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Wireless networks for mobile applications simple (for real)

Summary

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# Presentation

All lessons will be registered and made available on Moodle page.

One can also find material of reference (will not be updated overtime though): <https://www.math.unipd.it/~cpalazzi/WNMA.html>

Everything else is on Moodle. The program is as follows:

* Introduction, wireless systems, protocols architecture, issues and measures
* Physical Layer (fundamentals and mobility effects)
* Data Link Layer (fundamentals on duplexing, TDMA, FDMA, CDMA)
* Network Layer (addressing/routing with device mobility)
* Transport Layer (Reliable communication and mobility impact on TCP)
* Application Layer (Geolocalized services, DTN, smart applications, distributed sensing, crowd computing, intelligent transportation system,…)
* Wireless Network Architectures: management and challenges
* WLAN, Infrastructure and Hot-Spot Networks
* Wireless Mesh Networks (WMN)
* Sensor Networks (Sensor Networks)
* Mobile Ad Hoc Networks (MANETs)
* Vehicular Ad-Hoc Networks (VANETs)
* Flying (Drone) Ad-Hoc Networks (FANETs)
* Satellite systems, challenged networks
* Consumer market technology; main standards; advanced issues:
* IEEE 802.11b/g/a/e/n/s/p
* IEEE 802.15.1 (Bluetooth)
* IEEE 802.15.4 (ZigBee)
* RFID
* Services:
* Location-based services
* Client/Server and alternative service paradigms
* Wireless Internet
* Pervasive wireless communication systems
* Other fields where Wireless Networks apply: existing and visionary services

The project can be on whatever scenario for the exam, will be any kind of project.

* Practical implementation or study of course-related scenarios
* Performance evaluation of protocols in wireless scenarios
* Development of applications for mobile environments (e.g., videogames or other applications for smartphones)

The specs for the project are as follows:

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4 pages are enough, but students find them too short for the report for the project. We will discuss with the professor, and we both must agree on that (via a meeting or I don’t know). It may be much related to Networking but also something completely different.

One can create a big project to satisfy both Mobile Programming and Multimedia and this course; this is also a chance.

The project has this kind of evaluation criteria:

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This class convers:

* Design, analysis, and implementation of protocols and algorithms in (mobile) wireless network systems and their implication in the design of popular/innovative mobile applications

But does not cover:

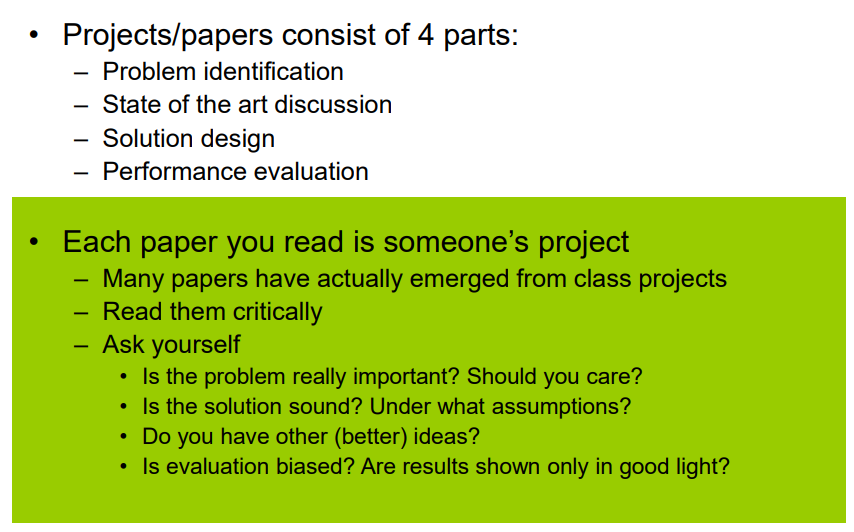
* Modulation schemes, transmitter/Receiver design, signal processing and antenna design, source coding / channel coding, privacy / Security

The project can be done in pairs (strongly suggested, 2/3 people per team)

The exam is oral, not written, which is an oral examination. Then the project can be delayed and decided to a term even after the examination. The teacher is flexible on this.

We are supposed to read papers to explore and further dive on a particular topic, to absorb concepts, for ourselves and to rationalize different ideas and different solutions. Via the intranet of UniPD inside the Department, we can freely access our specific papers.

General criteria on how to write the papers:



It’s important to discuss ideas and thoughts with the professor, mainly on an area and direction and find new solutions for more problems.  
Also:

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Descrizione generata automaticamente

Immagine che contiene testo, schermata, Carattere, documento

Descrizione generata automaticamente

# Mobile Communications and Wireless Systems

In the history of communication, overtime and especially after WW2, many ways developed with the goal of transmitting data, no matter the channel. Several ways of communication have born, but others have made their way to conquer the world: the mobile ones, with an exponential growth in connections and devices since 1988, with both Wi-Fi, mobile phone and 3G/4G/5G connections.

Now device penetration goes between 80% to over 120/140% all over the continents, with the most mobile subscriptions coming from Asia, Pacific Asia, China, Africa and India, at approximately 9 billion. Connection has overtime become ubiquitous, reaching billions of users and devices worldwide.

The following is an example of how networks are created differently, trying to penetrate the whole environment for the sake of communication universally. We want to run data making a good compromise between performance and effectiveness, depending on the scenarios listed above. We can’t plan them definitely: there will always be delays, energy struggles, position of nodes and other factors to consider in this environment.

Above, just for mobile and IOT, you can see the fragmentation, in which each one requires different specifications on how data will be transmitted (briefly described by me, Palazzi stayed here quite a bit just to give an overall view), starting from a massive number of low-power/low-cost devices (*massive/NB-narrowband*), others requesting high-bandwidth to continuously transmit heavy data (*broadband*), other cases it might be critical to have reliable communications in realtime (*critical*), achieving this way greater efficiency and productivity.

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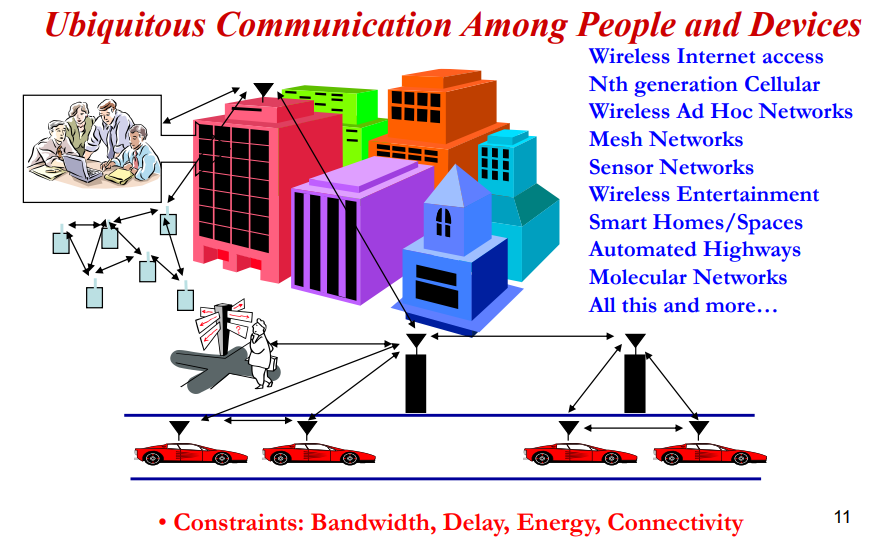
Descrizione generata automaticamente

The largest part of mobile data consumption is taken up by video data, may it be streaming, VoD (Video on Demand) and other video formats, possibly even HD/UHD, AR/VR. Following we may find social networking, software downloads and updates, etc. As years have passed, users have changed overtime their behavior, tending to consume media everywhere and devices with larger screens require better media and heavier networking use (so, reduce in usage of older G technologies such as 3G and increase in 4G and 5G).

Internet usage and the widespread adoption of laptops have reached unprecedented levels. This surge in demand for connectivity has driven advancements in wireless technology to support high-speed and reliable data transmission. Wi-Fi standards are continually improving, and the transition from 4G to 5G and now to 6G is reshaping wireless communication capabilities.

Wireless technology is now integrated into interdisciplinary applications, opening multiple realities scenarios (augmented-AR/virtual-VR/mixed-MR/tele-presence), ultra responsive at our touch (Tactile Internet) and intraconnected in realtime with wide range of data demands and devices (Web Squared).

To summarize, we can see below the different types of networks, whereas the need of expanding connectivity and enabling different applications according to a seemingly ever-evolving context and much more ubiquitous:



In designing networks, we face many challenges:

* Wireless channels have limited bandwidth compared to wired counterparts. This limitation poses a challenge in achieving high data rates, especially as the demand for wireless data continues to grow. One solution is trying to use protocols and techniques to maximize channel capacity.
* Wireless networks operate in dynamic environments where user locations, traffic patterns, and network conditions change continuously. This variability can lead to unpredictable performance. The solutions are using algorithms and protocols to adjust to changing conditions.
* There are applications with varying requirements posed by energy and delay constraints, having different Quality of Service (QoS) mechanisms to help prioritize traffic and having applications energy-efficient and protocols that use low-power algorithms to optimize consumption.

As said, energy and delay constraints *change design principles* across all layers of the protocol stack. Below the general multimedia requirements (where BER stands for Bit Error Rate):

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Descrizione generata automaticamente

We can’t have a *protocol which fits them all*; each media has specific requirements:

* For data we don’t care about content transmission of every single packet, but for the total time of having the whole thing downloaded, without losing packets. Usually data is burst continuously, minimizing the total download time
* On the other side, games, voice (VoIP) are requiring applications where data is streamed uninterruptedly to maintain a seamless user experience
* In the case of video, whether it's real-time streaming or playback of prerecorded content, video transmission involves the transfer of large volumes of data. To deliver a smooth viewing experience to end-users, it's essential to use larger packets and efficiently handle the bursty nature of video data

In computer networks design, we have layers, and dealing with them may be difficult given the overall differences. We base ourselves on the **crosslayer design,** where different layers blur between each other, reducing uncertainty and providing robustness, leading to better performances overall via abstraction. It’s advisable to focus “on your layer” when creating a network application, without having something universal but functional (without sacrificing exploitation of more possibilities).

What we essentially mean is creating something carefully, having each layer naturally interact with others, without “crossing borders” unsafely, but *propagated*. This design below is therefore commonly used.

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Descrizione generata automaticamente

Let’s introduce the **Current Wireless Systems**, ranking the ones most used:

* Cellular Systems, where geographic regions are divided into *cells*, with each having their own signal and with carefully crafted areas allowing the reuse spatially of frequencies/timeslots/codes in between, coordinating hand-offs via control functions thanks to base stations.
  + We also must consider cell size (shrinking it means increasing capacity but also networking burden) and conflicting technology between cells (horizontal – same technology/vertical – different technology), to keep the service alive (see figure below)
  + Data is bursty, having 3G widening the data pipe (with both voice and data), while 4G and 5G more focused on data (higher bandwidth and reliability, lower latency)

Immagine che contiene diagramma, pixel

Descrizione generata automaticamente

* Wireless Local Area Networks (WLANs), which connect local computers (between a 100m. range), breaking data into packets and sharing channel access randomly. This backbone provides best-effort service, which means they prioritize delivering data with no guarantees of quality or timeliness. In between there are access points, which act as bridges and break data further in between (devices are connected wirelessly to them and this is wired-connected to the internet).
  + This can lead to *overhead* due to the need to retransmit smaller packets but can be more forgiving in terms of data loss (splitting means not losing all packets in case of errors)
  + There is a trade-off in bandwidth utilization. The shared nature of the channel means that it's not always fully utilized because of the various tasks competing for time on the channel, which include voice communication, data consumption, and packet transmission: bandwidth usage can’t be determined beforehand then.

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Descrizione generata automaticamente

Just to give a quick overview of WLAN Standards:

* **802.11b (Old Generation) – free frequency, more crowded**
  + Frequency: 2.4GHz ISM band
  + Modulation: Frequency hopped spread spectrum
  + Speed: 1 - 11 Mbps
  + Range: Approximately 100 meters (nominal)
* **802.11g (Legacy Standard) – popular and with higher bandwidth usage**
  + Frequencies: 2.4 GHz and 5 GHz bands
  + Modulation: OFDM (Orthogonal Frequency-Division Multiplexing), transmitting data and dividing it into multiple subcarriers, resistant to interference and able to multipath
  + Speed: Up to 54 Mbps (nominal)
* **802.11n (Current Generation)**
  + Frequencies: 2.4 GHz and 5 GHz bands
  + Modulation: OFDM with time division
  + Technology: MIMO (Multiple-Input and Multiple-Output), uses multiple antennas at both the transmitter and receiver, enabling simultaneous transmission of multiple data streams
  + Speed: Up to 300 Mbps (nominal)
* **802.11ac (Current/Emerging Generation)**
  + Frequencies: 2.4 GHz and 5 GHz bands
  + Modulation: OFDM with time division
  + Advanced MIMO: More MIMO (Multiple-Input and Multiple-Output) channels
  + Speed: Up to 500 Mbps (nominal) for a single connection
* Satellite Systems, used to cover very large areas. We differentiate them according to the different orbit heights: GEO satellites (geostationary) stay at about 39000 km while LEO satellites (Low Earth Orbit) stay lower, at 2000 km.
  + They are optimized for one-way transmission, especially for radio and movie broadcasting (a delay of between 25/50 ms for the latter ones/LEOs to 120 ms for GEOs)
  + Most two-way systems like Iridium failed because of expenses and delays; usually satellite to Earth is faster than the other way
* Bluetooth, created as a low-cost cable replacement RF (radio frequency) technology, so this is why it’s this short-range (at about 10 m, extendable in case to 100 m through multihop). The band used is crowded (2.4 GHz), having originally 1 data channel and 3 voice channels.
  + The short range is mainly used to avoid consuming too much battery
  + It’s supported almost everywhere across devices nowadays, with very few applications beyond cable replacement (mainly used for device pairing)

# Emerging Wireless Network Systems

In this chapter, we will explain many kinds of emerging systems:

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  Descrizione generata automaticamenteAd-hoc networks, where you have no infrastructure fixed, but it’s very much flexible, given the nodes are equal and based on peer-to-peer communications. We have no backbone infrastructure here, so we can use router multihopping, because we can reach destinations in many ways and distant ones too (dynamic network topology)
  + The nodes can keep moving and going away, so they reorganize automatically. The initial meaning was mostly military, nowadays it simply means devices communicate with each other directly

Anyway, we can have many *design issues*:

* The capacity of these networks is very much unknown, bringing to packet collisions especially in case of parallel communications; depending on which node is transmitting, the nearby nodes will be blocked to avoid interference (can’t communicate both at the same time)
* Transmission, access, and routing strategies for ad-hoc networks are generally ad-hoc, so routing can’t be univocally determined all at once, given the “movable” nature of the network (on-the-fly)
* Crosslayer design critical and very challenging, so that may result in very low performance; just be very flexible and try to have secure routing, via data encryption and authentication mechanisms
* Immagine che contiene Elementi grafici, clipart, design, arte

  Descrizione generata automaticamenteEnergy constraints impose interesting design tradeoffs for communication and networking, carefully planning the right amount of energy spent (during days to keep the service active fully, but also in nights to “keep the service alive”, so specific calculations need to be made), giving the right QoS

Moving on:

* Mesh networks, which are a type of decentralized network topology between ad-hoc networks and wireless ones. In these each device, often referred to as a node, is connected to multiple other devices in the network, creating a mesh-like structure (see figure on the right).
  + In a mesh network, nodes not only communicate with their neighboring nodes but also serve as relays, forwarding data for other nodes. This redundancy and self-routing capability make mesh networks highly robust and resilient
  + Networks, this way, are created low-cost, easily deployable ad high performance, but when creating them is required to choose the correct routing protocol, considering balancing in between and having two nodes communicate may prevent others in range
  + It’s difficult to determine univocally a QoS mechanism and being able to assure it, given these networks formation

There are many challenges however:

1. **Optimum Routing Protocols:** Achieving efficient routing is a fundamental challenge in mesh networks. Optimum routing protocols are needed to determine the best paths for data transmission, ensuring fairness among nodes and load balancing to prevent congestion.
2. **Quality-of-Service (QoS):** Mesh networks often support various applications with different QoS requirements. Ensuring that multimedia applications, for example, receive the necessary bandwidth, low latency, and reliability can be challenging.
3. **MAC/Network Protocols for Multimedia:** Multimedia applications such as video streaming or voice over IP (VoIP) require specific MAC (Media Access Control) and network protocols to handle real-time data efficiently. These protocols need to be designed and optimized for mesh networks.
4. **Efficient Autonomous Operation:** Mesh networks are expected to operate autonomously, especially when the fixed infrastructure fails or experiences disruptions. Ensuring that nodes can self-organize, self-heal, and maintain network connectivity under adverse conditions is critical.

We define then a more specific kind of ad-hoc networks:

* Sensor networks, networks composed by sensors, where each sensor is used to monitor specific things.

Immagine che contiene diagramma, schizzo, cerchio, linea

Descrizione generata automaticamente

* + In these networks, the main drawback is consuming energy; to spare it, they are periodically turned on and off to monitor the environment. When they’re on, they may help sending messages overtime
  + The nodes are powered by non-rechargeable batteries (not always, but generally like this) and data flows to a centralized location, where each node has low per-node rates but up to 100,000 nodes (a lot of small data and transmitted limitedly)
  + Nodes can cooperate in transmission, reception compression, and signal processing (more transmission, more bandwidth consumed, so data must be highly correlated in time and space (flowing to centralized locations to aggregate more packets and avoid losing big payloads of data; the principle is “transmit less data to reduce errors”)
  + To avoid consuming a lot of energy in computations, optimum routing protocols are needed, creating protocols to handle multimedia efficiently and autonomously if possible, prioritizing QoS requirements

You need to have a good enough capability to transmit control signals and data between distributed control over wireless links. This approach is commonly used in various applications where control decisions must be made remotely (i.e. industrial automation, robotics, and remote monitoring). A few key points to be made:

* In wireless networks, packet loss and variable transmission delays are common due to factors like interference and network congestion and can have a significant impact on the design
* To address the challenges posed by wireless networks, controller design must be robust. Robust control algorithms are designed to maintain system stability and performance even in the presence of uncertainties, delays, and disturbances
* Distributed control systems should be designed to tolerate network faults gracefully (with error coming from nodes or malicious nodes, because we can’t trust anybody inside networks)
* Effective distributed control often requires a close collaboration between control system designers and network engineers. Joint application and communication network design is crucial to optimize both control performance and network efficiency

A specific kind of network based again on ad-hoc network is:

* Mobile Ad-Hoc Networks (MANET), which are self-configuring networks of mobile devices, such as laptops, smartphones, or IoT devices, where nodes communicate with each other directly without the need for a fixed infrastructure or centralized control, like routers or access points, configured ad-hoc via multihopping (so communications are keep via cooperation between nodes and each host can act as end-point or as router)

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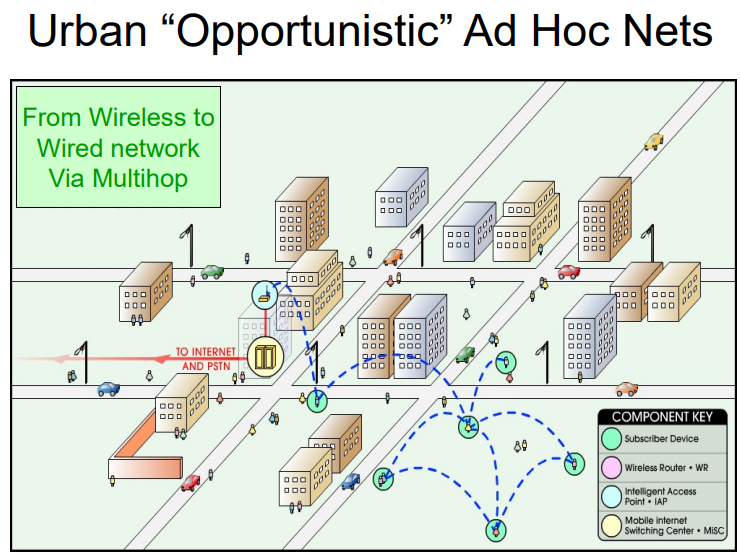
Descrizione generata automaticamente

* + They are designed with a focus on mobility, where the topology of the network continuously changes and the protocol used must adapt consequently, given they are instantly deployable, re-configurable (no fixed infrastructure), to satisfy a temporary need
  + They are portable (e.g. sensors) or mobile (e.g. cars), not organized to have infrastructure networks around to provide connectivity to mobile devices
  + They were created for battlefield military purposes (given how dynamic they are), but now we can categorized many civilian purposes, for example disaster recovery, law enforcement, homeland defense, search/rescue in remote areas, environment monitoring, space/planet exploration

Another kind of interesting networks are Opportunistic ad-hoc Networks, which also known as "delay-tolerant networks," are a type of wireless network that is characterized by its ability to form and operate under opportunistic conditions. These networks are often driven by commercial or practical application needs and thrive in scenarios where traditional infrastructure-based networks may be limited or expensive.

* They are driven by application needs, such as extending coverage indoor, sharing among friends via Bluetooth, P2P networking in a vehicle grid
* In opportunistic ad hoc networks, access to the internet may be available, but it can be "opportunistically" replaced by the ad hoc network when the internet connection is too costly, inadequate, or temporarily unavailable. This can be particularly valuable in scenarios with limited or expensive data plans.

A few examples visually, starting from the *Urban Opportunistic Ad Hoc Nets* ones, where wireless connections may be intermittent due to obstacles like buildings and signal interference. Opportunistic communication allows devices to make the most of brief connectivity windows, given they are deployed in densely populated urban areas, such as cities and metropolitan regions, adapting in routing and in communication.



Vehicular Ad-Hoc Networks (VANETs) are a specialized type of ad-hoc network designed to enable communication among vehicles via on-board units and between vehicles and roadside infrastructure in the context of transportation systems.

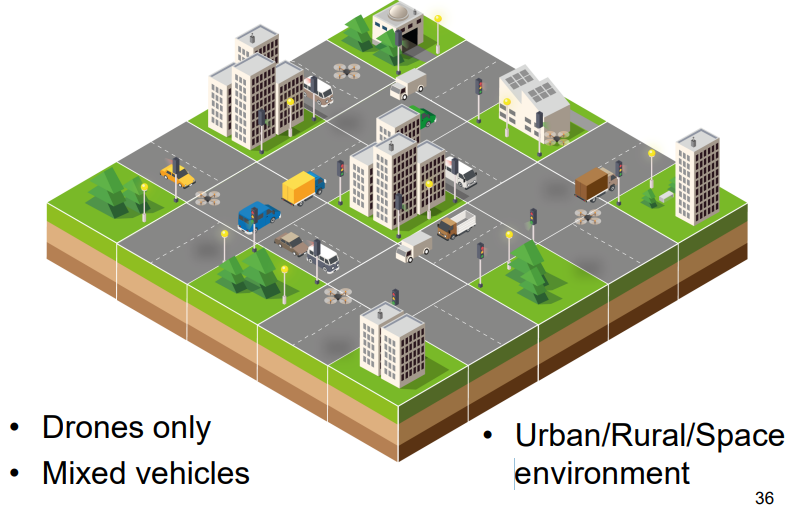
* This communication can be used for sharing information about road conditions, traffic incidents, vehicle safety, and more.
* Their purpose is to enhance road safety, having vehicles exchanging information in realtime and give fast access to emergency services; of course, legal problems and moral decisions must be considered (in case of accidents or the best decisions on when to pass, even though accidents are estimated to occur mainly when having automated cars mixed with regular cars)

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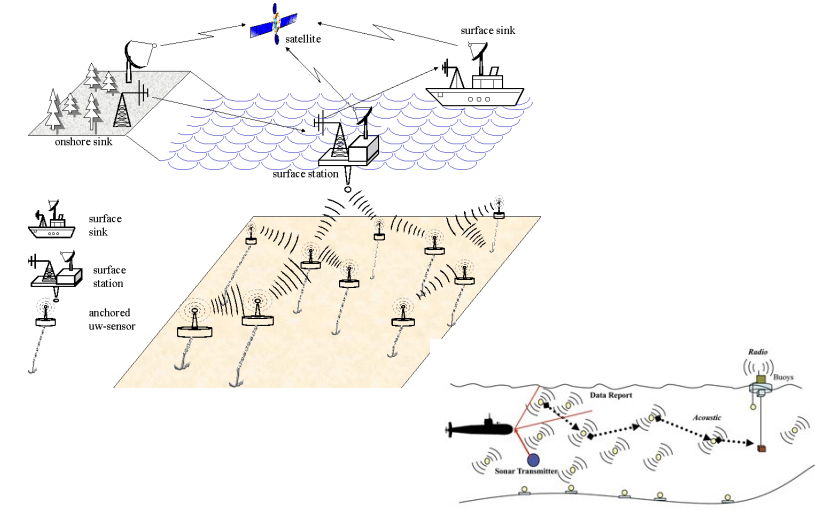
(Have a look at slide 35 of 43 inside WNMA01.pdf to have an overall look of all the possible applications in this field)

Another good example is the Flying Ad Hoc Networks (FANET), composed by drones only or mixed vehicles, usually inside a urban/rural/space environment. They are designed for communication among autonomous flying vehicles, such as drones, unmanned (without men/equipe) aerial vehicles (UAVs), or remotely piloted aircraft systems (RPAS). FANETs play a crucial role in enabling coordinated and efficient communication and data exchange among airborne platforms.



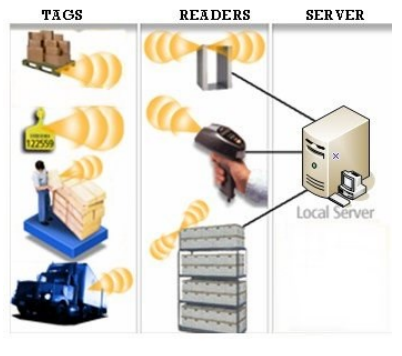
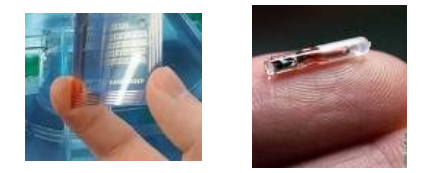
* They enable direct communication between autonomous flying vehicles, allowing them to exchange data, control commands, and real-time information while in flight
* The network topology in FANETs is highly dynamic and mobile, as flying vehicles move in three-dimensional space (3D Topology). This dynamic nature requires specialized routing protocols and communication strategies
* FANETs operate autonomously, with flying vehicles making decisions about data relay, routing, and collision avoidance. They may use GPS, onboard sensors, and communication protocols to navigate and communicate

An example coming from the slide are the *Underwater Sensor Networks (USNs)* are specialized networks of underwater sensors and communication devices designed to monitor and collect data from underwater environments. They communicate relying on sounds and light.



* USNs consist of sensor nodes, which are small, autonomous devices equipped with various sensors to measure physical and chemical properties of the underwater environment. These sensors can include temperature, pressure, salinity, acoustic ones, and more.
* The transmission must be properly regulated, operating on limited battery power, with collision happening because you can’t receive at the same time. The signal propagates much further, but the environment plays a huge role in how these networks are designed

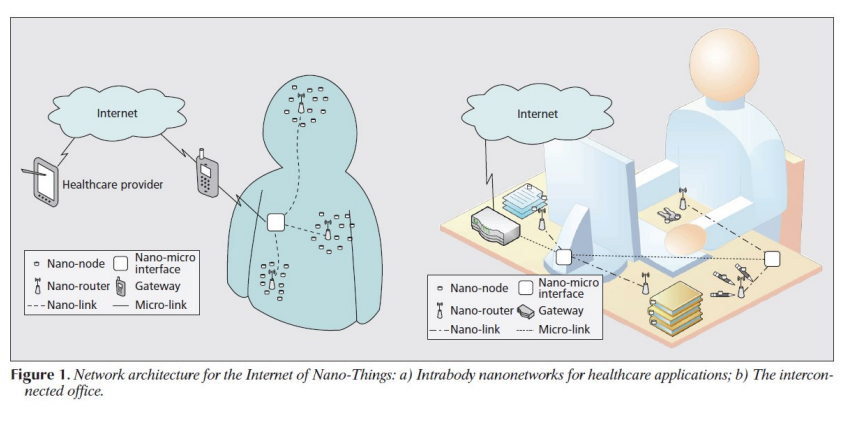
We also have Radio Frequency IDentification (RFID), which is based on magnetic fields, using *tags* that can be active (more battery needed, they emit signals) or passive (transmit signals only if electromagnetically charged). The system can be built with (lot of tags + one emitter = cheap | lot of emitters + one tag = expensive).



* One usage is like identifying a specific instance of a product (seeing preparation date, where it was created, who took care of it, etc., not like a simple barcode), so they are used in supply chains instead of barcodes (still, with standards under development)
* They have no need for direct optical reading, even though they are more expensive. They, instead, require an emitter of electro-magnetic waves that charge the tag. The charged tag sends a message containing all the information back to the server, that can then check it

We then categorize the nano-networks, also known as nanoscale networks, refer to a type of communication network where extremely small devices or components, often at the nanometer scale (one billionth of a meter), communicate with each other to perform specific tasks.

* They rely on communication mechanisms that operate at the nanoscale. This often involves techniques such as molecular communication, where nanoscale devices exchange information through chemical signaling, or quantum communication, which uses the principles of quantum mechanics for secure and efficient communication.
* They have potential applications in various fields, including medicine, materials science, environmental monitoring, and information technology. For example, they can be used for targeted drug delivery, monitoring environmental pollutants at the molecular level, or creating novel materials with unique properties (we can cite the 2010 Nobel Prize in Physics via graphene transmission or as recently as 2023 the Nobel Prize in Chemistry which focuses on atto-second () laser pulses of electrons)



Wireless technology offers vast potential in various applications, but it comes with technical challenges in signal propagation, interference, network protocols, and security. These challenges often limit performance and interoperability. Standards and spectral allocation govern wireless communication and influence system development, despite these challenges, wireless tech holds great potential for the future.

Some case studies and project topics (final slides in the same set, expanded just to give context and ideas):

1. **Internet of Space Things (Cubesat)**:
   * Network of small satellites (Cubesats) for space data collection and communication.
2. **Intelligent Transportation System**:
   * Advanced tech for safer and efficient transportation, including traffic management and smart traffic lights.
3. **AR and Interactive Games**:
   * Augmented Reality-based interactive games using smartphones or AR headsets.
4. **Industry 4.0**:
   * Integration of IoT, robotics, and AI in manufacturing for automation and productivity.
5. **Side Channel Attacks**:
   * Cybersecurity threats exploiting electronic system information leaks.
6. **Mobile Sensing & Mobile Cloud Computing**:
   * Data collection via mobile sensors, processed in the cloud for various applications

# Physical layer

(Not relevant to this chapter)

Palazzi started this lesson introducing how to structure a project paper; it started from a PowerPoint and a PDF of the Game of Ur (found inside the “Past Project Examples” folder on Moodle in its full “textual” form, not the slides sadly). Basically, it’s a two-player board race game which is dice-based kind of like backgammon. Basically, the main points of the presentation are:

* Presentation of the context
* Rules of the game
* Game modes
* Game technologies
* Game in app and components
* Game evaluation
* Future extensions

The paper itself is focused on the development of a mobile game to teach players something historical related to Sumerians, while at the same time testing how this subject can be used to further see how “serious” games can be accessible to almost anyone. In this we see a presentation of the context and the related work. We have then a complete game description, to delve into the whole context of the game. There are also hardware requirements that need to be respected, and design and implementation, while also delivering some screenshots of the final product. The final part is focused on the game evaluation and conclusions as results of the whole research work.