COMO

Wireless Transmission – Path Loss, Shadowing, Multipath, Capacity

1) How does an EM wave propagate in a wireless channel?

$\lambda=f/c$ $c=3*10^8$ (m/s)

fc=300MHZ -> λ=1m

fc=1GHZ -> λ=30cm

fc=3GHZ -> λ=10cm

fc=30GHZ -> λ=10mm

➔ <u>**Propagation Modes:**</u>

Ground-wave propagation:

»Follows contour of the earth
»Can propagate considerable distances
»Frequencies up to 2 MHz

Sky-wave propagation:

»Signal reflected from ionized layer of atmosphere
»Signal can travel back and forth between ionosphere and earth's surface
»Frequencies between 2 MHz and 30 MHz

Line-of-sight propagation:

»Transmitting/receiving antennas in line of sight
»Signal above 30 MHz not reflected by ionosphere

2) What is antenna and antenna gain?

➔ Couples of wires to space, for electromagnetic (EM) wave transmission or reception;

➔ Radiation pattern, EM radiation around an antenna;

➔ Isotropic radiator:
  - Equal radiation in 3 directions (x, y, x);
  - Theoretical reference antenna;

➔ Real antennas are not isotropic radiators:
  - Length of antenna is proportional to λ;
  - Radiation pattern of a simple Hertzian dipole;

➔ **Antenna Gain:**
  - Maximum power in direction of the main lobe (P_{main_lobe}), compared to power of an isotropic radiator (P_{iso}) transmitting the same average power

$$G = \frac{P_{main\_lobe}}{P_{iso}} = \frac{4\pi A_e}{\lambda^2} \qquad A_e = G\frac{\lambda^2}{4\pi} \quad [m^2]$$

  - A_e – Antenna aperture – depends on physical antenna characteristics, the longer the wavelength λ, the larger the aperture/area of the antenna;
  - Effective Isotropic Radiate Power (EIRP):
    - EIRP = P_t*G_t;
    - Maximum radiated power in the direction of maximum antenna gain;

3) What is shadowing, reflection, refraction, scattering, and diffraction?
➔ **Shadowning, Reflection** -> caused by objects much larger than the wavelength;
➔ **Refraction** -> caused by different media densities;
➔ **Scattering** -> caused by surfaces in order of wavelengths;
➔ **Diffraction** -> similar to scattering; deflection at the edges;

4) What is path loss? How to model it?
➔ Is the **dispersion of radiated power**;
➔ Depends mainly on the sender-receiver distance;
➔ Models:
- Free space path loss
  - Too simple; far from reality;
  - Path loss (PL) for unobstructed LOS path;
  - Power falls off proportional to 1/d^2, and proportional to λ^2 (inversely proportional to f^2);
- Ray tracing models
  - Demand site-specific information;
  - One LOS ray + one ray reflected by ground;
  - Ground ray cancels LOS path above critical distance;
  - Power falls off proportional to d^2, and proportional to d^4;
- Empirical models
  - Do not generalize to other environments;
- Simplified model
  - Good for high-lever analysis;
  - Used when path loss is dominated by reflections;

5) How to model shadowing?
➔ Models attenuation introduced by obstructions;
➔ Random due to random number and type of obstructions -> ψ (Gaussian distributed random variable);

6) What is multipath? How does it affect the power received? How does it affect narrowband and wideband communications?
➔ Multiple rays received;
➔ Multiple delays from transmitter to receiver;
➔ Time delay spread;
➔ Multipath channel has a time-varying gain caused by the transmitter/receiver movements; Location of reflectors which originate the multipaths;

➔ Narrowband Channel:
- Low B (Hz) -> low symbol rate (B symbol/s) -> large time/symbol (1/B);
- Multipath components arrive in the time interval of their symbol;
- Received signal:
  - No spreading in time (no distortion);
  - Multipath affects complex scale factor;
  - Doppler effect (velocity) may be important;

➔ Wideband Channel:
- Multipath components may arrive at the receiver within the time period of the next symbol; Causing Inter-Symbol Interference (ISI);
- Techniques used to mitigate ISI:
  - Multicarrier modulation – OFDM;
  - Spread spectrum – CSMA;

7) How does Rayleigh fading model narrowband multipath?

➔ **If there is no Line-of-Sight (LOS) component:**

- Power received (Watts) may be modelled by an exponential probability density function;
- The random variable Z is the $P_{received}$;
- P_r – average received power (path loss + shadowing);

➔ **If there is LOS:**

- Power received may be modelled by Ricean distribution;

8) What is the maximum theoretical capacity of a wireless channel?

➔ Assuming Additive White Gaussian Noise (AWGN).

- Given by Shannon's law;

$$C = B\ log_2(1+\gamma)\ \ [\text{bit/s}]$$

➔ Capacity in fading channel (shadowing+multipath)

- Smaller than the capacity of an AWGN channel;

$$\gamma = SNR = \frac{P_r}{N_0 B}, \quad \gamma = SNIR = \frac{P_r}{N_0 B + \sum_{i=1}^{I} P_{r_i}}$$

Wireless Transmission – Modulation, Coding, OFDM, Spread Spectrum, Diversity

1) How to transmit bits using a carrier? What are the modulations commonly used in wireless networks?

➔ A **carrier wave** is a pure wave of constant frequency. To include speech information or data information, another wave needs to be imposed, called an **input signal**, on **top of the carrier wave**. This process of imposing an input signal onto a carrier wave is called **modulation**. In other words, modulation changes the shape of a carrier wave to somehow encode the speech or data information that we were interested in carrying. Modulation is like hiding a code inside the carrier wave.

➔ **Amplitude and Phase Modulation:**

- Pulse Amplitude Modulation (MPAM) (information coded in amplitude);
- Phase Shift Keying (MPSK) (information coded in phase);
- Quadrature Amplitude Modulation (MQAM) (info coded both in amplitude and phase);

2) How does BER depend on the modulation and SNR?

➔ The **bit error rate (BER)** is the number of bit errors per unit time;

➔ The **BER** may be improved by **choosing** a **strong signal strength** (unless this causes cross-talk and more bit errors), by choosing a **slow and robust modulation scheme** or **line coding scheme**, and by **applying channel coding schemes** such as redundant forward error correction codes;

➔ The higher (better) the SNR the better the BER;

3) What is a code? What are its benefits in wireless communications? Why is interleaving combined with coding?

➔ Coding enables bits in error to be either detected or corrected by receiver;

➔ **Coding rate=k/n:**
  - Code generates **n** coded bits for every **k** uncoded bits;
  - If channel+modulation enables the transmission of R bit/s;
  - Information rate = R*k/n (bit/s);

➔ **Coding Gain = $C_g(P_b)$:**
  - The amount of **SNR** that can be reduced for a given P_b **by introduction of a code;**

➔ Codes designed for AWGN channels,
  - Do not work well on fading channels;
  - Cannot correct the long error bursts that may occur in fading;

➔ Codes for fading channels are usually,
  - Based on a code designed for an AWGN channel;
  - Combined with interleaving;
  - Objective -> spread error bursts over multiple codewords;

➔ Interleaving is frequently used in digital communication and storage systems to improve the performance of forward error correcting codes;
  - If the number of errors within a code word exceeds the error-correcting code's capability, it fails to recover the original code word;
  - Interleaving amends this problem by shuffling source symbols across several code words, thereby creating a more uniform distribution of errors. Therefore, **interleaving is widely used for burst error-correction.**

4) Why is adaptive modulation/coding used?

➔ Adaptive transmission techniques:
  - Aim at maintaining the quality; for data networks -> **low and stable BER**;
  - Work by varying: **data rate, power transmitted, codes**;

$$\gamma = \frac{P_r}{N_0 B}$$

➔ Adapting the data rate:
  - Symbol rate kept constant;
  - Modulation schemes/constellation sizes depend on γ -> multiple data rates;

➔ Adapting the transmit power:
  - Compensate γ variation due to fading by adapting the power;
  - Maintain a constant received γ;

➔ Adapting the codes:
  - γ large -> weaker or no codes;
  - γ small -> stronger code may be used;

5) What is multicarrier modulation? What is OFDM? Why is it so important?

➔ Divides a bitstream into **N** low rate sub-streams;

➔ Sends sub-streams simultaneously over narrowband sub-channels;

➔ Sub-channel:
  - Has Bandwidth, $\mathbf{B_N=B/N}$;
  - Provides a data rate, $\mathbf{R_N=R/N}$;
  - For **N** large, $\mathbf{B_N=B/N<<1/T_m \rightarrow 1/T_S<<1/T_m \rightarrow T_S>> T_m}$;
    - Flat fading (narrowband like effects) on each sub-channel, no ISI;

➔ **OFDM** is a method of encoding digital data on multiple carrier frequencies;
  - Is a frequency-division multiplexing (FDM) scheme used as a digital multi-carrier modulation method;
  - A large number of closely spaced orthogonal sub-carrier signals are used to carry data on several parallel data streams or channels;

- Each sub-carrier is modulated with a conventional modulation scheme (such as **quadrature amplitude modulation or phase-shift keying**) at a low symbol rate, maintaining total data rates similar to conventional single-carrier modulation schemes in the same bandwidth;
- The **primary advantage** of OFDM **over single-carrier schemes** is its **ability** to **cope with severe channel conditions** (for example, attenuation of high frequencies in a long copper wire, narrowband interference and frequency-selective fading due to multipath) without complex equalization filters;
- Channel equalization is simplified because <u>OFDM may be viewed as using many slowly modulated narrowband signals rather than one rapidly modulated wideband signal;</u>
- The **low symbol rate** makes the use of a guard interval between symbols affordable, making it **possible to eliminate inter Symbol interference (ISI);**

6) What is spread spectrum?

➔ **Spread-spectrum techniques** are methods by which a signal (e.g., an electrical, electromagnetic) generated with a particular bandwidth is deliberately spread in the frequency domain, resulting in a signal with a wider bandwidth;

➔ These techniques are used for a variety of reasons, including the **establishment of secure communications**, **increasing resistance to natural interference**, **noise** and **jamming**, **to prevent detection**, and **to limit power flux density**;

➔ <u>Spread spectrum techniques</u>;
- Hide the information signal below the noise floor;
- Mitigate inter-symbol interferences;
- <u>Combine multipath components</u>;
  - This techniques multiply the information signal by a spreading code;

7) What is diversity? How to benefit from it?

➔ Main idea:
- Send same bits by independent paths;
  - Independent fading paths obtained by **diversity** of time, space, frequency;
- Combine paths to mitigate the fading effects;

➔ <u>Combining Techniques:</u>
- **Selection Combining:**
  - Selects the path with the highest gain;
  - Combine SNR is the maximum of the branch SNRs;
- **Maximal Ratio Combining (MRC):**
  - Paths co-phased and summed with optimal weighting;
- **Equal Gain Combining:**
  - Paths co-phased and summed with equal weighting;
  - Simpler than MRC;

➔ <u>Multiple Antennas:</u>
- **Multiple Input Multiple Output (MIMO) combines:**
  - Signals generated by multiple transmit antennas;
  - Signals received by multiple receive antennas;
- **Antenna arrays used for:**
  - **Diversity:** different signals, same data, from different Tx antennas;
  - **Multiple Streams:** parallel data streams (SU-MIMO);
  - **Beamforming:** directional antennas;
  - **Multi-user MIMO:** directional beams to multiple simultaneous users;

Wireless Data Link – Wireless Medium Access Control

1) Radio Link Protocol – Packet Loss Ratio (PLR)

- ➔ **Packet Loss** occurs when one or more packets of data travelling across a network fail to reach their destination; Is typically caused by network congestion;
- ➔ **Packet Loss** can be caused by radio signals that are too weak due to distance or multipath fading;
- ➔ **Effects:**
  - Can **reduce throughput** (rate of successful message delivery in a communication channel);
  - **Increases latency** due to additional time needed for retransmission;

2) How to implement duplex communications in a wireless link?

- Transference of data in both directions; **Uplink** and **Downlink** channels required;

➔ 2 methods for implementing duplexing:

- Frequency-Division Duplexing (FDD):
  - Wireless link split into frequency bands;
  - Bands assigned to uplink or downlink directions;
  - Peers communicate in both directions using different bands;
- Time-Division Duplexing (TDD):
  - Timeslots assigned to the transmitter of each direction;
  - Peers use the same frequency band but at different times;

Characteristics	*FDD*	*TDD*
channel gain estimation	$\Downarrow$ requires separate estimation for uplink and downlink	$\Uparrow$ channel measurements in one direction are used in the opposite direction
interference between directions	$\Uparrow$ requires guard-bands	$\Downarrow$ requires guard-intervals and precise time synchronization
frequency planning	$\Downarrow$ demands frequency planning, normally using pairs of bands	$\Uparrow$ does not demand bands in pairs
asymmetric allocation of capacity	$\Downarrow$ difficult to provide asymmetric capacities in both directions	$\Uparrow$ easy to implement by changing the direction associated to time slots

3) How to enable multiple access?

➔ Types of multiple-access schemes:

- Frequency-Division Multiple Access (FDMA):
  - Resources divided in portions of spectrum (channels);
- Time-Division Multiple Access (TDMA):
  - Resources divided in time slots;
- Code-Division Multiple Access (CDMA):
  - Resources divided in orthogonal codes;
- Space-Division Multiple Access (SDMA):
  - Resources divided in areas;

➔ **FDMA:**

- Signal space divided along the frequency axis (into non-overlapping channels);
- Each user is assigned a different frequency channel;
- The channel often have guard bands;
- Transmission is continuous over time;

➔ **TDMA:**

- Signal space divided along the time axis (into non-overlapping channels);
- Each user assigned a different cyclically-repeating timeslot;

- Transmission not continuous for any user
- Main Problem:
  - Synchronization among the users in the uplink channels; Users transmit over channels having different delay (different distances); Uplink transmitters must synchronize;

➔ **CDMA:**
- Each user assigned a code to spread his information signal:
  - Multi-user spread spectrum;
  - Spread signal -> Occupy the same bandwidth; Transmitted at the same time;
- Different bitrates to users (control length of codes);
- Power control required in uplink:
  - To compensate near-far effect;
  - If not, interference from close user swamps signal from far user;

➔ **SDMA:**
- SDMA uses direction (angle) to assign channels to users;
- Implemented using sectored antenna arrays:
  - The 360^o angular range divided in N sectors;
  - TDMA or FDMA then required to channelize users;

➔ **OFDMA:**
- Based on OFDM;
- Time x Frequency space;
- Radio Block (**RB**);
- Blocks are allocated to users by a central entity;
- Subcarriers allocated in groups;
- Adjacent subcarriers have similar SINR;
- Group of subcarriers -> sub-channel;
- Opportunistic scheduling:
  - Schedule sub-channels and power levels based on **channel conditions** or **data requirements;**
  - Use channel variations as an opportunity to schedule the best choice in users:
    - **System Efficiency:** select users with best throughput;
    - **Fairness:** maintain some fairness between users;
    - **Requirements:** audio, video (e.g. delay);

4) What is a random access method?

➔ Medium Access Control (MAC):
- Assigns radio resources to terminals along the time (time division);

➔ 3types of resource allocation methods:
- <u>Dedicated Assignment:</u>
  - Resources assigned in a predetermined, fixed, mode (e.g. TDMA);
- <u>Random Access:</u>
  - Terminals contend for the medium (channel);
- <u>Demand-Based:</u>
  - Terminals ask for reservations using dedicated/random access channels;

➔ MAC Protocols:
- <u>Aloha (Efficiency of 18%):</u>
  - If a station has a packet to transmit:
    - Transmits the packet;
    - Waits confirmation from receiver (ACK);
    - If confirmation does not arrive in round trip time, the station computes random backofftime -> retransmits packet;

- <u>Slotted Aloha (Efficiency of 37%):</u>
    - Works as Aloha, but stations transmit just at the beginning of each time slot;
- <u>Carrier Sense Multiple Access (CSDMA) (Efficiency of 54%):</u>
    - Station listens the carrier before it sends the packet;
    - If medium busy -> station defers its transmission;
- **ACK required for Aloha, S-Aloha and CSMA;**

5) What is a hidden node? What is an exposed node?

➔ **Hidden node** -> C is hidden to A:
- A transmits to B; C cannot hear A;
- If C hears the channel it thinks channel is idle; C starts transmitting -> interferes with data reception at B;
- <u>In the range of receiver; Out of range of the sender;</u>

➔ **Exposed node** -> C is exposed to B:
- B transmits to A; C hears B; C does not transmit;
- But C transmission would not interfere with A reception;
- <u>In the range of the sender; Out of the range of the receiver;</u>

➔ **Capture** -> D captures A:
- A and D transmit simultaneously to B; But signal power to received by B from D is much higher than that from A;

6) How to avoid the hidden node?

➔ Increasing Transmitting Power From the Nodes;
➔ Using Omnidirectional antennas;
➔ Removing Obstacles;
➔ Moving the Node;
➔ Protocol Enhancement Software;

7) How does the CSMA/CA work?

➔ If the medium is sensed busy, a random backoff interval is selected. The backoff time counter is decremented as long as the channel is sensed idle, stopped when a transmission is detected on the channel, and reactivated when the channel is sensed idle again for more than a DIFS (Distributed Inter-Frame Space). The station transmits when the backoff time reaches 0;

➔ To avoid channel capture, a station must wait a random backoff time between two consecutive packet transmissions, even if the medium is sensed idle in the DIFS time;

➔ CSMA/CA does not rely on the capability of the stations to detect a collision by hearing their own transmission;

➔ A positive acknowledgement is transmitted by the destination station to signal the successful packet transmission;

➔ If the transmitting station does not receive the acknowledge within a specified ACK timeout, or it detects the transmission of a different packet on the channel, the station reschedules the packet transmission according to the previous backoff rules;

➔ The efficiency of CSMA/CA depends strongly of the number of competing stations and depends also on the hidden stations;

8) What is the minimum distance between nodes in CSMA/CA?

➔ Transmitted packets will be interfered by another transmission within 500 meters in 53% of the cases;

9) What are the services possibly provided by RLC(Radio Link Control) (to Upper Layer)?

➔ Transparent data transfer:
- No addition of information;
- Possible segmentation of data, forcing the transference of short-length packets;

➔ Unacknowledged data transfer:
- Frames are not acknowledged by the RLC receiver;
- Frame sent by the RLC transmitter has a sequence number;
- Frame arriving with errors at RLC receiver is discarded;
- **Upper layer** at the receiver **knows which frames were discarded**;
- **2** delivery nodes at RLC receiver:
  - **Out-of-sequence:** frame is delivered to the upper-layer as soon as it is received by the RLC receiver;
  - **Duplication avoidance and reordering:** frames are delivered by the same order they have been sent and with no duplications;

➔ Acknowledged data transfer:
- Guarantees error-free and unique delivery;
- Upper layer receiver will get the frames by the correct order;
- **Selective Repeat ARQ or Hybrid ARQ** are often used;
- Short frames are used, in order to have low FER -> $FER = 1-(1-BER)^L$;

Mobile Networking – Fundaments, IPv6, Mobile IPv6

1) What are the main differences between L2 and L3 networks?

➔ **L2 Networking – Single Tree Required:**
- Ethernet frame:
  - No hop-count;
  - Could loop forever;
  - Same for broadcast packet;
- Layer 2 network:
  - Required to have tree topology;
  - Single path between every pair of stations;
- Spanning Tree Protocol (STP):
  - Running in bridges;
  - Helps building the spanning tree;
  - Blocks ports;
- Uses a MAC address (Media Access Control Address) to send data around a local area on a Switch. The MAC address is a local, permanent and unique name for the device.

➔ **L3 Networking:**
- Packet Formats:
  - IPv4;
  - IPv6 (Source and Destination Addresses -> 4 words);
- Router;
- Multiple Trees:
  - Every router:
    - Finds the shortest path to the other routers and their attached networks;
    - Calculates its Shortest Path Tree (SPT);
  - Routing Protocol:
    - Runs in routers;
    - Helps routers build their SPT;
    - RIP, OSPF, BGP…

- Uses Internet Protocol (IP) Address to send information between larger networks using Routers.

2) How can a packet switch support terminal mobility?

➔ Packet switch can support terminal mobility through Mobile IP.
➔ Only routers need to be upgraded to implement Mobile IP;
➔ Home and Foreign Agent are needed (can be seen as a couple of servers);

3) What is a tunnel? What is a virtual network?

➔ **Tunnel:**
- Is an IP network communications channel between two networks;
- It is used to transport another network protocol by encapsulation of its packets;
- Is often used for connecting 2 disjoint IP networks that don't have a native routing path to each other, via an underlying routable protocol across an intermediate transport network;
- In conjunction with the IPsec protocol they may be used to create a virtual private network between two or more private networks across a public network such as the Internet;
- Another prominent use is to connect islands of IPv6 installations across the IPv4 Internet;

➔ **Virtual Network:**
- Extends a private network across a public network, and enables users to send and receive data across shared or public networks as if their computing devices were directly connected to the private network;
- Layer 2 Tunnelling Protocol (L2TP) is a tunnelling protocol used to support virtual private networks (VPNs) or as part of the delivery of services by ISPs.

4) How does IPv6 work?

➔ **Improvements:**
- 128 bit addresses (16 octets, separated by ':'); No classes;
- Better QoS support (flow label);
- Native security functions (peer authentication, data encryption);
- Auto configuration;
- Routing;
- Multicast;

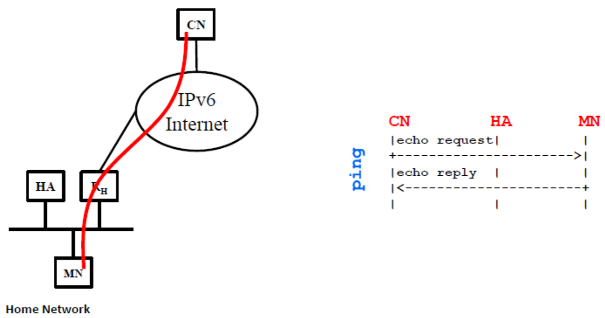
➔ **Addresses:**
- Link-Local:
  - Used for communication between hosts in the same LAN/link;
  - Address built from network interface MAC address;
  - Routers do not forward packets having a Link-Local destination address;
- Global Unicast:
  - Global addresses;
  - Address: network prefix + computer identifier;
  - Structured prefixes;
  - Network aggregation: less entries in router forwarding tables;
- Multicast:
  - Group address: packet received by **all the members of the group;**
- Anycast:
  - Group address: packet is received by **any (only one, the closest) member of the group;**

➔ **Header:**
- Flow label -> identifies packet flow;
  - QoS, resource reservation;
  - Packets receive same service;
- Payload length (Header not included);

    - Hop limit = TTL in IPv4 (maximum value=255; recommended initial value=64);
    - Next header (identifies next header/extension header);
    - Options -> included as extension headers;
- ➔ **Extension Headers:**
    - Hop-by-hop:
        - Additional info, inspected by every node traversed by the packet;
        - Other extension headers inspected only at the destination/pre-defined nodes;
    - Destination:
        - Information for the destination node;
    - Routing:
        - List of nodes to be visited by the packet;
    - Fragmentation:
        - Made by the source, that must also find PMTU (Path Maximum Transmission Unit);
    - Authentication:
        - Signature of packet header;
    - ESP:
        - Data encryption;
- ➔ **Neighbour Discovery (ND) Protocol:**
    - Uses ND protocol to:
        - Find other nodes in the same link/LAN;
        - Find a node MAC address -> ND substitutes ARP;
        - Find router(s) in the network;
        - Maintaining information about neighbour nodes;
    - Messages:
        - <u>Neighbour Solicitation:</u>
            - Sent by host to obtain MAC address of a neighbour/to verify its presence;
        - <u>Neighbour Advertisement:</u>
            - Answer to the request;
        - <u>Router Advertisement:</u>
            - Info about the network prefix; Periodic or under request;
            - Sent by router to IP address Link Local Multicast;
        - <u>Router Solicitation:</u>
            - Host solicits from router a Router Advertisement message;
        - <u>Redirect:</u>
            - Used by router to inform an host about the best route to a destination;

5) How does Mobile IPv6 work?

- ➔ **Overview:**
    - Mobile Node (MN) maintains its original IP address;
    - Mobile Node gets a second IP address (care of address);
    - Enables TCP session continuity;
    - <u>Requires mobility aware nodes;</u>
- ➔ **MN at Home Network:**



Standard exchange of packets

- **MN visits a Foreign Network:**
  - MN acquires a second IP address (Care of Address (COA)):
    - By DHCP or by listening ICMP Router Advertisement message sent by R_F;
  - MN informs HA about its new address:
    - MN sends Binding-Update; HA sends Binding-Acknowledge;
    - These are IPv6 messages using a new options mobility header;
  - HA:
    - Starts behaving as MN;
    - Receives traffic to MN at home;
    - Tunnels this traffic to the COA of MN;
  - MN sends traffic to HA, using tunnel;
- **MN optimizes the Route to CN:**
  - MN detects packet received in tunnel;
  - Optionally, it decides to optimize the route to the CN;
  - MN informs CN about its new address:
    - MN sends Binding-Update; CN sends Binding-Acknowledge;
    - These are IPv6 messages using a new options mobility header;
  - Traffic starts to be exchanged between MN<->CN:
    - MN->CN: use of options destination header;
    - CN->MN: use of option routing header;

6) How to optimize an IPv6 route?

- IPv6 packets in the **CN->MN** direction:
  - CN:
    - Before sending a packet to MN, reads its Bindings cache;
    - If there is no entry -> packet sent as usual;
    - If there is an entry:
      - Sends packet to CareOfAddress (IPv6 destination address);
      - Includes in the packet a RoutingHeader having 2 hops (list of addresses to be visited by packet):
        - 1º hop -> CareOfAddress;
        - 2º hop -> MN HomeAddress;
  - MN:
    - Receives packet in CareOfAddress;
    - Forwards packet to itself (MN HomeAddress);
- IPv6 packets in the **MN->CN** direction:
  - Source address = CareOfAddress;
  - Inclusion of DestinationHeader with information about HomeAddress;
  - CN replaces HomeAddress in the packet source address so that the socket structure may contain the correct information -> HomeAddress;

7) Fast Handover in Mobile IPv6.

- Fast Handover is a protocol used to reduce combined latency due to the Mobile IPv6 handover operation;
- For the Fast Handover, MN needs to send packets as soon as it detects new link, and needs to deliver to MN as soon as its presence is detected by NAR; The solution is to keep the MN's previous CareOfAddress until it establishes L2 connection to its NAR; This also allows MN fast establishment of new COA;
- The main operation of the Fast Handover involves **setting up a routing path between old and new ARs to enable MN to send and receive IP packets**. This **tunnel establishment could be triggered either by MN or by network**. <u>Once the tunnel is established, packet forwarding through the tunnel to MN begins when PAR receives Fast Binding Update (FBU) message from MN</u>;

Wireless Local Area Networks

1) **Wireless LAN 802.11.**

➔ **Infrastructure Network:**
  - Station:
    - Terminal with radio access;
  - Basic Service Set (BSS):
    - Set of stations in the same channel;
  - Access Point (AP):
    - Interconnects LAN to wired network;
    - Provides access to stations;
  - Stations communicate with AP;
  - Portal -> bridge to other networks;
  - Distribution System:
    - Interconnection network;
    - Logical network (EES, Extended Service Set; Based on BSS);

➔ **Ad-Hoc Network:**
  - Direct communication between stations;
  - Independent Basic Service Set, IBSS:
    - Set of stations working in the same channel;
  - IBSS and BSS are virtual networks:
    - Multiple (I)BSS may co-exist in the same channel and same space;

➔ **Layers and Functionalities:**
  - Data plane:
    - MAC – medium access, fragmentation, encryption;
    - PLCP – Physical Layer Convergence Protocol -> convergence, carrier detection;
    - PMD – Physical Medium Dependent -> modulation, codes;
  - Management plane:
    - PHY Management – channel selection, MIB;
    - MAC Management – synchronization, association, mobility, power, MIB;
    - Station Management – coordination of management functions;

2) **MAC Layer:**

➔ **Access Methods:**
  - MAC-DCF (Distributed Coordination Function): CSMA/CA:
    - Carrier sense, collision avoidance using back-off mechanism;
    - ACK packet required for confirmations (except for broadcast packet);
    - Mandatory;
    - **Having a packet to transmit:**
      - Station having a packet to transmit senses the medium;
      - If the medium is free during one Inter-Frame Space (IFS):
        - Station starts sending the frame;
      - If medium is busy:
        - Station waits for the medium to become free + one IFS + random contention period (collision avoidance, multiple of slot -> n*20µs);
      - If other station accesses to the medium during the contention time:
        - Waiting timer is suspended;
    - **Sending a frame in unicast:**
      - Station waits DIFS before sending the packet;
      - If packet is correctly received (no errors in CRC):

            - Receiver confirms reception immediately, using ACK, after waiting SIFS;
        - In case of errors, frame is re-transmitted;
        - In case of <u>retransmission:</u>
            - Maximum value for the contention window duplicates);
            - Contention window has minimum and maximum values (7; 255);
- MAC-DCF with RTS+CTS:
    - Used to avoid hidden terminal problem;
    - Typically used before the transmission of long packets;
    - Optional;
    - **Sending a frame in unicast:**
        - Station sends RTS with a reserve parameter, after waiting DIFS;
        - Receiver confirms with CTS, after waiting SIFS;
        - Transmitter sends frame, after waiting SIFS. Confirmation with ACK;
        - Other stations become aware of reserved time by listening RTS and CTS;
- MAC-PCF (Point Coordination Function):
    - Polling;
    - Access Point controls order of transmission;
    - Optional (rarely used);

➔ **Guard Time Intervals:**
- DIFS (DCF IFS):
    - Lowest priority, used for asynchronous data;
- PIFS (PCF IFS):
    - Medium priority, used for real time traffic/QoS;
- SIFS (Short Inter Frame Spacing):
    - Maximum priority -> used for signalling: ACK, CTS, answers to polling;

➔ **Virtual Carrier Sensing – Network Allocation Vector (NAV):**
- How a station does knows if the medium is free?
    - Usually, by listening the carrier;
- IEEE 802.11 also uses **NAV**:
    - 802.11 frames contain a duration field; used to reserve the medium;
    - Stations have a timer **NAV**:
        - Updated with the values seen in the frames;
        - Decremented in real-time;
        - If != 0 -> medium not free;

➔ **Frame Format:**
- Frame types:
    - Data, control, management;
- Sequence number;
- Addresses:
    - Destination, source, BSS identifier, etc;
- Others:
    - Error control, frame control, data;
- Special Frames – ACK, RTS, CTS:
    - Acknowledgement (ACK);
    - Request to Send (RTS);
    - Clear to Send (CTS);

➔ **Management:**
- Synchronization and association:
    - Beacons are generated;
    - Station discovers a BSS; station associates to an AP;
    - Stations synchronize clocks;

- Synchronization by Beacon:
  - Infrastructure Network:
    - Stations must be synchronized:
      - To preview PCF cycles;
      - To change state: sleep<->wake;
    - Infrastructure networks:
      - Access Point sends (almost) periodically a **Beacon with timestamp and BSSid;**
      - Timestamp sent is the correct;
      - Other stations adjust their clocks;
  - Ah-Hoc Network:
    - Every station tries to send a **beacon**;
    - Stations use normal method to access the networks -> CSMA/CA;
    - Only one station gains the medium -> the others differ attempt to next period;
- Power management:
  - Save terminal's power -> terminal enters sleep mode;
    - Periodically;
    - No frame loss; frames are stored;
  - Objective:
    - If transceiver not in use -> sleep mode;
  - Station in 2 states: sleep, wake;
  - Infrastructure network:
    - Stations wake periodically and simultaneously;
    - They listen beacon to know if there are packets to receive;
    - If a station has packets to receive -> remains awake until it receives them;
      - If not, go sleep after sending its packets;
    - Traffic information sent in the beacon;
      - TIM (Traffic Indication Map) – list of unicast receivers;
      - DTIM (Delivery Traffic Indication Map) – list broadcast/multicast receivers;
  - Ad-Hoc Network (a station):
    - Listens/sends the beacon;
    - Informs other stations it has packets for them;
    - Receives and sends packets;
    - Sleeps again;
- Roaming:
  - Station moves and changes access points;
  - Station without or with bad link? Then:
    - Monitor the medium:
      - Passively -> listen to **Beacon;**
      - Actively -> sending **Probe** message in every channel, wait for answer;
    - Re-association request. Station:
      - Selects best access point;
      - Sends Re-association Request to AP;
    - Answer to request:
      - Success -> AP answered; station can use new AP;
      - Fail -> station continues monitoring;
    - New AP accepts Re-association Request:
      - AP informs distribution system about the new station arrival;

    - Distribution system may inform old AP about the new location of station;
- MIB – Management Information Base;

3) IEEE 802.11n:

- Operates in 2.4GHz and 5GHz bands;
- Radio transmission schemes:
    - May combine two 20MHz channels;
        - Form 48 subcarriers per 20MHz to 108 carriers per 40MHz;
    - Shorter 400ns guard band (11% increase in data rate);
    - Higher coding rate of 5/6 (11% increase);
    - 150Mbit/s per 40MHz, 600Mbps for 4 parallel streams;
- Space Division Multiplexing:
    - MIMO: Multiple parallel stream, beamforming or diversity;
    - Multiple independent data streams:
        - Transferred simultaneously in a channel;
        - Between discrete antennas at transmitter and receiver;
    - Maximum number if simultaneous data streams:
        - Limited by the minimum number of antennas in use on both sides of the link;
- MAC Layer:
    - Less Overhead;
    - Block acknowledgements: one ACK to cover multiple packets;
    - Frame aggregation;
- Forms of Frame Aggregation:
    - A-MSDU aggregation: shared PHY and MAC headers and FCS;
    - A-MPDU aggregation: shared PHY header:
        - Still keep separate MAC headers, to less header reduction;
        - But not as much to retransmit if there is no error;
    - A-MPDU and A-MSDU aggregation – balances the two;

4) IEEE 802.11ac:

- 802.11ac is an evolution from 802.11n;
- 802.11ac is pioneering a **multi-user** form of MIMO:
    - Enables an AP to send to multiple clients at the same time;
- Beamforming/Multi-User MIMO (MU-MIMO):
    - For receivers located in different directions:
        - Beamformed transmissions may be used;
        - To send information to each receiver, **at the same time**;

802.11n	802.11ac
Supports 20 and 40 MHz channels	Adds 80 and 160 MHz channels
Supports 2.4 GHz and 5 GHz frequency bands	Supports 5 GHz only
Supports BPSK, QPSK, 16-QAM, and 64-QAM	Adds 256-QAM
Supports many types of explicit beamforming	Supports only null data packet (NDP) explicit beamforming
Supports up to four spatial streams	Supports up to eight spatial streams (AP); client devices up to four spatial streams
Supports single-user transmission only	Adds multi-user transmission
Includes significant MAC enhancements (A-MSDU, A-MPDU)	Supports similar MAC enhancements, with extensions to accommodate high data rates

5) IEEE 802.11ad:

- Gigabit Wi-Fi:
    - Up to 7Gbit/s:
        - Replacement of wires for video to TVs and projectors;
    - Uses 60GHz bans:
        - Called millimetre waves (mmWave);
        - Fewer devices operate in these bands;
        - Higher free space loss;

    - Poor penetration of objects;
    - Likely only useful in a single room;
  - Very high bandwidth: 2160MHz;
  - Adaptive beamforming and high gain directional antennas:
    - Can even find reflections when direct path is obstructed;
  - Four modulation and coding schemes;
  - Personal BSS so devices can talk directly;

6) WLAN Security:

- ➔ Three points of attack:
  - Client;
  - Access Point;
  - Wireless medium;
- ➔ Original Wired Equivalent Privacy (WEP) was to weak:
  - 802.11i provided stronger Wi-Fi Protected Access (WPA);
  - Robust Security Network (RSN) is the final 802.11i standard;
- ➔ 802.11i Services:
  - Authentication through an authentication server;
  - Access control;
  - Encryption for privacy with message integrity;
  - <u>Phases of Operation:</u>
    - Phase 1 – Discovery;
    - Phase 2 – Authentication;
    - Phase 3 – Key Management;
    - Phase 4 – Protected data transfer;
    - Phase 5 – Connection termination;

Ad-Hoc, Mesh and Multihop Wireless Networks

1) What is an ad-hoc network?

- ➔ Layer 3, IETF, IP, Multi-hop;
- ➔ Wireless links;
- ➔ Mobile nodes -> dynamic network topology;
- ➔ Nodes forward IP packets;
- ➔ Routing protocols;
- ➔ Topology:
  - Dynamic; Depends on nodes position;
- ➔ Link Characteristics:
  - Bitrates may vary along the time;
- ➔ Asymmetric Links:
  - Received powers and attenuations may be unequal in the two directions;

2) What types of routing protocols are commonly used in ad-hoc networks?

- ➔ Conventional routing protocols are built for wired networks -> topology varies slowly;
- ➔ In Ad-Hoc networks, dynamic topology, information required to be refreshed more frequently;
  - Leads to energy consumption;
  - Radio resources are consumed in the transport of signalling messages;
  - Wireless node may have scarce resources;
- ➔ Two types of routing protocols:
  - Proactive routing;
  - Reactive routing;

- ➔ <u>Proactive Routing:</u>
  - This type of protocols maintains fresh lists of destinations and their routes by periodically distributing routing tables throughout the network. The main disadvantages of such algorithms are:
    - Respective amount of data for maintenance.
    - Slow reaction on restructuring and failures.
  - <u>Example: Optimized Link State Routing Protocol (OLSR);</u>
- ➔ <u>Reactive Routing:</u>
  - This type of protocol finds a route based on user and traffic demand by flooding the network with Route Request or Discovery packets. The main disadvantages of such algorithms are:
    - High latency time in route finding.
    - Excessive flooding can lead to network clogging.
  - However, clustering can be used to limit flooding. The latency incurred during route discovery is not significant compared to periodic route update exchanges by all nodes in the network.
  - <u>Example: Ad hoc On-Demand Distance Vector Routing (AODV);</u>

3) How does AODV work?

- ➔ Decision to request a route: when a packet has to be sent;
- ➔ Broadcast of <u>Route-request</u>;
- ➔ Intermediate nodes get routes to node A;
- ➔ <u>Route-reply</u> sent in <u>unicast</u> by same path;
- ➔ Intermediate nodes get also route to node B;
- ➔ Routes have <u>TTL</u>, in every node;
- ➔ Needs symmetric graph;

4) How does OLSR work? Why is the MPR important?

- ➔ Main functions:
  - Detection of links to neighbours nodes;
  - Optimized forwarding/flooding (MultiPoint Relaying);
- ➔ Detecting Links to Neighbour Nodes:
  - Using HELLO messages;
  - All nodes transmit periodically HELLO messages;
  - HELLO messages group neighbour by their state;
- ➔ **MultiPoint Relaying (MPR):**
  - Special nodes in the network;
  - Used to:
    - Limit number of nodes retransmitting packets;
    - Reduce number duplicated retransmissions;
  - Each node selects its MPRs, which must:
    - Be at 1 hop distance;
    - Have symmetric links to the node;
  - MPR set selected by a node:
    - Must be minimum;
    - Must enable communication with every 2-hop-away nodes;
  - Node is MPR if it has been selected by other node;
- ➔ Link State:
  - Only the MPR nodes send link state (Topology Control) messages
    - Smaller number of nodes sending signalling messages;
  - Only nodes associated to MPR are declared in link state message
    - Reduced message length;

5) What is a Wireless Mesh Network?

- IEEE, MAC, layer 2;
- Multi-hop;
- Used to extend the infrastructure; fixed backbone, mainly;
- Serve wireless stations;
- User-to-gateway traffic, mainly;
- Not energy limited;
- Wireless mesh cloud becomes a virtual switch;
- **Multiple traffic flows in a shared medium:**
  - Assume all nodes send the same traffic flow of **G** bit/s towards GW;
  - **B** (bit/s) is the capacity of wireless medium;
  - Forwarding implies that a frame is transmitted multiple times;
  - In a collision domain, only one frame at time is transmitted;
- **Routing:**
  - Wired layer 2 network (e.g. Ethernet):
    - Uses a single spanning tree;
    - Simple, but leads to sub-utilization of the network capacity;
    - <u>No shortest path for every pair of nodes;</u>
  - Wireless mesh network:
    - Aimed at using shortest paths (IP like networking);
    - Re-uses some IETF MANET routing protocols and concepts (AODV, OLSR, etc);
    - Operates at layer 2 and uses MAC addresses;
    - <u>Defines new routing metrics;</u>

6) What are the routing metrics employed in wireless mesh networks?

- <u>Expected Transmission Count (ETX):</u>
  - Successful transmission probabilities in forward/reverse link:
    - S_f: probability that data frame successfully arrives to recipient;
    - S_r: probability that ACK packet is successfully received;

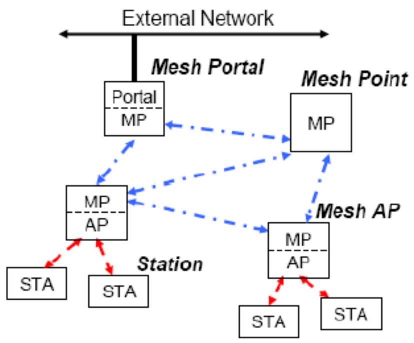
$$ETX = \frac{1}{S_f \times S_r}, \quad ETX \in [1, +\infty[$$

  - <u>EXT – mean number of times a data frame will be transmitted;</u>
  - Shortest path between two nodes:
    - Path having the minimum sum of ETXs;
- <u>Expected Transmission Time (ETT):</u>
  - Improves ETX by considering also link bandwidth;
  - Packet size: S, Link bandwidth: B;
  - ETT=ETX*S/B;
  - <u>ETT – mean time required to transmit a frame with success;</u>
  - Shortest path between two nodes:
    - Path having the minimum sum of ETTs;

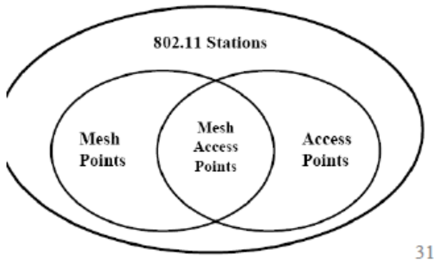
7) What technologies are adopting these techniques? Why?

- IEEE:
  - 802.11s – Mesh Networking in Wireless LAN;
  - 802.16j – Multihop Relay, WMAN;
  - 802.15.5 – Mesh Topology Capability in Wireless Personal Area Networks (WPAN);
- 3GPP:
  - Long Term Evolution;
  - Base stations interconnected through wireless links;

8) IEEE 802.11 Mesh Networking.



➔ **Devices in a WLAN Mesh Network:**
- Mesh Point (MP):
  - Establishes peer links with MP neighbours;
- Mesh AP (MAP):
  - MP collocated with AP;
  - Provides also BSS services to STAs;
- Mesh Portal (MPP):
  - Interfaces with the wired network;
- Station (STA):
  - Outside of the WLAN Mesh;
  - Connected via Mesh AP;



➔ **Topology Formation – Membership:**
- Mesh Points (MPs) discover neighbours:
  - Based on beacons and probe response frames;
    - New information elements (IEs);
      - Mesh ID;
      - WLAN Mesh Capability Element (routing protocol, metric);
- Secure peer links with neighbours;

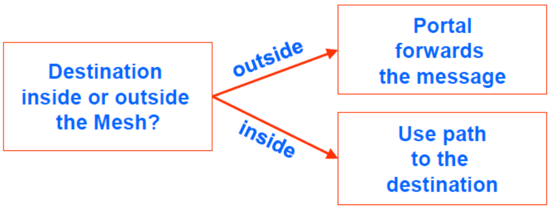
➔ **Mesh Association:**
- MP **X** <u>discovers</u> Mesh **mesh-A** with profile (**link state, distance vector, etc**);
- MP **X** <u>associates/authenticates</u> with neighbours in the mesh, since it can support the Profile;
- MP **X** begins participating in <u>link state path selection and data forwarding</u> protocol;
- <u>One active protocol in one mesh but alternative protocols in different meshes;</u>

➔ **Routing Schemes Supported:**
- <u>Hybrid Wireless Mesh Protocol (HWMP) – **mandatory;**</u>
  - Combines **proactive** and **on-demand** routing;
    - Proactive: Tree based routing, rooted at the Root Portal node;
    - On-demand: (Radio Metric) RM-AODV;
  - Uses Airtime Link Metric -> mandatory link metric defined in standard;
- <u>Airtime Link Metric:</u>
  - 802.11s default routing metric: **Airtime Link Cost:**
    - Amount of time c_a required to transmit a frame;
    - r = transmission bitrate;
    - e_{pt} = frame error ratio;

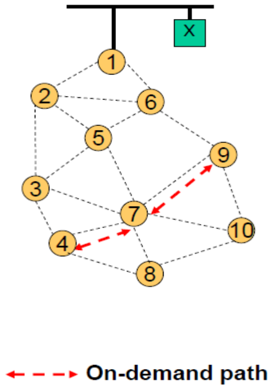
$$c_a = \left[O_{ca} + O_p + \frac{B_t}{r} \right] \times \frac{1}{1 - e_{pt}}$$

- <u>Tree Based Routing to Portal:</u>
  - Proactive part creates a unique spanning tree;
  - Tree creation:
    - The Root MP:
      - "broadcasts" PREQ with sequence number;
    - MPs:
      - May respond with PREP;
      - Update metric and rebroadcast PREQ;
    - Alternatively, Root MP broadcasts Root Announcement messages;
  - **MPs select best parent towards Root, based on path metric;**
  - Tree maintenance:
    - MPs monitor their upstream links;
    - Periodic RREQs sent to parents;
    - MPs may switch to backup links using RREP;
    - MP will notify its children;

- <u>Interworking – Packet Forwarding:</u>

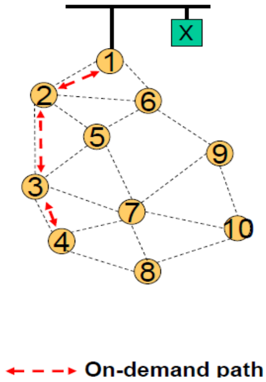


9) HWMP Examples:



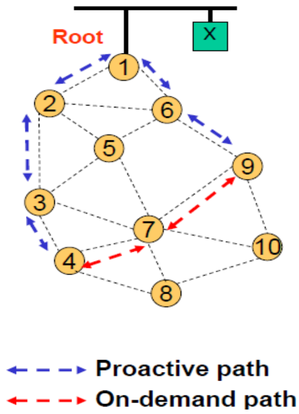
➔ 1 – <u>No Root</u>, Destination Inside the Mesh:

- Communication: MP4->MP9;
- MP4:
  - Checks its forwarding table for an entry to MP9;
  - If no entry exists, MP4 sends a broadcast RREQ to discover the best path to MP9;
- MP9 replies with unicast RREP;
- DATA communication begins;



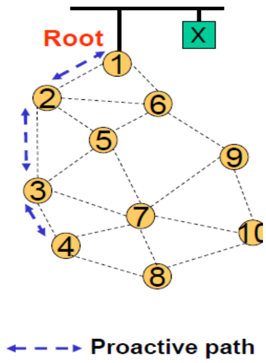
➔ 2 – <u>No Root</u>, Destination Outside the Mesh:

- Communication: MP4->X;
- MP4:
  - First checks its forwarding table for an entry to X;
  - If no entry exists, MP4 sends a broadcast RREQ to discover the best path to X;
  - When no RREP received, MP4 assumes X is outside the mesh and sends messages destined to X to Mesh Portal;
- Mesh Portal that knows X may respond with a unicast RREP;



➔ 3 – <u>Root</u>, Destination Inside the Mesh:

- Communication: MP4->MP9;
- MPs learn Root MP1 through <u>Root Announcement</u> messages;
- MP4 checks its forwarding table for an entry to MP9;
- If no entry exists, MP4 forwards message on the proactive path to Root MP1;
- When Mp1 receives the message, it forwards on the proactive path to MP9;
- MP9, receiving the message, may issue a RREQ back to MP4 to establish a path that is more efficient than the path via Root MP1;



➔ 4 – <u>Root</u>, Destination Outside the Mesh:

- Communication: MP4->X;
- MPs learn Root MP1 through Root Announcement messages;
- If MP4 has no entry for X in its forwarding table, MP4 may forward the message on the proactive path toward the Root MP1;
- When MP1 receives the message, if it does not have an active forwarding entry to X it may assume the destination is outside the mesh;
- Mesh Portal MP1 forwards messages to other LAN segments;

Wireless Personal Area Networks

1) IEEE 802.15.4 (WPAN) (Sensor Networks):

➔ **Introduction:**

- Low Rate WPAN (LR-WPAN):
  - Simple, low-cost communications network;
  - Wireless connectivity;
  - Applications with limited power and low throughout requirements;
- Characteristics of LR-WPAN:
  - Over-the-air data rates of 250kbit/s, 100kbit/s, 40kbit/s, 20kbit/s;
  - 64-bit addresses or allocated 16-bit short addresses;
  - Carrier sense multiple access with collision avoidance (CSMA/CA);
  - Low power consumption;
  - Energy Detection (ED); Link quality indication (LQI);
  - Radio channels:
    - 16 channels in the 2450 MHz band;
    - 30 channels in the 915 MHz band;
    - 3 channels in the 868 MHz band;

➔ **Types of Devices:**

- 2 types:
  - FDD – Full-Function Device:
    - Can operate in 3 modes: PAN coordinator, coordinator, device;
    - FFD can talk to RFDs or other FFDs;
  - RFD – Reduced-Function Device:
    - Intended for applications that are very simple (light switch, passive infrared sensor);
    - RFD can talk only to an FFD;
- WPAN shall include at least one FFD operating as the PAN coordinator;

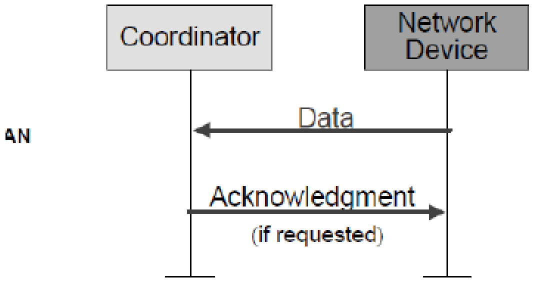
➔ **Topologies, Identifiers:**

- Topologies:
  - Star topology -> communication between devices and PAN coordinator;
  - Peer-to-peer topology -> devices may communicate directly; needs PAN coordinator;
- Identifiers:
  - Each device has a unique 64-bit address; short 16-bit addresses may be used;
  - Each PAN has an identifier;

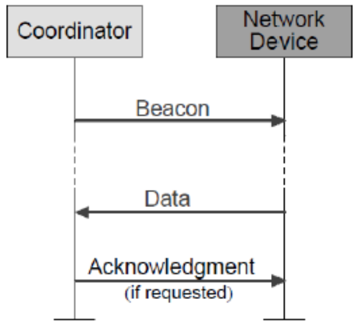
➔ **Architecture:**

- Physical layer (PHY):
  - Activation and deactivation of the radio transceiver;
  - ED, LQI, channel selection, clear channel assessment;
  - Transmitting and receiving data;
  - The radio operates at the following unlicensed bands:
    - 868–868.6 MHz (Europe);
    - 2400–2483.5 MHz (worldwide);
- MAC sublayer:
  - Beacon management;
  - Channel access;
  - Frame validation, frame acknowledgement;
  - Association and disassociation;
  - Hooks for implementing application-appropriate security mechanisms;

- **Superframe Structure:**
  - Superframe format:
    - Defined by the PAN coordinator;
    - Bounded by beacons;
    - Can have active and inactive portions;
  - Beacons used to:
    - Synchronize attached devices;
    - Identify the PAN;
    - Describe superframe structure;
  - Superframe may have 2 periods:
    - Contention access period:
      - Devices use slotted CSMA/CA mechanism;
    - Contention-free period (CFP):
      - Guaranteed timeslots (GTS) for devices;
  - If coordinator desires no superframe, it turns off beacon transmissions;
    - Unslotted CSMA/CA is used;



·Communication to a coordinator in a nonbeacon-enabled PAN



·Communication to a coordinator in a beacon-enabled PAN

MAC commands
- Association request and response
- Disassociation notification
- Data request
- Orphan notification
- Beacon request (in non-beacon enabled networks)
- GTS request
- Coordinator realignment
- PAN ID conflict notification

2) 6LowPAN:
- Problem:
  - IEEE 802.15.4 frame size is short: 127bytes;
  - IPv6 datagram:
    - Maximum Transmission Unit (MTU): at least 1280bytes;
    - IPv6 addresses: 128 bits;
  - Datagram in sensor networks may transport only few bytes of information;
    - Example: Temperature reading;
- 6LowPAN:
  - Compress IPv6 and UDP headers for low devices;

3) RPL – Routing Protocol for Low-Power and Lossy Networks:
- Low-power and Lossy Networks consist of constrained nodes:
  - Processing, memory, and energy;
- These routers are interconnected by links characterized by:
  - High packet loss ratio and low bitrate;

- ➔ Support multiple traffic patterns:
  - Point-to-point, point-to-multipoint, multipoint-to-point;
- ➔ In common situations nodes aim to send information to sink;
- ➔ Terminology:
  - A network may run multiple instances of RPL concurrently;
  - RPL operation demands bidirectional links;
- ➔ Control Messages:
  - DIO: DODAG Information Object:
    - Generated downward to announce an RPL instance;
    - Allows other nodes to discover an RPL instance and join it;
  - DIS: DODAG Information Solicitation:
    - Link-Local multicast request for DIO (neighbour discovery);
  - DAO: Destination Advertisement Object:
    - From child to parents or to root;
  - DAO ACK;
- ➔ Data Forwarding:
  - Case 1: To the root (n-to-1):
    - Packet addressed to root; each node in path delivers packet to its parent;
  - Case 2: X to Y:
    - 2A: Storing: Every node has a forwarding table:
      - Packet forward up from X to a parent common to X and Y;
      - Then, packet forwarded down from common parent to Y;
    - 2B: Non-storing: No forwarding tables except at root:
      - Packet forward up from X to DODAG root;
      - Root puts a source route on packet and forwards packet down to Y;
  - Case 3: Broadcast from the root (1-to-n):
    - 3A: Storing: Every node knows their children:
      - Broadcast to children;
    - 3B: Non-Storing: Every node knows only parents but not children:
      - Root puts a source route for each leaf and forwards;

3GPP Public Land Mobile Networks: GSM, GPRS

1) What is the architecture of the GSM network – network elements, interfaces, addresses, logical channels, protocol stack?

- ➔ **Services Provided by GSM:**
  - Basic services:
    - Voice services, short message service, data services;
  - Additional services:
    - Emergency number, group 3 fax;
  - Supplementary services:
    - Identification: forwarding of caller number;
    - Automatic call-back;
- ➔ **GSM Architecture – Public Land Mobile Network (PLMN):**
  - Radio Subsystem (RSS):
    - MS – Mobile Station:
      - Mobile terminal equipment;
    - BTS – Base Transceiver Station:
      - Transmitter, receiver and antennas;
    - BSC – Base Station Controller:
      - Control of several BTS and MS;

- Network Subsystem (NSS):
  - Data circuit switching, mobility management;
  - Interconnection to other networks, system control;
  - MSC – Mobile Switching Centre: circuit switching;
  - HLR – Home Location Register: associated to PLMN (telecom operator);
  - VLR – Visitor Location Register: associated to MSC;
  - GMSC – Gateway MSC: provides interconnection to other networks;
- Operation Subsystem (OSS):
  - Centralized operation, management and maintenance of GSM system;
  - OMC – Operation and Management:
    - Control of the radio and network subsystems;
  - AuC – Authentication Centre:
    - Executes security functions and contains security data;
  - EIR – Equipment Identity Register:
    - Registration and information on Mobile Stations;

➔ **Mobile Addresses:**
- IMSI – International Mobile Subscriber Identity:
  - Uniquely identifies the user; stored in the SIM card;
  - Composed by MCC + MNC + MSIN;
- MSISDN – Mobile Subscriber Integrated Services Digital Network Number:
  - The telephone number;
  - Associated to the service;
  - Stored in the SIM card;
- MSRN – Mobile Station Roaming Number:
  - A temporary location dependent ISDN number; generated by local VLR for each mobile station in its area;
  - Calls are routed to the MS by using the MSRN;
  - The MSRN has the same structure as the MSISDN;
- TMSI – Temporary Mobile Subscriber Identity:
  - 32 bits;
  - Local number allocated by VLR, may be changed periodically;
  - Hides the IMSI over the air interface; transmitted instead of IMSI;

➔ **Base Transceiver Station (BTS), Base Station Controller (BSC):**
- BTS executes radio related functions:
  - Radio channel coding and decoding;
  - Uplink signal measurements;
- BSC:
  - Switching centre for radio channels – switches calls from MSC to BTS;
  - Executes radio control functions;
    - Management of radio channels;
    - Traffic measurement;
    - Authentication;
    - Location registry, location update;
    - Handover management;

➔ **Mobile Switching Centre (MSC):**
- Switching of 64kbit/s channels;
- Paging and call forwarding;
- Location registration and forwarding of location information;
- Generation/forwarding of accounting and billing information;

- **Home Location Register (HLR):**
  - Central master database
    - Data from every user that has subscribed the operator;
    - One database per operator;
    - May be replicated;
  - HLR contains:
    - Subscriber data:
      - IMSI;
      - List of subscribed services with parameters and restrictions;
    - Location data:
      - Current MSC/VLR address;
- **Visitor Location Register (VLR):**
  - Local database:
    - Data on all users currently in the domain of the VLR;
    - VLR is associated to a MSC;
  - For each user, VLR has information on:
    - Subscriber identity:
      - IMSI;
    - Temporary addresses:
      - MSRN;
      - TMSI;
    - Temporary location:
      - LAI (Location Area Identification);
- **Burst Structures:**
  - Normal Burst: normal data transmission;
  - Access Burst: MS first time access;
- **Transmit Time Advance:**
  - Principle of operation:
    - Correct timing of uplink bursts are required to avoid overlapping at BTS;
    - Different path relays (MS-BTS distances) must be compensated;
    - Distant MS should transmit in advance so that its slot becomes time-aligned at BTS;
    - Transmission from the MS may be advanced 0-63 bits under BTS control;
    - Maximum cell radius is approximately 35km;
  - Initial ranging:
    - Access Burst is transmitted without time advance;
    - BTS measures path delay and sends required time advance on SACCH;
  - Then, MS introduces time advance on all bursts and uses Normal Bursts;
  - Adaptive control:
    - BTS monitors bursts and measures delays;
    - If path delay varies a new time advance is signalled on SACCH;
- **Power Control:**
  - Implemented on uplink and downlink;
  - Objective: lowest power level which provides desired quality (BER);
  - Procedure:
    - MS measures power received and BER and sends result on SACCH;
    - BTS sends new power level on SACCH, if and when necessary;
  - Channels with no power control - use maximum power for the cell:
    - Downlink BCH and CCCH: power set by BTS;
    - Uplink RACH;
      - BCCH broadcasts maximum power level for the cell;
      - MS uses this value to set RACH transmission power;

- **Protocol Layers for Signalling:**
    - CM (Connection Management):
        - Call control, short message service and supplementary service;
    - MM (Mobility Management):
        - Registration, authentication, location and handover management;
    - RR (Radio Resource Management):
        - Setup, maintenance and release of radio channels;
        - Control of radio transmission quality;
    - LAPDm ("Link Access Protocol D-channel" modified):
        - Modified version of ISDN LAPD protocol;
- **Security:**
    - Services:
        - Access control/Authentication:
            - User's SIM (Subscriber Identity Module) contain K_i, the subscriber secret authentication key;
        - Confidentiality:
            - Voice and signalling are encrypted on the wireless link;
        - Anonymity:
            - TMSI – Temporary Mobile Subscriber Identity;
            - Newly assigned at each new location update;
    - 3 algorithms specified in GSM:
        - A3 for authentication;
        - A5 for encryption;
        - A8 for key generation;

2) How are calls processed – Mobile Terminated Call, Mobile Initiated Call?

- **Mobile Terminated Call:**
    - 1: calling a GSM subscriber;
    - 2: forwarding call to GMSC;
    - 3: signal call setup to HLR;
    - 4, 5: get routing info (MSRN) from VLR;
    - 6: forward routing info to GMSC;
    - 7: route call to current MSC;
    - 8, 9: get current status of MS (LAI + TMSI);
    - 10, 11: paging of MS in location area;
    - 12, 13: MS answers paging and authentication request;
    - 14, 15: security checks;
    - 16, 17: set up connection;
- **Mobile Originated Call:**
    - 1, 2: connection and authentication request;
    - 3, 4: security check;
    - 5-8: check resources (obtain circuit);
    - 9-10: set up call;

3) How was GSM modified to support data transfer in GPRS?

- **GPRS – General Packet Radio Service:**
    - <u>Adds packet switching</u> to GSM:
        - Data transferred as packets;
    - Simplifies access to Internet;
    - Improves network efficiency;
- **Architecture:**
    - Addition of 2 new network elements: SGSN, GGSN;

- SGSN: Serving GPRS Support Node:
  - Authentication;
  - Packet switch;
  - Control of the logical link;
  - Mobility management;
  - Traffic accounting;
- GGSN: Gateway GPRS Support Node:
  - Router for the IPv4/IPv6 Internet;
- xGSNs network elements:
  - Interconnected by common packet network (e.g. IP over Ethernet);
  - Tunnels established between SGSN and GGSN – GTP (GPRS Tunnelling Protocol);

➔ **Terminal Attachment to GPRS:**
- Before using GPRS:
  - Terminal must perform Attach procedure;
- During Attach:
  - Network verifies if user is subscribed;
  - Subscriber profile transferred from HLR to SGSN;
  - Temporary packet identifier assigned to subscriber: P-TMSI;
- GPRS Attach may be combined with GSM attach;

➔ **Logical Channels:**
- Data channel:
  - PDTCH: Packet Data Traffic Channel; used to transfer data packets;
- Control channels:
  - Common:
    - PBCCH: Packet Broadcast Control Channel; BSS->MS network organization; relationship between logical and physical channels;
    - PRACH: Packet Random Access Channel; used by MS to request PDTCH;
    - PAGCH: Packet Access Grant Channel; used by BSS to grant PDTCH to MS;
    - PPCH: Packet Paging Channel; used by BSS to locate terminal;
  - Dedicated:
    - PACCH: Packet Associated Control Channel – channel associated to a PDTCH;
- If control channels, PDP, are unavailable, GSM control channels are used;

➔ **Protocol Architecture – Data Plane:**
- GTP – GPRS Tunnelling Protocol:
  - Tunnel: transports IP packets;
  - Used at the networks backbone;
  - GTP packets transported over UDP/IP;
- SNDCP – Subnetwork Dependent Convergence Protocol:
  - Packet transference between MS e SSGN;
  - Header compression, data protection;
- LLC (MS-SSGN):
  - Logical link connection between MS and SSGN; based on LAPDm (GSM);
  - In order delivery, flow control;
  - Acknowledge and not-acknowledge services;
- RLC:
  - Reliable link between MS and BSS;
  - Segments and reassembles LLC frames into RLC blocks;
  - ARQ of blocks;
- MAC:
  - Based on slotted Aloha;
  - Logical channels;

- PLL+RLF (Physical Link Layer):
  - Provide physical channel for data;
  - Error detection, FEC;
  - Modulation; same used in GSM;

4) What is PDP context?

➔ Establishment of a packet session (after successful Attach procedure):
- Terminal obtains IP address;
- PDP context is defined and stored in MS, SGSN and GGSN;

➔ PDP context contains:
- Type of external packet network (e.g. IPv4 or IPv6);
- Address assigned to the MS (e.g. IPv4 address);
- GGSN address (default gateway);

➔ GGSN makes the association between IMSI and IP addresses;

➔ Context created -> terminal reachable -> data can be transferred;

3GPP Public Land Mobile Networks: WCDMA, LTE

1) PLMN (Public Land Mobile Network):

➔ Is a network that is established and operated by an administration or by a Recognized Operating Agency (ROA) or the specific purpose of providing mobile telecommunications services to the public;

➔ PLMN is identified by the Mobile Country Code (MCC) and the Mobile Network Code (MNC);

➔ Each operator providing mobile services has its own PLMN;

➔ PLMNs interconnect with other PLMNs and Public switched telephone networks (PSTN) for telephone communications or with internet service providers for data and internet access of which links are defined as interconnect links between providers;

➔ **GSM PLMN:**
- The general objective of a PLMN is to facilitate wireless communication and to interlink the wireless network with the fixed wired network;
- Objectives:
  - To give access to the GSM network for a mobile subscriber in a country that operates the GSM system;
  - To provide facilities for automatic roaming, locating and updating of mobile subscribers;
  - To provide the subscriber a wide range of services and facilities, both voice and non-voice, which are compatible with those offered by existing networks like PSTN and ISDN;

2) WCDMA:

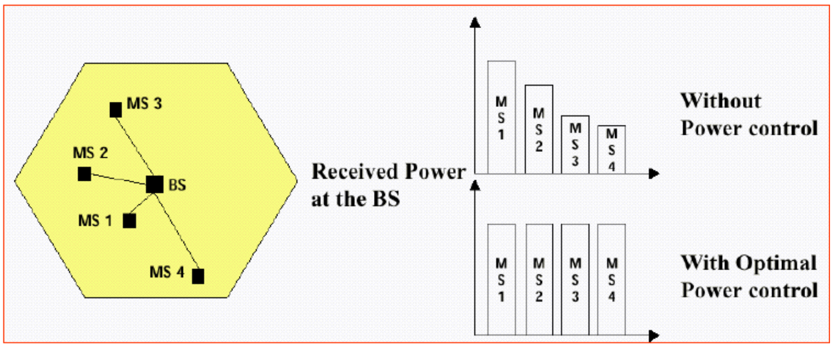
	WCDMA	GSM
Carrier spacing	5 MHz	200 kHz
Frequency reuse factor	1	1–18
Power control frequency	1500 Hz	2 Hz or lower
Quality control	Radio resource management algorithms	Network planning (frequency planning)
Frequency diversity	5 MHz bandwidth gives multipath diversity with Rake receiver	Frequency hopping
Packet data	Load-based packet scheduling	Time slot based scheduling with GPRS

➔ **Uplink Capacity – Maximum Number (N) of users:**

- Ideal power control (every signal received with same power);
- N users transmitting at bitrate R (bit/s);
- <u>E_b/I_o decreases -> BER increases;</u>

➔ **Power Control:**

- Enable equal powers to be received at the Base Station;
- Enable terminals to transmit at lowest possible power:
    - Low power -> low interference on other terminals -> more calls admitted;



- **Adaptation Mechanisms:**
    - <u>Open Loop Control:</u>
        - Used in the uplink during call establishment;
        - Power Tx determined based on the power Rx in common channel:
            - Power Tx by BaseStations are known -> terminal measures Rx power -> terminal calculates (down)link attenuation ->terminal assumes same attenuation in uplink;
        - Problem -> duplex in frequency -> different attenuations for both directions;
    - <u>Closed Loop Control:</u>
        - Frequent commands sent by Terminal/BS to increase/decrease Tx power one command per timeslot (1500 command/s);
        - SIR measurement -> comparison with SIR objective->request to increase/decrease Tx power;
    - <u>External Control:</u>
        - Determines SIR objective $(SIR)_{SET}$
            - Using session requirements: FER (Frame Error Ratio);

3) UMTS:

➔ **Network Architecture:**

- Architecture UMTS: UTRAN + core network;
- UTRAN – UMTS Terrestrial Radio Access Network;
- Core Network:
    - Circuit domain (CS) -> MSCs, GSM, ISDN, voice, video;
    - Packet domain (PS) -> xGSNs, GPRS, IP, Data;

➔ **Radio Interface:**

- <u>Protocols in the Radio Interface:</u>
    - Physical (PHY):
        - WCDMA, frame formats, modulations;
    - Medium Access Control (MAC):
        - Multiple access to shared channels;
    - Radio Link Control (RLC):
        - Segmentation | Flow control | Encryption;
    - Packet Data Convergence Protocol (PDCP):
        - Compression of IP headers (TCP/IP, RTP/UDP/IP);
        - Re-localization with no losses;

        - Broadcast/Multicast Protocol (BMC):
            - Broadcast of common information in non-confirmed node;
        - Radio Resource Control (RRC):
            - Broadcast of system information. Paging. Cell selection;
            - Establishment of the RRC connection;
            - Mobility of the RCC connection;
            - Power control in downlink;
            - Open loop power control;
    - <u>Dedicated Channel – Uplink;</u>
        - 1) Channel estimate + SIR estimate for PC;
        - 2) Detect PC command and adjust DL Tx power;
        - 3) 10ms frame: Detect TCFI;
        - 4) Interleaving: Detect Data;
        - DPCCH: dedicated control channel | DPDCH: dedicated data channel;
        - DPCCH and DPDCH sent respectively as In-phase and Quadrature components of modulation;
            - Pilot symbols -> used to estimate channel response and interference (SIR);
            - TFCI (Transport Format Combination Indicator) -> code, frame bitrate;
            - TPC (Transport Power Control) -> controls the power to be transmitted in downlink;
        - Different codes for DPCCH and DPDCH;
    - <u>Dedicated Channel – Downlink:</u>
        - QPSK Modulation;
        - DPCCH and DPDCH multiplexed in time;
        - Non-continuous data transmission;
    - <u>Dedicated Channel – Variable Bitrate in Uplink:</u>
        - DPDCH bitrate may vary from frame to frame (by changing the code);
        - High bitrates -> high transmission powers -> high interference;
        - Continuous transmission, independently of the bitrate;
    - <u>Dedicated Channel – Variable Bitrate in Downlink:</u>
        - DPDCH bitrate may vary from frame to frame;
        - Transmission at the maximum bitrate;
        - Low bitrates achieved using non-continuous transmission:
            - Low average power;

➔ **High-Speed Downlink Packet Access (HSDPA):**
- Introduction of a new transport channel:
    - HS-DSCH (High-Speed Downlink-Shared Channel;
- ARQ closer to the MS, at node B;
- Variable Spreading Factor and fast power control are disabled:
    - Substituted by Adaptive Modulation and Coding;
    - Usage of multiple simultaneous codes;

Channel	HS-DSCH	Downlink DCH	FACH
SF	Fixed, 16	Fixed, (512–4)	Fixed (256–4)
Modulation	QPSK/16QAM	QPSK	QPSK
Power control	Fixed/slow power setting	Fast with 1500 kHz	Fixed/slow power setting
HARQ	Packet combining at L1	RLC level	RLC level
Interleaving	2 ms	10–80 ms	10–80 ms
Channel coding schemes	Turbo coding	Turbo and convolutional coding	Turbo and convolutional coding
Transport channel multiplexing	No	Yes	Yes
Soft handover	For associated DCH	Yes	No
Inclusion in specification	Release 5	Release 99	Release 99

4) Long Term Evolution (LTE):

➔ **Purpose:**

- UTRAN – LTE:
  - Universal Mobile Telecommunication System (UMTS) terrestrial radio-access network (UTRAN) – Long Term Evolution (LTE);
  - Evolution of UTRAN;
- Aimed at providing:
  - All-IP packet switched network:
    - No support for circuit-switched voice!
  - High bitrates (tens, hundreds of Mbit/s);
  - Latency less than 5ms (between terminal and base station);
  - Handover in less than 1 RTT;
  - Use OFDM;

➔ **Evolved UTRAN Architecture – EPC/LTE:**

- EPC – Evolved Packet Core:
  - MME: Mobility Management Entity;
  - S-GW: Serving Gateway;
  - P-GW: Gateway for the Packet Data Network;
- E-UTRAN – Evolved UTRAN, known as LTE:
  - eNB – enhanced NodeB, base stations:
    - Based on OFDMA (instead of CDMA);
- Architecture simpler than 3G UTRAN:
  - EPC/LTE – 2 nodes in user-plane: eNB, S/P-GW;
  - 3G UTRAN – 4 nodes in user-plane: NodeB, RNC, SGSN, GGSN;
  - Consequences – new functions performed at eNB:
    - Radio resource control, admission control;
    - Ciphering and header compression;
    - Handovers between eNBs handled through X2 interface;

➔ **EPC (Evolved Packet Core) Components:**

- Mobility Management Entity (MME):
  - Supports user equipment context, identity, authentication, and authorization;
- Serving Gateway (SGW):
  - Receives and sends packets between the eNodeB and the core network;
- Packet Data Network Gateway (PGW):
  - Connects the EPC with external networks;
- Home Subscriber Server (HSS):
  - Database of user-related and subscriber-related information;
- Interfaces:
  - S1 interface between the E-UTRAN and the EPC:
    - For both control and data traffic;
  - X2 interface for eNodeBs to interact with each other:
    - For both control and data traffic;

➔ **Protocol Layers – Radio Interface:**

- Radio Resource Control (RRC):
  - Control of radio resources;
- Packet Data Convergence Protocol (PDCP):
  - Header compression, ciphering;
  - Integrity protection, in-sequence delivery;
  - Buffering/forwarding of packets during handover;
- Radio Link Control (RLC):
  - Segments or concatenates data units;
  - Performs ARG when MAC layer H-ARQ fails;

- Medium Access Control (MAC):
  - Performs Hybrid-ARQ (H-ARQ);
  - Prioritizes and decides which UEs and radio bearers;
    - Will exchange data on which shared physical resources;
  - Decides modulation format, code rate, MIMO rank, power level;
- Physical layer transmits the data;

➔ **Non-Access Stratum (NAS) Protocols:**
- For interaction between the EPC and the UE (User Equipment);
  - Not part of the Access Stratum that carries data;
- EPS Mobility Management (EMM):
  - Manage the mobility of the UE;
- EPS Session Management (ESM):
  - Activate, authenticate, modify and de-activate user-plane channels for connections between the UE, SGW and PGW;

➔ **Transmission and Duplex:**
- LTE downlink radio transmission:
  - Orthogonal Frequency-Division Multiplexing Access: OFDMA;
  - Narrow-band subcarriers of ~15kHz; bandwidth up to 20MHz;
- The LTE uplink radio transmission:
  - Single-carrier frequency division multiple access: SC-FDMA;
- Duplex: FDD or TDD;

➔ **Radio Resource Block:**
- Addressable in the time-frequency space:
  - Frequency domain 12 subcarriers, 180kHz;
  - Time domain sub-frames of 1ms;
- Resource Blocks are allocated to users/calls;
  - MIMO:
    - 4x4 in LTE, 8x8 in LTE-Advanced;
    - Separate resource grids per antenna port;
  - eNodeB assigns RBs with channel-dependent scheduling;
  - Multiuser diversity can be exploited:
    - To increase efficiency;
    - Assign resource blocks for UEs
      - With favourable qualities on certain time slots and subcarriers;
- Wide range data rates supported by:
  - Allocating resource blocks to users;
  - Using Adaptive Code-Modulation;

➔ **Physical Transmission:**
- Release 8 supports up to 4x4 MIMO;
- eNodeB uses PDCCH (Physical Downlink Control Channel) to inform UEs about:
  - Resource block allocations;
  - Timing advances for synchronization;
- UE determines a CQI index (modulation and code) that:
  - Provides the highest bitrate;
  - While mainting at most a 10% block error ratio;
- Convolution codes, 1/3 coding rate;
- Modulations: QPSK, 16QAM, 64QAM (6bit/symbol);

➔ **Power-On Procedures:**
- Power on the UE;
- Select a network;
- Select a suitable cell;
- Use contention-based random access to contact an eNodeB;

- Establish an RRC connection (for control);
- Attach: Register location with the MME; the network configures control and default EPS bearers;
- Transmit a packet;
- Mobile can then request improved quality of service. If so, it is given a dedicated bearer;

5) LTE-Advanced:

➔ **Key improvements:**

- Carrier aggregation;
- MIMO enhancements;
- Relay nodes;
- Heterogeneous networks involving small cells (femtocells, picocells, relays);

System Performance		LTE	LTE-Advanced
Peak rate	Downlink	100 Mbps @20 MHz	1 Gbps @100 MHz
	Uplink	50 Mbps @20 MHz	500 Mbps @100 MHz
Control plane delay	Idle to connected	<100 ms	< 50 ms
	Dormant to active	<50 ms	< 10 ms
User plane delay		< 5ms	Lower than LTE
Spectral efficiency (peak)	Downlink	5 bps/Hz @2×2	30 bps/Hz @8×8
	Uplink	2.5 bps/Hz @1×2	15 bps/Hz @4×4
Mobility		Up to 350 km/h	Up to 350—500 km/h

➔ **Carrier Aggregation:**

- LTE-Advanced may have 100MHz:
  - Combine up to 5 Component Carriers (CCs);
  - Each CC can be 1.4, 3, 5, 10, 15, or 20MHz;
  - Up to 100MHz;
- Three approaches to combine CCs:
  - Intra-band Contiguous:
    - Carrier adjacent to each other;
  - Intra-band non-contiguous:
    - Multiple CCs belonging to the same band used in a non-contiguous manner;
  - Inter-band non-contiguous:
    - Use different bands;

➔ **Enhanced MIMO:**

- Expanded to 8x8 for 8 parallel layers;
- Or multi-user MIMO:
  - Can allow up to 4 mobiles to receive signals simultaneously;
  - eNodeB can switch between single user and multi-user every subframe;

➔ **Relaying:**

- Relay nodes (RNs) extend the coverage area of an eNodeB:
  - Receive, demodulate and decode the data from a UE;
  - Apply error correction as needed;
  - Then transmit a new signal to the base station;
- RN functions as a new base station with smaller cell radius;

➔ **Heterogeneous Networks:**

- Difficult to meet data transmission demands in densely populated areas;
- Small cells provide low-powered access nodes:
  - Operate in licensed or unlicensed spectrum;
  - Range of 10m to several hundred meters indoors and outdoors;
  - Best for low speed or stationary users;
- Macro cells provide typical cellular coverage:
  - Range of several kilometres;

- Best for highly users;
- Femtocell:
  - Low-power, short-range self-contained base station;
  - In residential homes, deployed and use the home's broadband for backhaul;

Quality of Service in Wireless Networks

➔ **Quality of Experience:**
- Evaluated by panels:
  - Mean Opinion Score (MOS);
- Measured objectively:
  - Selection of Key Quality Indicators or Quality of Service parameters;

Layer	Indicators / Parameters	
	VoIP	Video streaming
Application	R-factor, speech distortion, acoustic echo, SNR speech, latency speech	PEVQ, PSNR, frame rate, pixilization, video frame loss, lip-sync, contrast
Network (packet switched)	*Packet Delay, Packet Loss Ratio, Throughput*	

➔ **UMTS/LTE Bearer Service – QoS Parameters:**
- Packet Loss Ratio;
- Transfer delay, P(D<TransferDelay)>=0.95;
  - Maximum delay guaranteed for 95% of packets;
- Guaranteed Bit Rate (GBR):
  - Policed by token bucket (GBR, MaxSDUsize);
- Maximum Bit Rate (MBR):
  - Policed by token bucket (MBR, MaxSDUsize);

➔ **UMTS Traffic Classes:**
- Conversational class:
  - Guaranteed bitrate, guaranteed delay (low), high packet loss ratio;
- Streaming class:
  - Guaranteed bitrate, guaranteed delay (high), high packet loss ratio;
- Interactive class:
  - Priorities (instead of guarantees), low packet loss ratio;
- Background class:
  - No guaranteed, Lowest priority, low packet loss ratio;

➔ **UMTS Radio Resources:**
- UMTS uses Code Division Multiple Access;
- Simultaneous transmissions possible by using orthogonal codes;
- Transmitted power causes also interference;
- Transmitted powers have to be managed;
- **Management:**
  - Packet Loss Ratio
    - Used to define $\mathbf{P_t}$; PLR->BER->$(E_b/N_0)_j$->SNIR->P_r->P_t;
  - Guaranteed Bit Rate:
    - Used to control total interference (load) in cell;
  - Transfer delay:
    - Used to define ARQ operation mode (acknowledged, non-acknowledged);

QoS Class	*Conversational*	*Streaming*	*Interactive*	*Background*
Admission control	*Yes*		*No*	
Transport channels	*Dedicated (code)*		*Shared*	
Scheduling	*Non-scheduled*		*Scheduled by packet scheduler*	

- **UMTS Admission Control:**
  - Arrival new flow **j** characterized by $\mathbf{R_j}$ (bit/s);
  - New flow **j** is admitted if $\boxed{\eta + L_j < \eta_{\max}}$
- **LTE Traffic Classes:**
  - GBR:
    - Guaranteed bitrate, low guaranteed delay, high packet loss ratio;
  - Non-GBR:
    - No bitrate guarantees, low packet loss ratio;
- **LTE Radio Resources:**
  - LTE uses OFDMA;
  - Time x Frequency space;
  - Radio Block RB;
  - Blocks are allocated to flows;

Mobility Management

1) What is the functionality associated to Mobility Management?

- **Mobility Management:**
  - Enables network to be aware of the terminal location;
  - Maintains the route/connection when terminal moves;
  - Consists of 2 main functions:
    - Location management:
      - Location registration/update:
        - Terminal informs network about its current Access Point (regularly);
        - Network updates terminal location;
      - New Call/Session/Data delivery:
        - When a new Call/Session/Data arrives to terminal's home network:
          - Network is requested to find the terminal location either by querying location databases or by paging the terminal;
    - Handoff management:
      - Maintains terminal connection/routes when terminal moves;
      - Initiation: need for handoff identified;
      - New connection/route generation:
        - Radio Resources found for the handoff connection:
          - In Network-Controlled Handoff (NCHO) -> the network finds the resources;
          - In Mobile-Controlled Handoff (MCHO) -> terminal finds resources, network approves;
        - Routing operations performed;
      - Data-flow control: delivery of data from old to new path, maintaining QoS;

2) Micro-mobility solutions defined by IETF.

- **Micro-mobility solved at the IP Layer:**
  - Micro-mobility -> frequent movements in an IP domain;
  - Problems of using Mobile IPv6 in micro-mobility scenarios:
    - Time to detect the new network;
    - Time for the terminal to configure COA (Care of Address);
    - Time to update new location (BindingUpdate) near the HomeAgent;
    - Frequent movement -> lots of signalling;

- Micro-mobility solutions:
  - <u>FastHandover;</u>
  - <u>ProxyMIP;</u>

➔ **Fast Handover in MIPv6:**
- MN learns about new router (NAR) while connected to previous router (PAR):
  - Fast detection of the New Access Router (NAR);
  - Auto-configuration of the new COA can be while MN is associated to PAR;
- MN can move to NAR <u>and exchange packets</u>:
  - Using PAR: Tunnel PAR-NAR;
  - While BindingUpdate for nCOA (MIP6, HomeAgent, CNs) is being performed;
- <u>Predictive Handover:</u>
  - MN discovers NAR:
    - Using layer 2 mechanisms (e.g. scan);
    - By exchanging messages:
      - RouterSolicitationforProxyAdvertisment (RtSolPr);
      - ProxyRouterAdvertisment (PrRtAdv);
  - MN forms NCOA:
    - After receiving PrRtAdv;
  - MN requests tunnel establishment between PCOA and NCOA:
    - By sending FastBindingUpdate (FBU) to PAR;
  - MN starts exchanging packets through NAR:
    - After sending Unsolicited Neighbour Advertisement (UNA) to NAR;
- Fast Handover is Combined with MIP6:
  - MNs <u>shall also execute MIPv6 BindingUpdate</u>, so that packets can be sent directly to NAR;

➔ **Proxy MIPv6:**
- MN <u>mobility is managed by the network;</u>
- MN moves and <u>believes it continues in the same (host) link;</u>
- Router in new link emulates the behaviour of router in home link;
- MAG is the MN proxy;
  - MAG – Mobile Access Gateway – Access router with proxy mobility function;
  - LMA – Local Mobility Anchor – Home Agent;

3) Mobility management in 3GPP networks – GSM:

➔ **Four types of Handover:**
- Between different sectors of the same cell;
- Between different cells within the same BSC domain;
- Between different BSC domains within the same MSC domain;
- Between different MSC domains;

➔ **Mobile-Assisted Handover (MAHO):**
- MS scans, measures and reports power received from several RF carrier based on BCCH information;

➔ **Location Update:**
- MS is aware of location:
  - BTS broadcasts <u>Location Area Identification (LAI)</u> on BCCH;
  - SIM stores current LAI;
- Events which determine a <u>current location update:</u>
  - MS is switched on and current LAI equals the stores LAI;
  - A timer set by the network expires and MS reports position;
- Events which determine a <u>new location update</u>:
  - MS is switched on and current LAI differs from stored LAI;
  - MS enters a new location area;

4) Mobility management in 3GPP networks – LTE:

➔ **LTE Handover Principles:**

- Handovers are network controlled:
  - E-UTRAN decides when to make the handover and what is the target cell;
- Handovers are based on the UE measurements;
- Handovers in E-UTRAN aim to be <u>lossless</u>:
  - By using <u>packet forwarding between Source eNodeB and Target eNodeB;</u>
- Core network updated <u>after radio handover is completed:</u>
  - The <u>late path switch</u> concept;
  - Core network has no control over handovers;