**Immagine che contiene testo, Carattere, Elementi grafici, logo

Descrizione generata automaticamente**

**Master’s Degree in Computer Science**

**Academic year 2024/2025**

**WIRELESS NETWORKS FOR**

**MOBILE APPLICATIONS**

**Prof. Claudio Palazzi**

Written by Michael Amista’

**Index of contents**

[**1. Introduction on wireless communication** 3](#_Toc180794252)

[**1.1 Current wireless systems** 4](#_Toc180794253)

[**1.2 Emerging wireless systems** 5](#_Toc180794254)

[**2. Physical layer** 9](#_Toc180794255)

[**2.1 Radio frequencies** 9](#_Toc180794256)

[**2.2 Antennas** 11](#_Toc180794257)

[**2.3 Wireless technologies, coverage and multiplexing** 14](#_Toc180794258)

[**3. MAC layer** 17](#_Toc180794259)

# **1. Introduction on wireless communication**

Modern wireless networks are rapidly expanding in popularity, driven by an increasing number of constantly connected devices and rising demands for higher data rates. This trend has led to significant growth in Wi-Fi technologies and cellular generations (3G, 4G, 5G, and soon 6G) alongside the rise of applications requiring both low and high data throughput.

Wireless technology is now embedded in various interdisciplinary applications:

* **Continuous data modification and upload**: social media platforms, for example, enable users to frequently update and share new content (Web 2.0).
* **Multi-reality experiences**: enabling diverse immersive environments (AR/VR/MR/tele-presence).
* **Ultra responsive to our touch**: enabled by ultra-low latency and high availability (tactile Internetprovides instant feedback to touch, enabling real-time, responsive interactions).
* **Real-time connectivity across diverse data demands**: devices communicate and gather data continuously.

Future wireless networks aim to enable seamless, ubiquitous communication between people and devices, facilitating wireless access and cellular connectivity everywhere, often with intelligent data services and network infrastructure. Achieving this vision requires careful attention to constraints like bandwidth, latency, energy consumption, and connectivity.

Designing these networks presents several challenges:

* **Wireless channels are complex and capacity limited**. Unlike wired networks, wireless channels face unique constraints: interference, error rates, delay, and nominal speed are key factors to consider.
* **Network planning is challenging**. Factors like traffic patterns, user locations, and network conditions are in constant flux. Node positioning can vary unpredictably, complicating uniform solutions.
* **Applications impose diverse** requirements. Networks must support a variety of applications with unique demands. Some applications are delay-tolerant, while others require immediate responses, which necessitates tailored network management.
* **Energy and latency constraints affect protocol design**. Efficient traffic regulation is challenging yet essential on shared channels. Battery constraints are particularly critical in mobile devices, underscoring the need for energy-efficient solutions across network layers.

**Multimedia requirements**

Immagine che contiene testo, schermata, Carattere, numero

Descrizione generata automaticamente

Some considerations about these requirements:

* The delay in data transmission is not a crucial factor. In fact, since data is transmitted over several packets, we do not care about the delay of each single packet but instead we care about the time transmission of the whole file, which is the throughput, the total amount of time, not the delay.
* Note there is no packet loss in data transmission, this is due to the way packet transmissions are implemented, allowing to retransmit a packet when it is not received.

From these different requirements, it is obvious that **one-size-fits-all protocols and design do not work well** because each media has specific requirements. Wired networks use this approach with poor results.

In wireless network design, employing a **cross-layer design** is preferable. Unlike traditional designs where layers operate independently, cross-layer design allows for better integration and interaction across hardware, link, access, network, and application layers. This approach is especially important in wireless systems, where constraints such as delay, data rate, and energy efficiency must be balanced. By allowing layers to communicate and share information, cross-layer design improves adaptability, reduces uncertainty, and enhances robustness, ultimately leading to more efficient performance in dynamic wireless environments.

## **1.1 Current wireless systems**

**CELLULAR SYSTEMS**

A cellular system is divided geographically into cells, each cell uses a different frequency than the nearby cells, but cells that are separated by others can reuse some frequencies. Each cell is controlled by a base station, that manages the transmission and reception of signals between networks and devices.

Note on hand-off: there are means that understand if a handoff is going to happen and duplicate the communication to both antennas to keep the communication stable and then change the antenna. In this way we don't perceive anything during calls.

**WIRELESS LOCAL AREA NETWORK (WLAN)**

Wireless Local Area Networks (WLANs) connect nearby devices, typically within a range of around 100 meters, allowing them to communicate through an Internet access point. Data transmitted over WLANs is broken into packets, and devices share channel access, often using random access methods to send and receive data. While the backbone Internet provides a best-effort service, some applications, like video streaming, may experience poor performance due to the shared nature of the wireless channel and the unpredictable delays this can cause. WLANs are a popular choice for local connectivity, providing flexible and convenient access for multiple devices.

Note on the “real” throughput: the nominal Mbps shows the maximum amount of data that can be received in our device, the subscription to an operator determines the correct amount of data that can effectively be received.

**SATELLITE SYSTEMS**

Satellite systems provide coverage over very large geographical areas and operate at different orbit heights, with geostationary satellites (GEOs) at around 39,000 km and low-Earth orbit satellites (LEOs) at around 2,000 km. These systems are typically optimized for one-way transmissions, such as radio and television broadcasting.

**BLUETOOTH**

Bluetooth is a low-cost, radio frequency (RF) technology primarily designed for replacing cables in short-range communication. Typically, it operates within a range of 10 meters, though it can be extended up to 100 meters through multihop connections. Bluetooth uses the crowded 2.4 GHz frequency band and supports one data channel with speeds up to 700 Kbps, along with three voice channels. It is widely adopted across industries, including telecommunications, personal computers, and consumer electronics. However, beyond its use as a cable replacement, Bluetooth has relatively few applications, limiting its broader utility.

## **1.2 Emerging wireless systems**

**AD-HOC NETWORKS (ANETs)**

Immagine che contiene linea, diagramma, cerchio

Descrizione generata automaticamente

They have a *peer-to-peer* communication architecture, devices communicate with each other without relying on an intermediary (AP or router). Routing can be multi hop to extend area of coverage or to reduce interference devices can pass the data between each other to reach a further destination. Devices in an ad-hoc network automatically discover and connect with other devices in range, they automatically create routes to reach the other devices (a device when part of an ad-hoc network broadcasts its presence to other devices to build a route). They topology is dynamic, it can change frequently (devices join or leave without requiring manual configuration). In an ad-hoc network there is not a communication with the internet, the aim is to create a really close network.

It was created in the military field, now they provide a flexible infrastructure for many emerging applications. The capacity of such networks is generally unknown, it depends on how many nodes are part of that network, on the interference, transmission available, how much area they cover. All the strategies (transmission, access, routing) that are used in these networks are ad-hoc. Energy constraints are very important because the devices (nodes) that are part of the ad-hoc network consume battery (usually we are talking about phones or sensor, with vehicles there is not this problem).

**MESH NETWORKS**



They can be seen as an ad-hoc extension of a WiFi in an urban infrastructure. The aim is to create a low cost, high performance wireless coverage. Here is possible to have multiple routers that are connected to different access point wirelessly, this way WiFi coverage can be extended to very large areas without the need to use wired connections between access points. An example could be that there are a few routers (more specifically modems) connected to the internet through cable, and then more routers (mesh nodes) are wireless, and they extend the coverage of the signal in large areas. Unlike traditional networks that rely on a single central router or switch, mesh networks do not have a single point of failure. This allows for improved redundancy and coverage. This means if one node fails or goes offline, data can be rerouted through other nodes.

The main challenges are finding routing protocols to achieve load balancing, QoS, efficient autonomous operations when the infrastructure fails.

**SENSOR NETWORKS**

This is a specific type of ad-hoc network nodes are sensors used to monitor specific aspects. A sensor can collect data from the environment and send the information back to the central system for analysis and action. Sensor communicates wirelessly. When a sensor collects data and process it, it sends the data to a central node called sink or base station (centralized location) where it can be analysed, this communication can happen through multi hop communication. Sensors are powered up by batteries or energy harvesting methods, to minimize power consumption. Note that here the driving constraint is the energy.

**DISTRIBUTED CONTROL NETWORKS**

These are systems designed to control operation across devices and sensors. The nodes that are part of these network perform their specific task, they communicate with each other in a P2P fashion or another way depending on the network architecture. In these systems some distributed control algorithms are implemented to enable the collaboration between nodes. Each node can apply some decision making by performing certain actions.

**MOBILE AD-HOC NETWORKS (MANET)**

A type of network that establishes wireless communication in dynamic and decentralized environments. In this case the nodes (mobile devices) communicate with each other without the need for centralized control (router or AP). The difference between an ad-hoc network and a MANET is just the emphasis that the nodes are mobile devices (they keep moving), just ad-hoc is a little more static because I can have cabled nodes. This kind of networks are mainly created to satisfy a temporary need, are easily deployable and re-configurable.

**OPPORTUNISTIC AD-HOC NETWORKS**

These are a specific type of ad-hoc networks, nodes communicate opportunistically, they operate in environments where nodes may not always be in direct communication range, so when two nodes come within contact, they can exchange data before they move apart again. Here nodes store data until they encounter another node that can help move that data to a closer destination (store carry forward paradigm). The routing is called opportunistic because data forwarding decision are based on the contacts that occur between nodes, they decide dynamically when to send data.

**VEHICULAR AD-HOC NETWORK (VANET)**

A specialized form of MANET, designed for communication between vehicles. This Networks aim to improve road safety, traffic efficiency. The communication must be really fast, it must have low latency.

**FLYING AD-HOC NETWORK (FANET)**

A specialized form of MANET, designed for communication between aerial vehicles such as drones. Here drones can communicate with each other, and possibly with ground stations or other infrastructures.

**UNDERWATER NETWORKS**

These networks consist of various interconnected underwater sensors and vehicles deployed in water (oceans, lakes, rivers) to perform tasks like environmental monitoring, disaster prevention. Unlike terrestrial sensor networks, underwater networks face unique challenges due to the properties of water, such as higher communication latency, limited bandwidth, and energy constraints. In this case the medium that transports data is sound (acoustic waves), radio wave are attenuated in water, that’s why they are used in shallow water. This kind of communication has significant latency, and that is because sound waves propagation in water is a lot slower than electromagnetic waves propagation in the air. Also, the available bandwidth for sound is much narrower compared to the terrestrial wireless communication and that makes difficult to send large amount of data.

**RADIO FREQUENCY IDENTIFICATION (RFID)**

RFID technology is used to identify and track objects and consists of three main components: RFID tags, readers, and a backend system. RFID tags, which can be attached to objects, contain microchips to store data and an antenna for communication. Tags can be passive (no internal power, activated by the reader's electromagnetic field, and have limited range) or active (powered by their own battery, allowing longer-range communication). RFID readers, either fixed or mobile, emit radio waves to communicate with the tags. When a passive tag comes within range, the reader activates it, and the tag sends its data. Active tags continuously transmit signals. The backend system (a server) processes, stores, and analyses the data received from the readers. RFID operates on different frequency bands, each suited for specific uses, like scanning items in a store instead of barcodes, where tags provide detailed product information.

**NANO NETWORKS**

They refer to communication networks at the nanoscale that consist of nano-sized devices or machines (often referred to as nanomachines) that are able to interact and communicate with each other. Traditional electromagnetic-based communication techniques are often unsuitable for devices at such small scales due to power and size constraints. Instead, communication in nano networks could rely on novel communication paradigms such as molecular communication or terahertz-band communication.

# **2. Physical layer**

## **2.1 Radio frequencies**

Radio frequencies (RF) refer to the range of electromagnetic waves that are used to transmit and receive information through the air without the need for physical connections like wires or cables. These frequencies range from 3 Hz to 300 GHz, covering everything from very low frequency (VLF) radio waves to extremely high frequency (EHF) microwaves. Electromagnetic energy is generated by high frequency alternate current (AC) in antennas where is converted into RF and vice versa. RF are fundamental for wireless communication.



The **amplitude** of the wave (measured as the difference between the highest and lowest peak) is the energy the wave carries, is varied in proportion to the information being transmitted. The greater the amplitude the more energy the waves carry. The higher is the amplitude the further the signal goes. Amplitude depends on the transmission medium (air, outer space, etc.). The transmission power is measured in Watts = Energy / Time = Joule / Sec.



The **frequency** of a wave refers to the number of complete oscillations of the wave that occur in a specific amount of time, typically measured in **hertz (Hz).** The higher the frequencythe more information is transmitted, but it’s difficult to penetrate objects, with lower frequencies have longer wavelengths and can travel longer distances and penetrate objects (penetration can weaken the signal). Frequency allows two nodes to hear communications each other, if both are set on the same frequency value. It is a portion of wireless spectrum assigned to wireless technologies by regional authorities.



The **phase** of a waverefers to the position of a point in time on the wave cycle, indicating the specific stage of the wave's oscillation. It describes the relative displacement between different points of a wave or between two waves of the same frequency. It is the shift of a wave in degrees or radians. The phase can be positive (left-shift) or negative (right-shift).



The **polarization** (physical position of the antenna) refers to the orientation of the electric field in an electromagnetic wave. Polarization can be horizontal if the electric field oscillates parallel to the ground, vertical if the electric field oscillates perpendicular to the ground. Vertical polarization is typically used in WLANs, the antennas must be placed parallel to each other (otherwise less signal is received). RF waves are made of two fields, *electric* that is parallel to the antenna and *magnetic* filed that is perpendicular.



* 1. **Propagation** determines the RF coverage of the signal (how far it can go). After a certain point the signal is no longer detectable It depends on the strength of the signal itself. Signals become weaker in an exponential decline. Propagation ranges depends on power, obstacles, receiver’s sensitivity and many factors. It is quite useful to consider the following ranges of RF detection:
* *Transmission range* = how far the communication reaches. Communication possible, low error rate.
* *Detection range* = how far can the signal be found. Detection of the signal is possible, no communication possible via exchanging messages.
* *Interference range* = the distance at which the signal is too far away from the sender to be detected. Signal may not be detected.
  1. Remember that obstacles can reflect or absorb waves, and it depends on material and frequency used. In general, remember the following rule of thumb:
     + **high frequencies = good for short distances/more affected by obstacles**. They get weaker faster at some point the signal cannot be read anymore.
     + **low frequencies = good for long distances/less affected by obstacles**. These signals remain more readable over long distances.

The **receiving power** is proportional to 1/d2 where d = distance between sender and receiver. The receiving power can be influenced by different factors, such as:



**Multipath propagation:** signals can take many different paths between sender and receiver due to phenomena like reflection, scattering, diffraction.

**Time dispersion** happens when the signal is dispersed over time, it can happen that a signal is scattered into more signals, and some of those annihilate each other. The receiver ends up getting a really bad signal. We use Decibel (dB) as a power measurement to express power loss.

## **2.2 Antennas**

Antennas are devices that transmit and receive electromagnetic waves, enabling communication between devices over a distance, such as radio, TV, cellular, and Wi-Fi systems. They work by converting electrical signals into electromagnetic waves for transmission and vice versa for reception. During transmission, an antenna converts electric signals (which carry information, like voice or data) into electromagnetic wavesthat can travel through the air. This is achieved by applying an alternating current (AC) signal to the antenna, which generates oscillating electric and magnetic fields.

The size of antenna is related to RF frequency of transmission and receptions, the shape is related to RF radiation pattern. Is important also to notice that antennas are positioned with the aim of reach maximum area coverage.

Real antenna types are: omni-directional, semi-directional, highly-directional.

**OMNI-DIRECTIONAL ANTENNA**



A type of antenna that radiates electromagnetic signals uniformly in all directions around the vertical axis. It is commonly used in situations where coverage in all directions is needed, such as for radio stations, Wi-Fi routers, mobile networks, and some types of broadcast communication, outdoor with point to multipoint connection. Examples of this type of antenna can be the **dipole antenna,** two equal-length conductive elements (usually metal rods or wires) arranged in a straight line. These elements act as the radiating and receiving structure for electromagnetic waves. The dipole antenna has a passive gain due to the shape of radiation. **Gain** measures how well an antenna can focus energy on a particular direction.

**SEMI-DIRECTIONAL ANTENNA**



A type of antenna that focuses the radiation of electromagnetic signals in a specific direction (a specific sector), but not as narrowly as highly directional antennas. Semidirectional antennas are often used in applications where moderate coverage over a specific area or in a certain direction is required. Examples are Patch/Panel Antennas that are flat antennas mounted on walls, or Yagi that are rods with tines sticking out.

**HIGHLY DIRECTIONAL ANTENNA**



Focus the transmission and reception of radio waves in a very narrow and specific direction. This allows them to achieve greater signal strength and range over long distances compared to omnidirectional or semidirectional antennas. These antennas are used in applications where precise point-to-point communication or long-distance signal transmission is required. Example are the Parabolic dish or the grid.

**LOS (Line of Sight):** is the unobstructed path (a straight line) between transmitter and receiver.



**Fresnel Zone**: describes the elliptical region around the direct line-of-sight (LOS) path between a transmitter and receiver. It is essential for understanding how obstacles near the direct path can impact the strength and quality of a radio signal. Most additive RF signal is concatenated in the Fresnel Zone and is important that this zone is free from obstacles. The FZ radius depends on the distance between antennas and the frequency of RF.

The **beam** of an antenna describes the directionand shapeof the area where the antenna concentrates its energy. If aa FZ is partially obstructed it is not useful to use higher gain antennas, with smaller degree beam.

**SECTORIZED-DIRECTIONAL ANTENNA**



A type of antenna designed to cover a specific, limited area or sector, typically used in cellular networks, Wi-Fi networks, and other communication systems that require focused, directional coverage over a defined geographic region. These antennas divide a wide coverage area into multiple smaller sectors, each served by a different directional antenna. This enables more efficient use of radio frequency (RF) spectrum and improves signal strength within the target.d areas. They also provide space multiplexing (channel reuse).

## **2.3 Wireless technologies, coverage and multiplexing**

The **wireless spectrum** is the range of all radio frequencies used for wireless communication and that may be licensed or unlicensed.

The **bandwidth** of a wireless channel refers to the range of frequencies over which the channel can transmit data, and this range can vary widely depending on the application and environment. Wireless channels can have different bandwidths based on several factors, including the frequency spectrum being used, regulatory limitations, modulation techniques, and the specific technology or communication standard. Basically, different channels may have different bandwidth because they require less time to accommodate one bit on the channel, sending bits more frequently means making them more packed (look the figure here below).



There are different wireless technologies that influence the bandwidth:

* **Narrowband radio system** where transmission and reception are executed using a single radio frequency. Undesired cross talk between channels requires coordination and license for each site. There is low data rate.
* **Spread Spectrum technology**, used to spread a signal over a wide range of frequencies, making it less susceptible to interference, jamming, and unauthorized interception. There are two main types of spread spectrum techniques:
  + **Frequency Hopping spectrum (FHSS)**, where the signal does not stay on one frequency for long but moves across several frequencies within the band in a synchronized way known only to the transmitter and receiver. To unintended receiver FHSS appears as impulse noise.
  + **Direct Sequence Spread Spectrum (DSSS),** the signal is spread across a wider frequency band by multiplying the original data signal with a high-rate pseudo-random noise (PN)sequence, also called a chipping sequence. Each bit of data is transmitted as multiple bits called "chips," which effectively spreads the signal. To unintended receiver DSSS appears as low power Wideband noise.
* **Infrared technology** is LOS or diffused, short range. The frequencies are just below the visible light, cannot penetrate opaque objects, it allows high data-rate potential.
* **Radio Transmission Coverage** refers to the geographic area or range over which a radio signal, transmitted from a source such as a transmitter, antenna, or base station, can be effectively received. In wireless communication systems, the coverage area is the region where the transmitted signal remains strong enough for reliable communication between the transmitter and receiver. With Txwe indicate the transmission power with which the radio transmitter sends out a signal. **Symmetric links** are communication channels where the data transfer rates are equal in both directions. **Asymmetric links** are communication channels where the data transfer rates differ between the two directions.



Immagine che contiene testo, schermata, Carattere, numero

Descrizione generata automaticamente

**Multiplexing** is a technique used to combine multiple signals or data streams into a single transmission channel or medium. The primary goal of multiplexing is to make efficient use of available bandwidth by allowing multiple communications to occur simultaneously over the same physical medium, such as a wire, fiber-optic cable, or radio frequency spectrum. By using multiplexing, multiple signals can share the same channel without interfering with each other, which improves the capacity and efficiency of communication systems.

There can be different types of multiplexing:

* **Frequency Multiplexing.** The available bandwidth of the channel is divided into multiple frequency bands. A channel gets a certain band of the spectrum for the whole time. No dynamic coordination is required, it works for similar systems, it is not flexible and there is waste of bandwidth if the traffic is distributed unevenly. Each signal is transmitted on a different frequency, allowing several signals to be sent simultaneously without interference. It is used in radio and tv broadcasting.
* **Time Multiplexing**. Multiple data streams share a single channel by dividing the available time into separate time slots. Each signal is assigned a specific time slot, during which it can transmit its data. It is used in digital telephone networks, where multiple voice calls are combined over a single line. Precise synchronization is necessary, only one carrier ate the time in the medium.
* **Code Multiplexing**. Each signal is assigned a unique code. All signals (all channels) are transmitted simultaneously over the same frequency spectrum, but because each signal has a different code, the receiver can distinguish between them. It is used in mobile communication systems like 3G and GPS. Coordination and synchronization are not necessary, has a good protection against interference, has lower data rates and more complex signal generation. It is implemented using spread spectrum technology.

# **3. MAC layer**

…