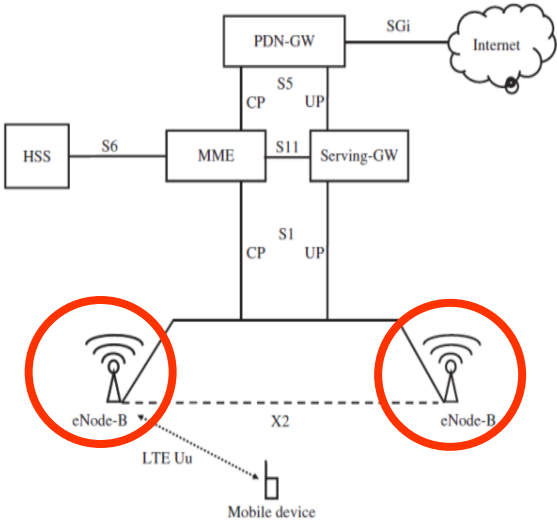
Overview of LTE Architecture



The **removing of RNC network element** and the **introduction of X2 interface for direct communication between the eNodeBs makes the radio network architecture more simple and flat**

→ Leads **to Lower Networking Cost**, **Higher Networking Flexibility** and **lower data delays**.

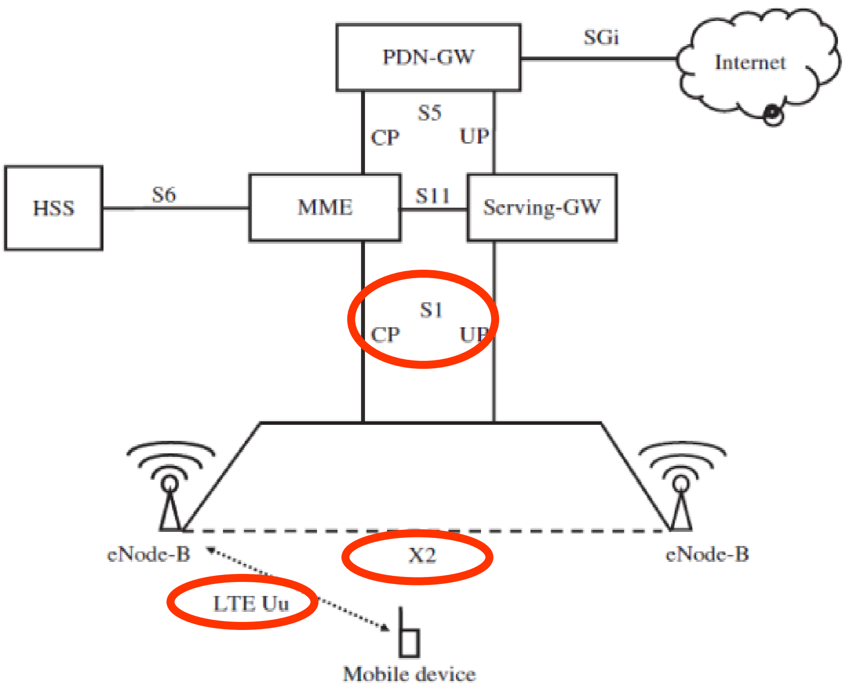
LTE Network Architecture
The eNode-B



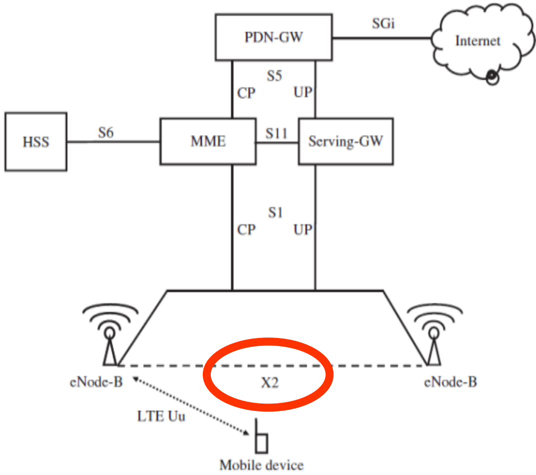
- The **most complex device** in the **LTE network** is the **Base Station, referred to as eNode-B (eNB)**.
- **Unlike in UMTS, LTE Base Stations are autonomous units**.
  - In **LTE, it was decided** to **integrate most of the functionality (i.e., Radio Resource Management) that was previously part of the Radio Network Controller into the Base Station** itself.
  - For example, **the eNode-B decides on its own to handover ongoing data transfers** to a **neighboring eNode-B**, **a novelty in 3GPP systems**.

LTE Network Architecture
The eNode-B

- The **air interface between the eNodeB and the LTE UE** is referred to as the **LTE Uu interface (this interface implements the OFDM physical Channels)**
- The **interface between the eNodeB and the Core Network** is referred to as the **S1 interface.**
- The **interface between two eNodeBs** is referred to as the **X2 interface.**



LTE Network Architecture
The eNode-B



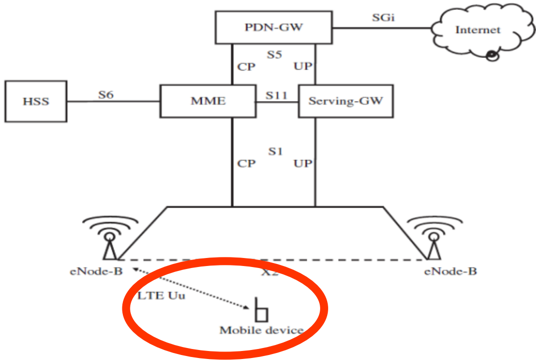
- **As LTE Base Stations** are **autonomous units**, they **communicate directly with each other over the X2 interface** for **two purposes**:
  1. **Handovers are now controlled by the eNodeBs themselves. If the Target cell is known and reachable over the X2 interface, the cells communicate directly with each other. Otherwise, the S1 interface and the CN are employed to perform the handover.**
  2. **The X2 interface can be used for Inter-Cell Interference Coordination (ICIC). For example, as Mobile Devices can report, the noise level at their current location and the perceived source (i.e., the eNodeB that causes the noise), to their Serving eNodeB, the X2 interface can then be used by the Serving eNodeB to contact the neighboring eNodeB, in case the Neighbouring eNodeB causes a lot of noise, and agree on methods to mitigate or reduce the noise problem.**

Key Features of LTE

Most Important Key Features of LTE:

- **Multicarrier Transmission**
  - Orthogonal Frequency Division Multiple Access (OFDMA) in the Downlink (DL) Direction
  - Single Carrier - FDMA (SC-FDMA) in the Uplink (UL) Direction
- **Adaptive Modulation and Coding**
  - DL and UL modulations: QPSK, 16QAM, and 64QAM
  - Coding: Convolutional code and Rel-6 Turbo Code
- **Advanced MIMO Spatial Multiplexing**
  - (2 or 4) x (2 or 4) MIMO Downlink and Uplink supported.
- **Hybrid-Automatic Repeat ReQuest (HARQ)**
  - For fast reporting and retransmission of packets that received with errors, aiming to minimize the resulting packet delay and jitter.

Air Interface in LTE



- The **major evolution in LTE** compared to previous 3GPP wireless systems is the **completely revised air interface (based on OFDMA).**
- **When UMTS was designed an air interface, based on WCDMA, with** a **Carrier Bandwidth of 5 MHz was specified**.
- With today's **Hardware** and **Processing capabilities**, **Higher data rates can be achieved** by **using an Increased Carrier Bandwidth**.

Air Interface in LTE

- **UMTS**, however, **does not scale in this regard as** the **WCDMA transmission scheme (being a single carrier transmission scheme)** is **not ideal for wider channels**.
  - When the **carrier bandwidth is increased**, the **symbols need to become shorter (and thus the time between consecutive symbols needs to be reduced)** to take **advantage of the additional bandwidth (as more bits will be sent at the same amount of time)**.
  - **By increasing the transmission speed** (i.e., Data Rate), which results in a **decrease of the symbol time**, the **negative effect** of the **InterSymbol Interference (ISI) increases**.
  - **As a consequence**, **CDMA is not suitable for carrier bandwidths beyond 5 MHz**.
- **Thus, Multicarrier Transmission** has been **defined for LTE** to **mitigate the problems of Multipath (Fast) Fading and InterSymbol Interference (ISI)** to some degree **at the expense of rising complexity**.

Air Interface in LTE
OFDMA for Downlink Transmission

- **Instead of sending a data stream at a very high speed over a single carrier as in UMTS, OFDMA splits the data stream into many slower data streams that are transported over many subcarriers simultaneously.**
  - **Carrier Bandwitdh: 180 KHz**
  - **Subcarrier Spacing (bandwidth): 15 kHz**
  - The **advantage** of **many slow but parallel data streams** is that **symbols' duration can be sufficiently long (even 10 times greater than the Delay Spread caused)** to **avoid the effects of multipath transmission (i.e., InterSymbol Interference (ISI))**

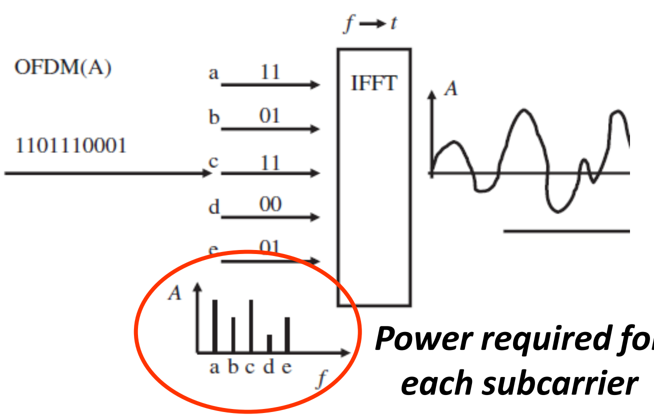
Air Interface in LTE
OFDMA for Downlink Transmission

- **Note that regardless of the overall channel bandwidth (i.e., 1.4 MHz, 5 MHz, 10 MHz, 20 MHz, etc.) the subcarrier spacing (i.e., bandwidth) remains the same (i.e., 15 KHz)**
  - For example, for a **Wider Bandwidth**, the **number of subcarriers is increased** while the **individual subcarrier bandwidth (which is 15KHz) remains the same**.

Bandwidth (MHz)	Number of subcarriers
1.25	76
2.5	150
5	300
10	600
15	900
20	1200

Air Interface in LTE
SC-FDMA for Uplink Transmission

- **For Uplink data transmissions, the use of OFDMA is not ideal because of its high Peak to Average Power Ratio (PAPR) when the signals from multiple subcarriers are combined.**
  - In practice, the **amplifier in a radio transmitter circuit has to support the Peak Power output required to transmit the data**
  - **This Peak Power output value defines the power consumption** of the **transmitting device.**
    - **Note that the Average output power required for the signal to reach the Receiver is much lower.**
    - **Hence, it can be said that the PAPR of OFDMA is very high.**



Power required for each subcarrier

With OFDMA, Data stream is divided into lower data rate streams and transmitted in a number of subcarriers (a, b, c, d, e)

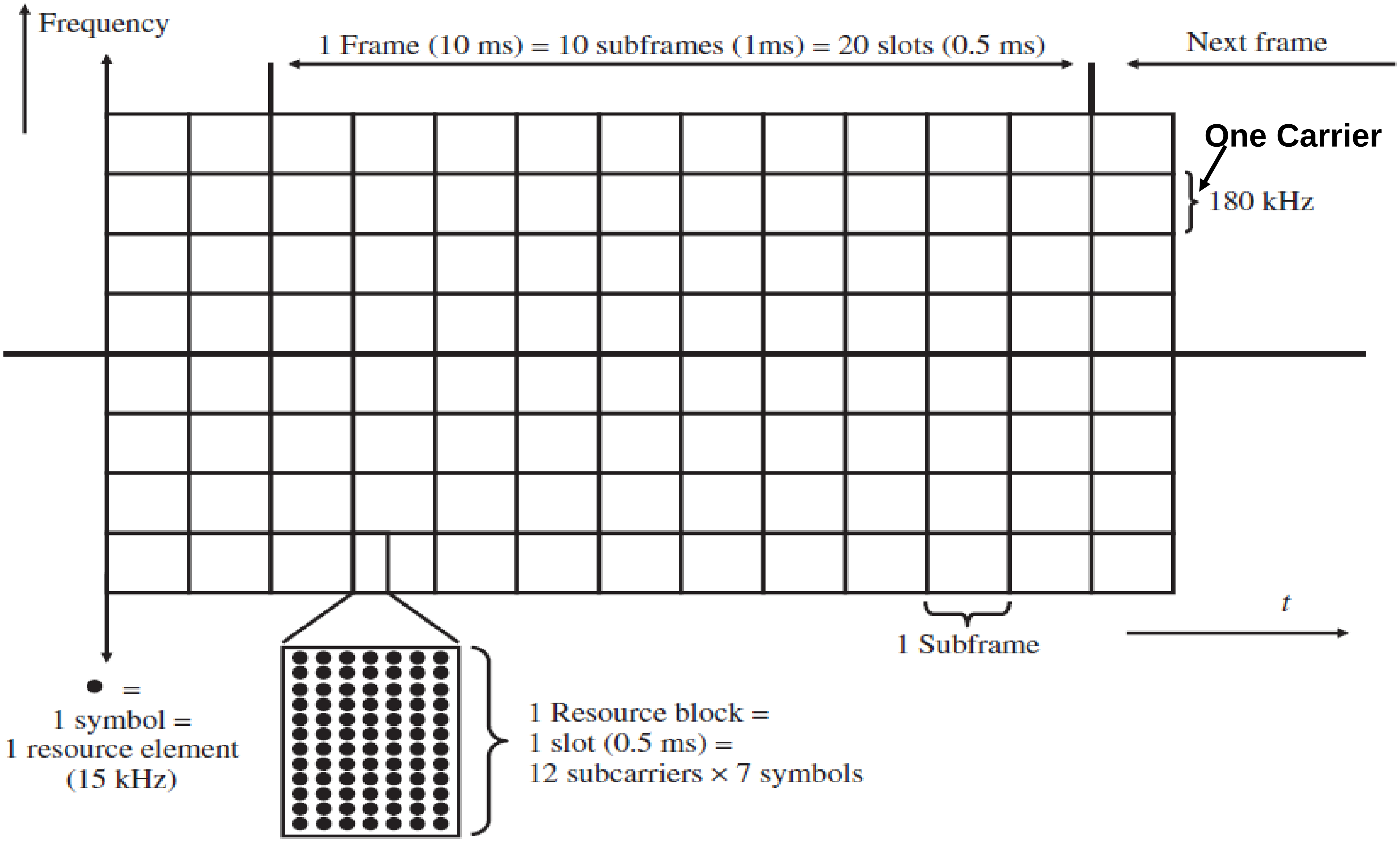
Air Interface in LTE
SC-FDMA for Uplink Transmission

- **For a Base Station, a high PAPR can be tolerated as power is not a problem (power is abundant).**
- **However, for a Mobile Device that is Battery driven, the transmitter should be as efficient as possible.**
- **3GPP has hence decided to use a different transmission scheme, referred to as Single-Carrier Frequency Division Multiple Access (SC-FDMA).**
- **SC-FDMA** is a **misleading term** as **SC-FDMA is essentially a multicarrier scheme similar to OFDMA.**

Air Interface in LTE
SC-FDMA for Uplink Transmission

- **SC-FDMA contains some additional transmission processing steps beneficial for reducing the PAPR required.**
  - **During these steps, the information of each bit is distributed onto all subcarriers used for the transmission reducing in this way the power differences between the subcarriers → In this way a much lower PAPR than that obtained with OFDMA is achieved** (by approximately **2 dB**).
  - **However, the tradeoffs are additional processing complexity during the transmission and lower transmission date rates in the uplink.**

Symbols, Resource Blocks, Slots, Subframes and Frames

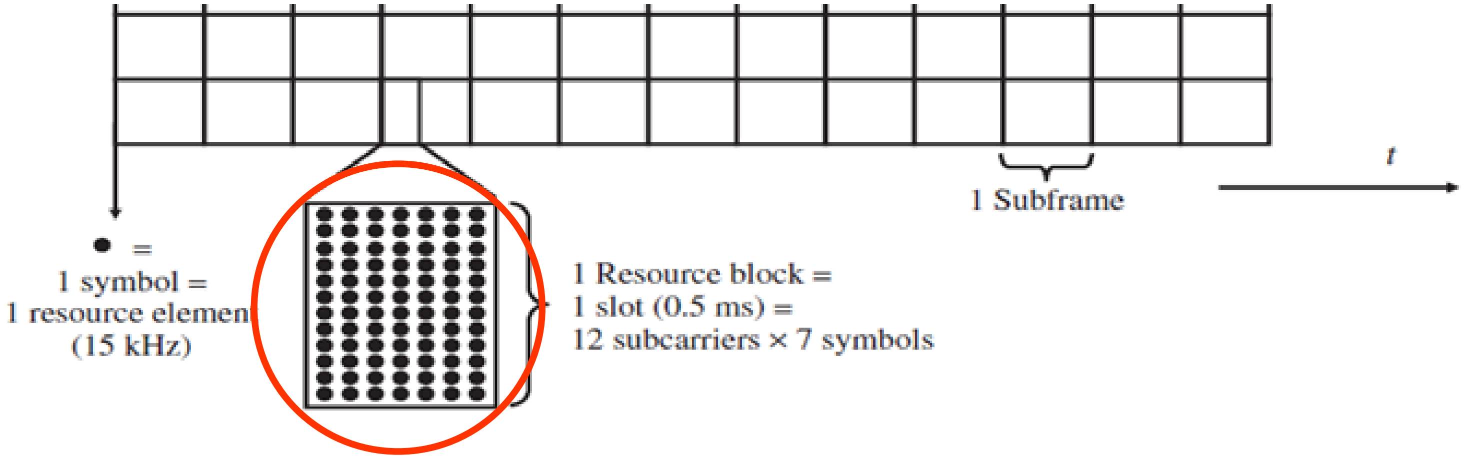


Symbols, Resource Blocks, Slots, Subframes and Frames

- **As the overhead involved in assigning each individual symbol to a certain user would be too great, the symbols are grouped together into a number of different steps. These are:**
  - **Resource Block (RB; 1 slot time that is 0.5 ms)**
  - **Subframe (2 slots → 2 subsequent RBs): Subframe represents the LTE scheduling time. That is every 1 ms the eNodeB schedules the parallel RBs to one or more Users.**
  - **LTE Radio Frame (10 Subframes; 20 slots → 20 subsequent RBs)**

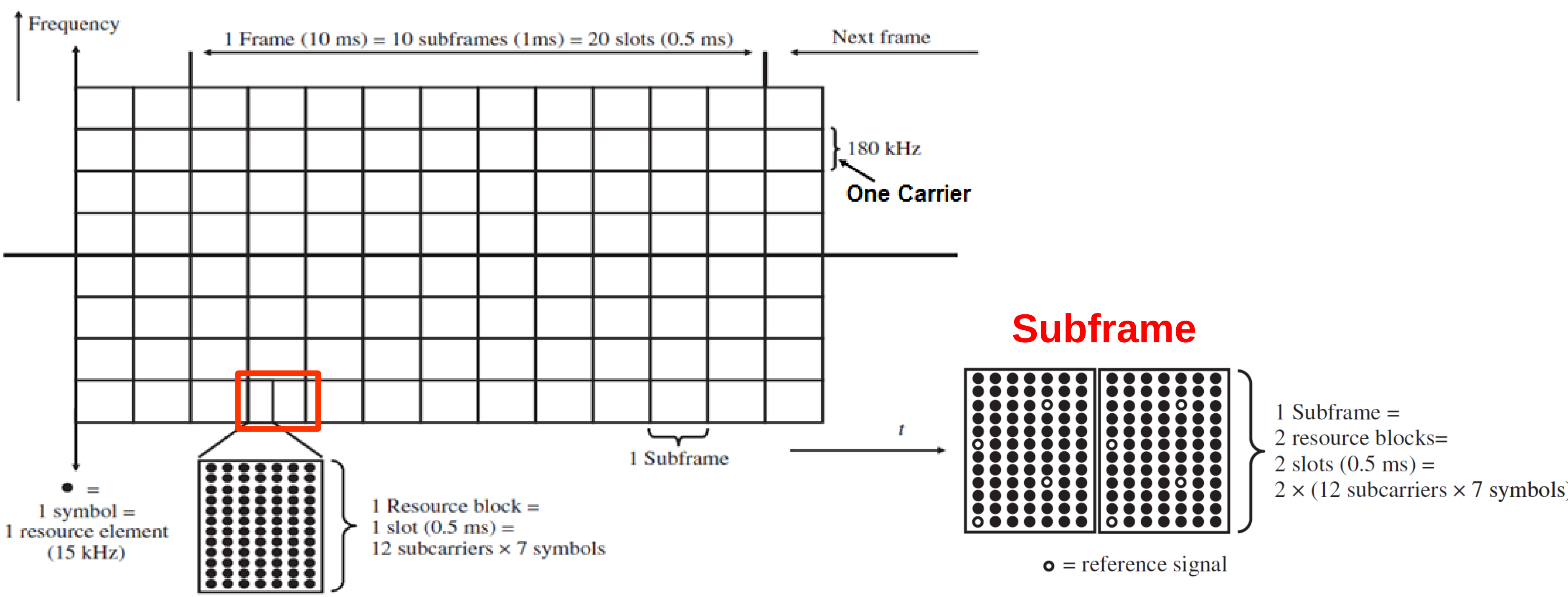
Symbols, Resource Blocks, Slots, Subframes and Frames

- **Resourse Block (RB)**
  - **Seven (7) consecutive symbols on 12 subcarriers are grouped into a Resource Block (RB).**
  - **A Resource Block (RB) occupies exactly one slot with a duration of 0.5 milliseconds**



Symbols, Resource Blocks, Slots, Subframes and Frames

- **Subframe**
  - **Two (2) slots form a Subframe** with a **duration of 1 millisecond (10^{-3} sec)**
  - **A Subframe represents the LTE scheduling time, which means that at each millisecond the eNode-B decides which users are to be scheduled and which Resource Blocks (RBs) are assigned to which user.**

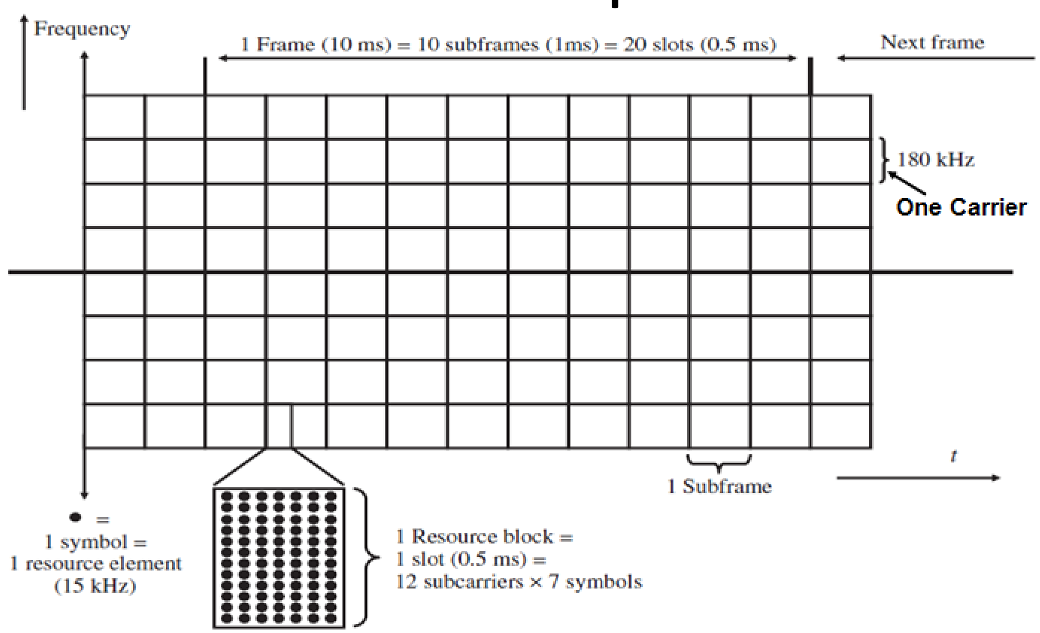


Symbols, Resource Blocks, Slots, Subframes and Frames

Bandwidth (MHz)	Number of subcarriers
1.25	76
2.5	150
5	300
10	600
15	900
20	1200

- The **number of parallel Resource Blocks (RBs)** in each **Subframe period** depends on the **system Bandwidth**.
- For example, if a **10-MHz bandwidth carrier** is used, **600 subcarriers are available**. As a **Resource Block (RB)** includes **12 subcarriers**, a **total of 50 parallel RBs** are **available in each slot of a Subframe.**
  - As a Subframe is **formed by two slots** (and each slot includes one RB), **100 RBs** can be **scheduled for one or more users** per **Subframe time**.

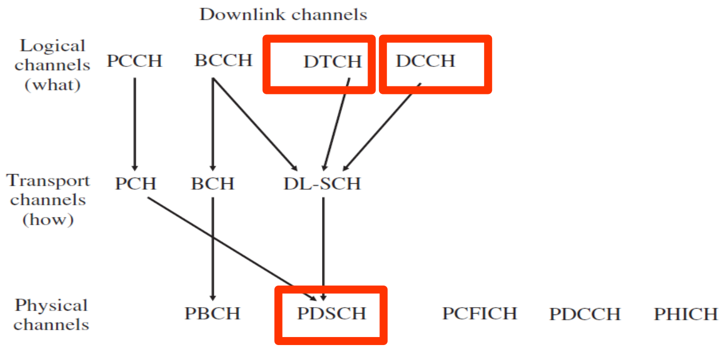
Note that on the figure on the right (for simplification) only eight parallel Resource Blocks are shown in the y-axis. On a 10-MHz carrier, for example, 50 Resource Blocks are used in parallel in each slot of a Subframe.



LTE Channel Model Downlink Direction

- All Downlink **Control Signaling** and **User Data traffic** are organized in:
  - **Logical channels → Determines the Data and type of data that will be transmitted; e.g., Control signaling, User Traffic**
  - **Transport channels → Determines how the data will be transmitted; e.g., Multiplexing, Transport Format that will be used**
  - **Physical channels → Determines the RBs that will be assigned to the users for the data to be transmitted**

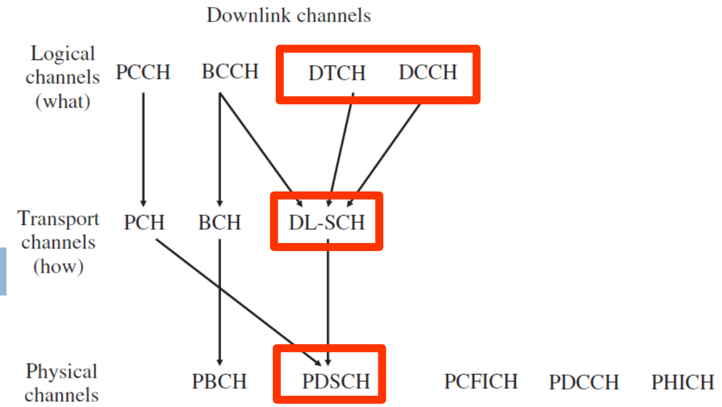
LTE Channel Model Downlink Direction



- **On the Logical Layer, data (user traffic) for each user** is transmitted in a **Logical Dedicated Traffic Channel (DTCH)**
  - **Each User has an individual DTCH.**
- **A UE that has been assigned a DTCH** also **requires a Dedicated Control Channel (DCCH)** for the **management of the connection**.
  - **Here, the control signaling that is required, for example, for handover control, channel reconfiguration, is sent.**

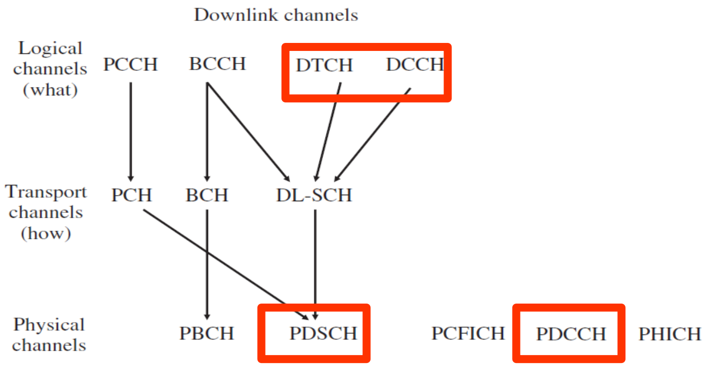
- **On the air interface** (i.e., on the **Physical layer**), **all Dedicated Channels** are **mapped to a single shared channel** that **occupies all Resource Blocks (RBs) that will be assigned to the users** (this channel is the **Physical Downlink Shared Channel (PDSCH)**).

LTE Channel Model Downlink Direction



- The **DTCH** and the **DCCH assigned to each user** are **mapped** to **individual Resource Blocks** in the **Physical Downlink Shared Channel (PDSCH)** in two steps.
- **In the first step, the logical DTCH and DCCH of each user are multiplexed (into a data stream) to the Transport layer in the Downlink Shared Channel (DL-SCH) and the Transport Format (Modulation, Coding and MIMO used) that will be used during their transmission is determined.**
- **In the second step, this data stream is then mapped to the Physical Downlink Shared Channel (PDSCH) (i.e., to the Resource Blocks that are allocated to the users)**
  - **Which Resource Blocks** are **assigned** to **which user** is **decided** by the **scheduler in the eNodeB for each Subframe**, that is, **once per millisecond.**

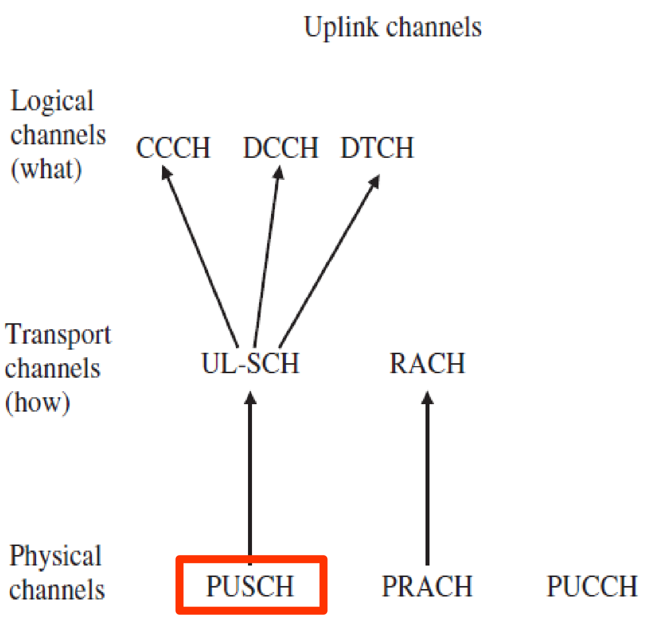
LTE Channel Model Downlink Direction



- **Note that <u>ALL</u> the DTCH and DCCH of all the users** are **mapped to a single PDSCH.**
- Therefore, a **mechanism is required to indicate to each UE:**
  - **When and where (i.e., which RBs in the Subframe), what kind of data (i.e., traffic or control) is scheduled for them and how (i.e., the Transport Format (TF) that will be used) data are transmitted to them** on the **PDSCH in the Downlink Direction.**
  - **Which RBs is allowed to use in the Uplink direction**.
- This is done via **Physical Downlink Control Channel (PDCCH)** messages.

LTE Channel Model
Uplink Direction

- In the **Uplink direction**, a similar channel model is used as in the downlink direction.
- The **most important channel** is the **Physical Uplink Shared Channel (PUSCH)**.
- The **PUSCH** main task is to **carry** the **User Data Traffic** and **Control Signaling as well as Downlink Signal Quality Feedback.**
  - **Signal Quality Feedback will be considered by the eNodeB to adapt the Transport Format that will be used in the Downlink for the specific UE (for the subsequent RBs) according to its downlink channel conditions.**



LTE Channel Model
Uplink Direction

- When a **Mobile Device has been granted resources (i.e., RBs have been reserved and assigned for it in the next 1ms)**, the **PUSCH** is used for **transmitting the user data traffic (over the DTCH)** and also for **transmitting Control Signaling Data (over the DCCH)**
  - The **Control Signaling Data** is **required to**
    - **Maintain the Uplink connection** and
    - **Optimize the data transmission over the Downlink connection**.

LTE Channel Model Uplink Direction

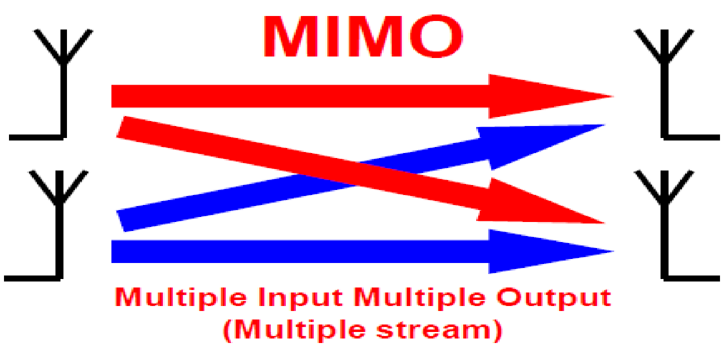
- The **main Control Signaling Data sent in the PUSCH is**:
  - The **Channel Quality Indicator (CQI)** that the **eNode-B considers to adapt the Modulation and Coding Scheme** for the **Downlink direction.**
  - **MIMO-related parameters (Rank Indicator (RI)) that the eNode-B can use for adapting the MIMO transmission in the Downlink direction (i.e., number of independent data streams the UE can receive based on its channel conditions).**
    - **Rank 1 signifies a single-stream transmission (i.e., a single stream is sent over multiple antennas which boost the SNIR at the UE)**
    - **Rank 2 signifies a two-stream MIMO transmission (i.e., two independent data streams are sent over the same air interface increasing the achievable throughput).**

LTE Channel Model Uplink Direction

- **The UE, every one millisecond, based on its downlink channel conditions, sends to the eNode-B (along with other control information) a Rank Indicator (RI) and a Channel Quality Indicator (CQI).**
  - **The RI informs the eNode-B about the number of data streams that can be sent over the channel from the receiver's point of view.**
  - **The CQI information is considered by the eNode-B to decide as to which modulation (QPSK, 16-QAM, 64-QAM) and which coding rate, that is, the ratio between user data bits and error detection bits in the data stream that should be used for the transmission.**

MIMO Transmission & Adaptive Modulation and Coding

- In addition to **Adaptive Modulation and Coding,** LTE allows **the use** of **Multi-Antenna techniques**, also referred to as **Multiple Input Multiple Output (MIMO)** in **the Downlink direction**.
- The **basic idea behind MIMO techniques** is to **send several independent data streams** over the **same air interface channel simultaneously (e.g., Spatial Multiplexing)**.
- **In Spatial Multiplexing, a high-data rate signal is split into multiple lower-rate streams and each stream is transmitted from a different transmit antenna in the same frequency channel.**



MIMO Transmission & Adaptive Modulation and Coding

- Once the interference gets too strong (this is indicated in the CQI sent by the UE to the eNodeB), the Modulation scheme has to be lowered, that is, instead of using 64-QAM and two stream operation MIMO together, the Modulation is reduced to 16-QAM and single stream operation MIMO.
  - The Transport Format and the MIMO transmission that will be used depends on the characteristics of the downlink channel, and it is the eNodeB's task to make a proper decision on how to transmit the data.

MIMO Transmission & Adaptive Modulation and Coding

- **Only in very ideal conditions, that is, no interference and very short distances between the Transmitter and the Receiver, can 64-QAM and MIMO be used simultaneously.**
- **As Modulation and Coding and the use of MIMO can be adapted every millisecond (scheduling time of RBs to the UEs) on a per device basis, the system can react very quickly to changing radio conditions (e.g., like the Fast Power Control used in UMTS).**