Chapter 3

Network Technologies

3.1. Local connectivity and networks

Local connectivity means that two or more than two devices communicate one with each other within a geographically limited area. Networks composed by such entities are known as Local Area Networks (LAN). LANs have been increasing in complexity in the last decade. Initially, a LAN was only constituted of computers in a controlled environment, like an office or a home, with the aim to share resources (i.e. printers, disk space) and enable the communication between them. Today, however, the equipments or nodes that can participate in a LAN have varied substantially, from personal computers (PCs) to Personal Digital Assistant (PDAs), mobile phones, various types of sensors, even Radio Frequency IDentification (RFID) chipsets. As a consequence, numerous LAN technologies have appeared so as to connect such heterogeneous devices in a local environment, involving hardware and software components.

Subsequent sections will be focused on the different LAN technologies that have been developed to cover home user requirements, with the aim to illustrate the

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principal alternatives that can be deployed in a home environment. The analysis will start with a brief background about the relationship between existing technologies.

3.1.1. Background of LAN technologies

Ethernet is the most widely deployed technology for high-performance in LAN environments. Although its origins date back to 1972, it was ratified by the Institute of Electrical and Electronics Engineers (IEEE) in 1983 only, under the name of "IEEE 802.3 10BASE5", shortened to 802.3. The first specification of the standard achieves data rates up to 10Mbps, supporting a variety of physical implementations (i.e. coaxial cable, Unshielded Twisted Pair - UTP - and optical fiber). Several evolutions of the technology are mainly designed to increase the peak data rate, with results over 100Mbps and 1Gbps for Fast Ethernet and Gigabit Ethernet, respectively. With the ambition to increase the initial 10Mbps data rates of Ethernet, an alternative technology based on optical fiber emerged. The American National Standards Institute (ANSI) committee X3-T9 standardizes in 1990s the Fiber Distributed Data Interface (FDDI), a technology for data transmission over fiber optic lines in a LAN, with a range up to 200Km. FDDI (Also known as ISO 9384) uses two fiber rings, one of them for data transmission and another for backup, achieving a maximum data rate of 100Mbps over the first of them, although it is possible to extend this value up to 200Mbps if the backup ring is used to carry data. However, Ethernet achieves the same data rates as FDDI at lower cost, making it a more popular option than FDDI.

Yet, the deployment of wired technologies is difficult and costly. Moreover, in a home environment, the network is usually fixed once installed, unless the user moves the cables physically. This makes wired networks less resilient to changes, which is a problem in a home environment populated by mobile devices (e.g. laptops, PDAs). Wireless local area networks (WLAN) have been developed to solve such problems, since stations communicate one with each other through the air interface. As a prominent feature, wireless technologies allow the stations to stay connected to the network as long as they are in the coverage area (which may be the entire house). This gives high flexibility to the user for moving from one room to another, while accessing to a service.

The most popular WLAN technology in home networking is the IEEE 802.11x family of standards, known commonly under the name of Wi-Fi (Wireless Fidelity). Since the first 802.11 specification published in 1997, the maximum data rates have varied from 1-2Mbps in earliest versions to 600Mbps in latest versions (802.11n). In addition, laptops have integrated some variants of this technology, such as 802.11b/g and 802.11n more recently. Furthermore, routers can be easily extended to be operative for 802.11x, which fosters its expansion in digital home networks. Nevertheless, Wi-Fi was developed with the aim of achieving the same data rates of wired technologies, and the energy consumption of the protocols was not considered as a major priority. As a result, Wi-Fi is not very suitable to connect small devices with restricted power resources (e.g. mobile phones).

To bring a wireless answer for this type of devices, an alternative to Wi-Fi is Bluetooth, invented by Ericsson in 1997 and managed by the Bluetooth Special Interest Group (SIP). Bluetooth is a technology developed for wireless personal area networks (WPAN), allowing two devices to connect one with another over a point-to-point WLAN. Moreover, one device can be able to discover and view any other devices located in the Bluetooth coverage area specified by the technology. This technology, thanks to its high usability, has been integrated in a large amount of commercial products, from PCs to mobile phones, even in smalls MP3 players. Bluetooth can be used for data transmission in short-distances with low power consumption, but without reaching high data rates.

One solution to perform high-speed communications with efficient power consumption is UltraWideBand (UWB). Such technology is suitable for power-constrained mobile devices with rich multimedia needs (i.e. PDAs, mobile phones), on short distances. In spite of the multimedia benefits, this technology has not been welcomed by the market as well as Bluetooth, and, actually most of its implementations are for High Definition TV (HDTV) and Digital Light Processing (DLP) video projection. Nonetheless, for some devices (e.g. sensor devices) UWB is very demanding and cannot be optimally implemented. In order to satisfy the needs of those devices, IEEE ratified in 2003 the first version of the 802.15.4 standard. This standard is a low-cost and low-power consumption protocol for wireless local area networks. This solution is not optimal for transmitting large amounts of data, but it is ideal for applications such as house monitoring, where data transmission is both sporadic and limited. In fact, the battery life of devices that make use of this standard can range from days to years.

3.1.2. Ethernet

Ethernet references a family of packet-switched wired technologies for local area networks. Its origin dates back to 1972 when Xerox PARC developed the Alto Aloha

Network, an experimental system to interconnect Xerox Alto computers, servers and printers. The next year, the name was changed to Ethernet (based on the "ether" concept, a deprecated theory of electromagnetic waves propagation) to clarify that the network could support any computer [SPU 00]. Up to now, the original technology has undergone several evolutions (i.e. Ethernet, Fast Ethernet, Gigabit Ethernet and 10GB Ethernet), which differ in the peak data rate as well as other characteristics (presented later), but share the same frame format, frame length and the 48-bit address scheme and provide backward compatibility. The technology is maintained and standardized by the IEEE 802.3 Working Group [IEE 10]. In spite of its age, and even in the wireless era, Ethernet is one of the most widely implemented LAN standards.

The original Ethernet provides 10 Mbps and supports several physical implementations (i.e. coaxial cable, UTP and optical fiber), which use either bus or star network topologies. In order to prevent and detect collisions in the shared physical medium, the CSMA/CD access control protocol was selected. The maximum network length was initially determined by signal attenuation in the wire (e.g. in the popular coaxial cable, implementations had a limit of 500m in 10Base 5 and 185m in 10Base2). Repeater devices can be used to increase this limitation, although the maximum network length was limited by design decisions about the minimum frame length, nominal speed and by the CSMA/CD protocol, which requires that, in case of collision, the signal reaches the receiver and returns to the sender before the frame transmission ends.

Since the first Ethernet release, several improvements have been introduced. In the bus network topology, all the nodes share the same physical medium, therefore they have to compete with the other nodes to send their data and their transmissions are vulnerable to collisions. The introduction of multiport bridge devices enabled the division of the network in several domains (as many as ports) so that the bandwidth was only shared with the nodes in the same domain and the number of collisions thereby reduced. Switched Ethernet networks took this approach further as every node is directly connected to the switch and collisions may accordingly occur between two devices only. Furthermore, full-duplex communications, which allow transferring data in both ways simultaneously, duplicated the effective bandwidth of each domain and turned the CSMA/CD protocol unnecessary.

Fast Ethernet increases the nominal rate to 100 Mbps and supports star, but not bus topologies with both semi-duplex and full-duplex configurations. It maintains the CSMA/CD protocol due to backwards compatibility, although it is not really necessary in full-duplex configurations. An autonegotiation feature was added, which allows the devices to negotiate the speed and operation mode. The subsequent

Ethernet Gigabit further increases the data rate to 1Gbps. CSMA/CD is no longer used in full-duplex mode, as it only allows point-to-point and switched star topologies where collisions cannot occur. As a result, the maximum length of a segment is determined by signal attenuation in the physical medium. The half-duplex mode still allows the use of hub devices and maintains the CSMA/CD access control method. The latest 10GB Ethernet supports up to 10 Gbps and includes compatibility with other technologies such as Frame Relay and ATM. Only full-duplex mode is supported and CSMA/CD is finally deprecated.

Although home networks are turning, to a great extent, towards wireless technologies, there are several features of wired-based Ethernet networks which should be still considered. Home wireless technologies use unlicensed frequency bands such as ISM which are a crowded portion of the electromagnetic spectrum. Even considering an individual wireless technology, the stations have to share the physical medium, therefore leading to lower effective bandwidth, collisions and retransmissions (like in the early Ethernet days). Based on a guided and dedicated transmission media, switched Ethernet networks in full-duplex mode avoid the possibility of collisions in the cable and nodes do not have to compete to access the media, which turns into a higher effective bandwidth and a more reliable network, especially in higher load scenarios. In switched networks, frames are not visible by all the network nodes, but only by the routing devices from sender to receiver, which conceptually increases data privacy (although security mechanisms are required to avoid possible attacks). Last, but not least, historically, Ethernet networks have provided higher data rates than their wireless alternatives. In particular, at the time of this writing, Ethernet Gigabit network adapters are included in most actual Ethernet-capable devices and 10GB Ethernet adapters have been commercially available for years while well-known wireless technologies have not reached yet the gigabit barrier. However, Ethernet solutions require the deployment of wires, which increases the installation and maintenance costs. As a result, digital homes should consider the deployment of Ethernet networks as the backbone network, or in applications and services which would benefit from the presented features of the technology.

3.1.3. IEEE 802.11x

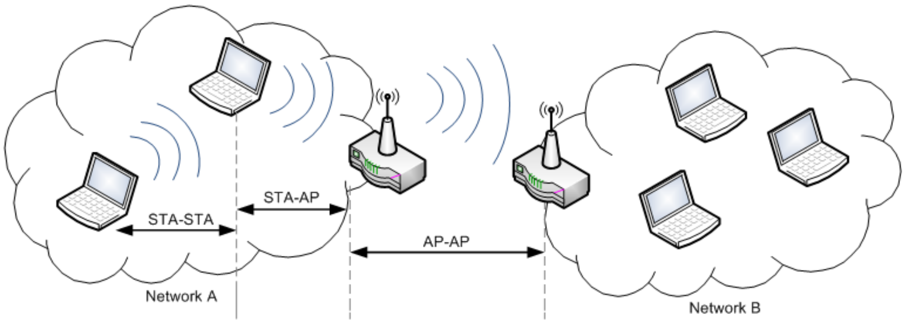

Figure 3.1. *802.11 Entities*

The purpose behind the IEEE 802.11x family of standards is to build a LAN without wires but sharing characteristics similar to the widely adopted Ethernet. In fact, the interoperability between both standards is crucial for enabling the use of 802.11 without major challenges in the devices used for the transmission. As a result, both standards share the same Logical Link Control (LLC) layer, and the 802.11 standard focuses on designing Physical (PHY) and Medium Access Control (MAC) layers that can make use of the air as the transmission medium.

As shown in Figure 3.1, the architecture of 802.11 involves two types of entities: stations (STA) and access points (AP). The stations (e.g. laptops, PDAs) are the endpoints of the communication in a Wi-Fi network. The communication between the stations can be performed directly without the use of an infrastructure (Ad-Hoc) or through a third-party entity, the access point (AP). This is a static device (e.g. Wi-Fi router) that forwards the data from a STA to another one in the network. Moreover, APs are usually connected to wired networks (e.g. Internet access points in a household). The architecture defines the communication between the following pair of entities: STA-STA, STA-AP and AP-AP. In general, APs are devices with higher range of transmission than STAs. Therefore, although STAs could communicate with other stations within their range, the use of APs enables the communication with out-of-range stations. In other words, the STA-AP communication can increase the coverage area for the station, since the AP can reach devices at longer distances than the station. The AP-AP communication is used to forward messages between networks. We have to notice that the use of an AP instead of a direct communication increases the overhead of the network, since data has to be transmitted through the AP. Due to this, the throughput decreases as the system spends more time to send the same data. The 802.11e defines the STA-STA direct communication, instead of passing through an AP, when the stations are within the same network [SAU 06].

	Ratified	Methods (PHY)	Methods (MAC)	Speed(min-max)	Spectrum
802.11	1997	DSSS	CSMA/CA	1-2Mbps	2.4GHz
802.11a	1999	OFDM	CSMA/CA	6-54Mbps	5GHz
802.11b	1999	HR/DSSS	CSMA/CA	1-11Mbps	2.4GHz
802.11g	2003	OFDM	CSMA/CA + RTS/CTS	1-54Mbps	2.4GHz
802.11n	2009	OFDM+MIMO	CSMA/CA + frame aggregation	1-600Mbps	2.4/5GHz

Table 3.1. *IEEE 802.11 Standards*

The initial specification for 802.11 uses the direct sequence speed spectrum (DSSS) modulation technique to provide a maximum data rate of 2Mbps in the 2.4GHz band at the PHY level. The solution adopted in 802.11 for the MAC level is the carrier sense multiple access collision avoidance (CSMA/CA) method, which checks the status of the channel before initiating the transmission. However, once a transmission has started, it is not possible to detect a collision [RAC 07], and thus the overall performance decreases. There is another factor that influences over the performance of this standard and any other standards that are compatible to it: the physical layer convergence procedure (PLCP) headers. These headers synchronize the sender and the receiver and provide information about e.g. the data transfer speed. As a result, the PLCP header should be transmitted at the minimum data rate.

Both the 802.11b and 802.11g revisions of the standard make use of the same unlicensed band (2.4 Ghz), but they can be able to increase the maximum data rate by changing the modulation scheme. On the one hand, 802.11b (1999) is the first revision of the standard used in commercial devices [OLE 05][RAC 07], and was developed to be used in short range networks, with a maximum speed of 11Mbps achievable using the High Rate DSSS (HR/DSSS) scheme. On the other hand, 802.11g (2003) achieves data rates up to 54Mbps using the orthogonal frequency division multiplexing (OFDM) scheme, but can interoperate with 802.11b devices if necessary. This interoperability is achieved by decreasing the maximum speed for 802.11g devices from 54 Mbps to 11Mbps, and by introducing additional countermeasures to avoid potential collision problems: the Request to Send (RTS) and Clear to Send (CTS) messages [RAC 07][BRO 03]. There are two ways in which these messages can be used. First, a station can send a CTS packet (known as CTS-to-self message) in order to announce an upcoming data transmission. Second, in the RTS/CTS mode, the station first sends a RTS message, and waits for a CTS message from the access point before starting the data transmission. These mechanisms will preclude 802.11b clients from transmitting simultaneously with 802.11g clients, thereby avoiding collisions that decrease throughput due to retries.

Like 802.11g, the 802.11a specification (1999) reaches data rates up to 54Mbps using OFDM, but is based on the 5GHz UNII (Unlicensed National Information Infrastructure) band, shared by other technologies like satellite communications [RAO 09]. IEEE 802.11a does not need to ensure backward compatibility in such band, and as a result the overall performance is better but the standard is not compatible with 802.11b/g. A balance between performance and compatibility is achieved in the 802.11n specification ratified in 2009: not only it achieves data rates up to 600Mbps using OFDM in conjunction with MIMO technology, but also maintains backward compatibility with 802.11a/b/g by using both 2.4GHz and 5GHz bands. One of the keys for achieving the 802.11n data rate is the usage of multiple transmitter and receiver antennas (MIMO), spatially separated. That is, both sender and receiver can use multiple directional antennas for transmitting each data stream through a different antenna and in a specific direction. This increases the throughput compared to previous specifications due to a more efficient use of the radiofrequency spectrum. For example, in order to achieve 600Mbps, a 4x4 configuration (4 transmitters and 4 receivers) is required. Finally, the "frame aggregation" feature added at the MAC level allows to group several data frames in a single large frame, reducing the overhead caused by the radio preamble and other frame fields [CIS 09].

3.1.4. Bluetooth

Bluetooth is a short-range wireless communication technology which enables the connection of devices in the user's personal space (i.e. up to 10m in most scenarios). The initial purpose of Bluetooth was to replace the cables required to connect computers with peripheral devices and mobile phones with headsets. However, the technology has spread into a wide range of portable and fixed devices enabling several applications, which will be presented later. Originally invented by Ericsson in 1994, the name was inspired by the 10th century Danish King Harald Blåtand (Bluetooth in English). Under the reign of this king, different warring factions collaborated with each other, and by using Bluetooth, different devices from different companies and industries can collaborate with each other. Nowadays, the technology is developed and administered by the Bluetooth Special Interest Group (SIG) association [BLU 10] which involves the promoters Ericsson, Intel, Lenovo, Microsoft, Motorola, Nokia, and Toshiba, as well as more than 13.000 associates or adopted companies.

Bluetooth is oriented as a low power and low cost, but robust technology. It uses the frequency range 2.4-2.485 GHz, which belongs to the industrial, scientific and medical (ISM) band, unlicensed and available worldwide. The communication range and transmission power depend on the class of radio implemented. The most widespread Class 2 radio, commonly found in portable devices and computers, provides a 10m range with 2.5mW; while Class 1 (focused in industrial scenarios) provides 100m with 100mW and the more restricted Class 3 provides 1m with 1mW. Regarding its data rate, it provides up to 3 Mbps data rate in Bluetooth v2.0+EDR. Version 3.0 allows up to 24 Mbps, but in order to achieve this performance, this version includes the Protocol Adaptation Layer (PAL) that makes use of the 802.11 channel (with the connection being initiated and negotiated over Bluetooth). Version 4.0 includes a novel mode for low speed, ultra-low energy operation, and consumes from one hundredth to one half of what consume previous versions.

In order to establish a communication, a Bluetooth-enabled device must belong to one (or more) “piconets”. A piconet is an ad hoc and dynamic network comprised of a master node and up to seven active slaves. The master provides the synchronization reference for the frequency hopping pattern followed by all the piconet nodes and it controls medium access by inquiring each slave device in a round-robin fashion. The master maintains a communication channel with each slave, but slave nodes cannot establish direct connections between them. This size-limited network topology can be extended into a ’scatternet’ by the interconnection of different piconets. This is achieved by bridge nodes which act as the master in one piconet and as a slave in another one. The initial connection between two devices entails a pairing protocol which allows the generation of a link key to enable data encryption and device authentication. Several pairing mechanisms have been designed including "just works" which does not require user interaction or input/output capabilities in the devices, at the cost of providing a reduced security level; the legacy "passkey" where the user inputs a (typically 4-digit) password in both devices; ’numeric comparison’ where user compares if the numbers displayed are identical; and ’out of band’ which requires a side channel (such as a short-distance RFID connection) in order to exchange the necessary cryptographic materials for the secure association. Once the devices have been paired, they can connect automatically without any user intervention (if previously required), although the user can remove the relationship at any moment.

In a digital home, Bluetooth is adequate to provide hassle-free connection of devices in use cases which involve portable or battery-dependent devices in close proximity (i.e. in the same room and require low bandwidth. Therefore, Bluetooth is a suitable technology to transfer data (such as text, pictures or music) between portable devices (e.g. digital camera, mobile phone or PDAs) and computers or synchronize their state (e.g. calendar and appointments). Input/Output devices (such as keyboards, mice and printers) can be connected wirelessly to desktop computers (reducing the number of cables required) or to portable devices in order to improve the user experience compared to on-screen keyboards and provide direct printing capabilities. Multimedia applications may also benefit from the Bluetooth approach which enable remote control of Hi-Fi equipment and music/video streaming between data sources (e.g. computers, mobile phones, media players) and receivers (e.g. home stereos, speakers, headphones or TVs). Bluetooth low power devices also enable new types of applications such as monitorization of user's health parameters in fitness and medical use cases, as well as smart energy applications. In order to ensure compatibility between devices, Bluetooth SIG has developed an extensive range of application-oriented profiles that devices have to fulfil. The presence of the appropriate Bluetooth Experience Icons allows the user to identify which types of applications are supported by each device, although the range of icons defined do not cover all the possible applications and they are not always available.

3.1.5. IEEE 802.15.4

In contrast to the previously described technologies, the main goal behind the IEEE 802.15.4 standard is not to offer a wireless replacement for Ethernet and/or computer buses (e.g. USB), but to provide a low-cost and low-power consumption protocol to create small-scale and large-scale networks composed by highly constrained battery-powered devices [MIS 08]. By using this technology, it is possible to deploy specific types of networks, such as Wireless Sensor Networks (WSN), where different devices collaborate with each other in a distributed manner towards a common goal (e.g. monitor the temperature and humidity of a house). IEEE 802.15.4 defines the PHY and MAC layers of the OSI architecture, and is used by the ZigBee standard to enable home automation solutions (cf. next chapter, Section 4.2.3).

At the PHY level, several functions are provided to detect and adjust the energy level of the channel (ED), as well as measure the quality of the received signal (LQI), and check for activity in the medium (CCA) [JEL 08][SOH 07]. Furthermore, the standard provides several data transmission strategies with different maximum data rates depending on the spread spectrum and modulation techniques used. The first specification of the standard, ratified in 2003, only considers the 868MHz, 915MHz and 2.4GHz bands at a maximum data rate of 20Kbps, 40Kbps and 250Kbps respectively, using DSSS as the modulation scheme [LAT 05]. Subsequent revisions of the standard add optional configurations to increase the maximum speed when the 868/915MHz bands are used [IEE 06b]. However, in such specifications the maximum speed does not exceed 250Kbps at ranges up to 10m [SOH 07]. Due to a growing interest in developing real-time applications with transmission of multimedia content, subsequent revisions of the standard define new PHY layers. For example, the 802.15.4a revision of the standard [IEE 07] defines two new methods: Ultra-Wideband (UWB) and Chirp Spread Spectrum (CSS). Through the adoption of UWB, it is feasible to provide support to applications that demand relatively higher throughput (e.g. video), and precision ranging (e.g. medical imaging). On the other hand, the CSS PHY can be used to provide higher radio coverage to devices moving at high speeds (e.g. vehicle-to-vehicle communication[KAR 10]). The UWB PHY supports a mandatory data rate of 851Kbps but can achieve up to 27.24Mbps, while the CSS PHY supports an maximum data rate of 1Mbps [IEE 07].

There are two types of devices in a 802.15.4 network. The devices that implement all the functionalities of the standard, and, therefore, can adopt different roles in the network (e.g. data forwarder) are known as full-function devices (FFD). The devices that only implement a restricted set of features are called reduced-function devices (RFD). RFD require little memory, processing and power resources to operate, and can only communicate to a single FFD in the network [JEL 08]. Regarding the network topologies, the standard defines two types: star and peer-to-peer. Both of them require a FFD device, known as the PAN coordinator. The difference between the two topologies is that, while in the star topology every communication is performed through the PAN coordinator, in a peer-to-peer topology the communication can be established between FFDs directly. However, the PAN coordinator is needed in order to build the initial cluster of devices, and maintain global information.

The MAC layer provides support for both star and peer-to-peer topologies [JEL 08]. Moreover, it defines two operation modes in order to access the medium: beaconed and non-beaconed modes. In the beaconed mode, the PAN coordinator uses beacon frames to synchronize the devices. Then, the time slots for transmission are assigned by the PAN coordinator which collects all data in a superframe. In fact, each node in the network sends request messages to the PAN coordinator to reserve slots within the superframe. This mechanism allows to take advantage of the adaptive sleep technique in long beacon periods, used by the PAN coordinator to send beacon messages to the nodes which wake up and check for the availability of new data. After this, the devices can go back to sleep or process the data [SOH 07]. When the beacon period expires, the devices can compete again for the resources, using CSMA/CA to access the channel in the contention access period (CAP). The applications which require low latency request the access during the contention free period (CFP) which takes place after CAP. To reduce the general duty cycle in the system, the battery life extension (BLE) technique is used by the access protocol to save energy in networks with low activity. The BLE reduces the channel sensing period, and, therefore the devices sleep more. However, while it decreases the duty cycle, the chance for a collision increases [SOH 07].

In the beaconless mode, the devices compete to access the channel using CSMA/CA, without using time synchronization mechanisms. Therefore, the communication between a pair of nodes can start at any time, without the intervention of the PAN coordinator. Consequently, the beaconless mode is directed to peer-to-peer topologies, in constrast with the beacon mode, which is oriented to star topologies [JEL 08]. The latter is used for applications that require specific data rates and for networks where the devices work depending on the events collected from the environment (e.g. monitoring systems).

3.1.6. Comparison of LAN Technologies

The coexistence of different network technologies in the same home, including the most relevant ones presented previously, is nowadays a reality. Table 3.2 summarizes the principal characteristics of the LAN technologies studied in this section in order to make a comparison regarding to their usability in a home.

Ethernet offers high data rates but requires a wired infrastructure and, therefore, is not very flexible for the user. As a result, Ethernet is commonly used to connect the devices of the network that have a fixed location (e.g. access points). This way, Ethernet provides a backbone network to interconnect different LANs within a home. Wireless solutions can be used to connect devices within a room, or mobile devices through the entire home.

In contrast to Ethernet, Wi-Fi provides flexibility in the deployment as it does not require the use of cables, enabling the mobility of user devices and favouring a dynamic network composition. Although Wi-Fi usually achieves lower data rates than Ethernet, its speed is good enough to fulfil the requirements of a home network.

However, in the case of Wi-Fi, the throughput can be widely affected by the collisions in the medium. When a collision occurs during the transmission of a message, the entire transmission is compromised as stations using a single antenna are not able to transmit and listen at the same time. Due to this, the station is not able to detect the collision and abort the transmission, decreasing the performance.

In fact, Wi-Fi uses CSMA/CA to prevent collisions before the transmissions starts. In contrast, Ethernet uses CSMA/CD which is able to stop the transmission of a message if a collision is detected, providing a more efficient use of network bandwidth. Moreover, the full-duplex access mode used in recent Ethernet versions do not require CSMA/CD and enables simultaneous data transmission in both directions between a pair a nodes, therefore duplicating the effective bandwidth..

		Ethernet	*Wi-Fi*	*Bluetooth*	*802.15.4*
Access Control Mechanisms		CSMA/CD	CSMA/CA	BT piconet	CSMA/CA
Medium		wired: coaxial cable, UTP, optical fiber	air: 2.4 GHz IMZ	air: 2.4GHz IMZ	air: 868MHz, 915MHz, 2.4GHz IMZ 6
Speed (max)		10Gbps (10GB Ethernet) (+)	600Mbps (n)	24Mbps (3.0) (-)	250Kbps(2.4GHz band), 1Mbps(a) (-)
Distance (max)		100m(UTP), 10Km(fiber)	250m(n) 7	10m(2.5mW), 100m(100mW) (-)	10m (-)
General Features	*Energy Consumption*	-not relevant-	Medium	Low (+)	Very Low (+)
	Flexibility	Very Low (-)	High (+)	Medium	Medium
	Cost	Low	Low	Very Low (+)	Very Low (+)
	used in hand devices	Low	Medium	High (+)	Low
Highly depen- dant on		Wired Infras- tructure	Interferen ces and Collision	Distance	Loss of packets (beaconed mode)
Applicability		Fixed networks	Dynamic Net- works	Portable or battery-dependant devices in close proximity	battery-dependant devices in close proximity with- out throughput requirements

Table 3.2. *Comparison of LAN technologies*

Wi-Fi power consumption is higher than Bluetooth. Therefore, Bluetooth is usually a better alternative for battery-dependant devices in close proximity, providing a moderate bandwidth at low-cost. However, the transmission area in Bluetooth is typically limited to a few meters, therefore limiting the range of scenarios where this technology can be used in a home network. Although the profile based on 100mW allows to achieve a transmission range up to 100m, it may not fit the capabilities of power-dependant devices.

Regarding 802.15.4, its power consumption is even lower than Bluetooth, mainly due to the maximum data rate and mechanisms such as adaptive sleep in long beacon periods. The main drawback of this strategy is that several packets can be lost due to the inactivity period, thus decreasing the throughput. Nevertheless, this technology fits the characteristics of monitoring networks that do not require a high throughput (e.g. supervision of environmental conditions based on sensor technologies), and in critical applications where the main requirement is the reception of data in a specific time period. Bluetooth is better suited to applications which require the reception of all the packets. Nowadays, several multimedia applications are used by home users, and it is expected that bandwidth requirements for the transmission of multimedia streams will increase in the future. Bluetooth can be used for the transmission of multimedia data which require low to moderate bandwidth, while Wi-Fi and Ethernet are more adequate for high-definition formats. Bluetooth has been widely implemented and used in multiple personal devices, therefore represents a well-known and user-friendly alternative to 802.15.4 for mobile and moderate bandwidth applications.

3.2. Connectivity to Main networks

Home networks are able to reach high data rates, as they are a controlled environment where the number of participants is known (i.e. computers in a home) and the network resources are used only by a few users. When home networks are connected to the Internet, or to another external network, the link for the connection ("the last mile") can become a bottleneck, as the link will be shared by many Service Providers or customers. However, the growth of bandwidth-intensive services available in the Internet (i.e. IPTV, multi-player games) increases the need for higher and higher data rates downstream (from the service provider to the user) and upstream (from the user to the service provider). Furthermore, in digital home, these services should be available using all equipments, from high-capacity devices (i.e. work station, TV) to constrained and mobile devices (i.e. mobile phone, PDA). Another aspect to take into account is the location of the home, as a wired broadband link needs an existing wiring infrastructure next to the home, or, when such an infrastructure is not available, wireless broadband technologies will have to be used.

Subsequent sections will focus on both the wired and broadband technologies that were developed for the “last mile” access to the Internet. The analysis will start by giving a brief background on the evolution of these technologies in Section 3.2.1, and we will present the main different technologies deployed and offered by the service providers in subsequent sections.

3.2.1. Technologies Providing Internet Access – an Overview

The Plain Old Telephone Service (POST), previously referred to as the Public Switched Telephone Network (PSTN), is the first network that has been used for connecting the homes between them, the telephone being the communication device. This system was inefficient, sensitive to breakdown and noise. Furthermore, the analog lines were quite limited in bandwidth and were only able to transmit signals within the frequency range of voice communication, and the telecommunication industry began to migrate its connections to a packet switched network (the technique used in ARPANET, the precursor of the actual Internet). However, the “last mile” links have been using POST for a long time. To send data through POST, digital modems where developed in 1962, and the 56Kbps dial-up modems build-in in most computers appeared at the end of the 1990s, for implementing the connection to the Internet. Later, these modems were replaced by faster technologies, such as the Integrated Services Digital Network (ISDN) or the Digital Subscriber Line (DSL). ISDN was defined in 1998 by the Telegraph and Telephone Consultative Committee (CCITT), at present known as ITU-T (Telecommunication Standardization Sector of the International Telecommunication Union), to support simultaneous digital voice, video and data over the POST, packet switched, Telex or CATV networks, to deliver data rates up to 128Kbps. Moreover, as an extension of ISDN to handle high-bandwidth applications, Broadband ISDN (B-ISDN) was developed in the 1990s. B-ISDN provides data rates up to 622Mbps using the Asynchronous Transfer Mode (ATM), a connection-oriented packet switching technique able to carrying a wide variety of services in real-time (i.e. multi-conference). However, the B-ISDN deployment requires a considerable investment in terms of infrastructure (i.e. 622Mbps needs the use of optical fibers) and equipments, and when multimedia services became available via the Internet, other solutions were developed and deployed in place of the B-ISDN technology.

The Digital Subscriber Line (DSL) was a new way to connect the Internet that not only reduced the costs but also provided a higher throughput than ISDN. The most popular DSL technology is the Asynchronous DSL (ADSL), which provides POST service and Internet access simultaneously without interruption (“always-on”). ADSL (1999) has an asymmetrical bandwidth structure, achieving maximum speeds of 8Mbps/650Kbps (downstream/upstream). The last specifications of the DSL family (xDSL) supports higher data rates (i.e. VDSL2 up to 200Mbps), and provides new services such as High Definition TV (HDTV). Another technology that coexisted with xDSL in the 1990s is the Hybrid Fiber-Coaxial (HFC). HFC is a broadband network that uses an optical fiber to connect the central office of the service provider to a distributor near to the residential place. Such distributors deploy coaxial cables used for Cable Television (CATV) and repeaters in order to deliver the signals to the homes. The aim behind HFC was to extend the CATV services (limited to analog video distribution) to VoD, telephony and AMT-based services. However, xDSL still remains the best solution for delivering low-cost and high-throughput to residential customers. Hybrid approaches as “Fiber to the x” (FTTx), have made possible the gradual replacement of copper sections by fiber optical cables. Fiber to the Home (FTTH) is a broadband network architecture that uses optical fibers to connect the central office to the customer's home, providing more bandwidth in a more efficient way than previous technologies. Moreover, FTTH also substantially increases the upstream capacity.

The development of the wired technologies was complemented by the development of a set of wireless technologies that were designed to implement the “last mile” link. Around 1998, they were known as the Wireless Local Loop (WLL), Radio in the Loop (RITL), Fixed-Radio Access (FRA) or Wireless in the Loop (WITL) technologies. These first systems were based on cellular, satellite or microcellular networks, including for example the Global System for Mobile Communications (GSM) and the Digital Enhanced Cordless Telecommunications (DECT). In these technologies, an antenna needs to be added to the customer's house to connect the home network to a base station that will redirect the signal through a cable (coaxial or optical) to the central office. GSM is an evolution of the first generation of mobile telephony (1G), which was using analogic communications (Frequency Modulation, FM). GSM provides digital data transmission, and support for Short Message Services (SMS). For these and other reasons GSM belongs to the second generation technologies (2G). The third generation cellular technologies (G) bring together mobile communications and high-speed data services, including Internet access. The Universal Mobile Telecommunications System (UMTS) is the most widely adopted 3G technology. It provides a download peak rate of up to

384Kbps, and it is expected to be enhanced to 84Mbps with the advent of the Evolved High Speed Packet Access (HSPA+) technology.

During the last few years, the demand for accessing the Internet from mobile devices has greatly increased, and the communication industry has developed new standards to efficiently deliver high-speed broadband mobile access services, at low cost for both operators and users. Nowadays, WiMAX and Long Term Evolution (LTE) are the main candidates to be approved as 4G technologies. On one hand, WiMAX, based on IEEE 802.16, is a wireless broadband alternative to the wired broadband technologies (i.e. xDSL) for the last mile access. WiMAX provides high quality Internet access, as well as high-speed services for mobile and handset devices, with range coverage up to 48Km. Furthermore it is expected that new revisions of the standard make it able to reach a data rate of up to 1Gbps. On the other hand, 3GPP LTE, the new generation evolution of UMTS, is a packet-optimized radio-access technology designed to provide high data rates with low power consumption. Moreover, LTE Advanced (2010) is expected to provide download peak rates between 100Mbs and 1Gbps for high-mobility and low-mobility respectively.

3.2.2. xDSL

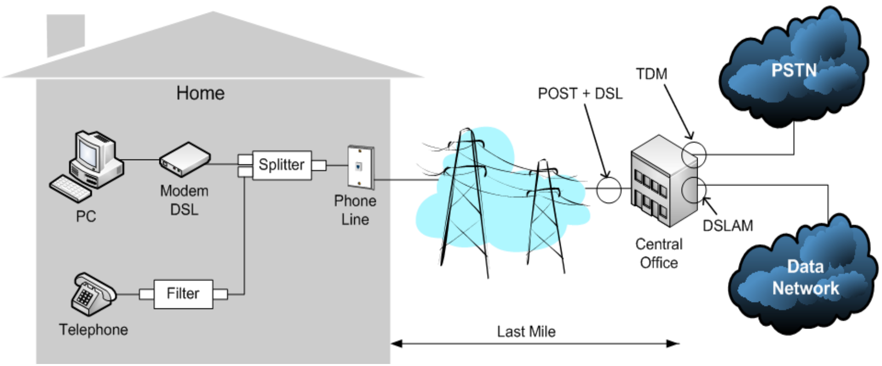

Figure 3.2. *xDSL last mile*

The family of Digital Subscriber Line technologies (xDSL) was designed to provide data transmission over the existing infrastructure of copper coming from the plain old telephone service (POTS). xDSL was initially proposed as a intermediary solution between the Hybrid Fibre-Coaxial (HFC) and Fibre to the Home (FTTH) technologies. Unlike HFC and FTTH, xDSL is able to use an already existent infrastructure, and therefore, has a very low deployment cost [HUM 97]. Precisely, the purpose behind xDSL was to provide affordable broadband services between the customer and the central office of the service provider (the "last mile" or "local loop" [VER 03]). The two main applications for xDSL are Internet access, file sharing, Video on Demand (VOD), broadcast TV, telecommuting, telemedicine and on-line education, shopping and gaming [DSL 09]. Most of the DSL technologies offer simultaneous POTS and data transmission services. To support these two set of services, these technologies use frequencies above 4KHz for data transmission, and frequencies under 4KHz to maintain the telephone service [HUM 97]. Moreover, in order to prevent interferences due to the sharing of the wire, they integrate a splitter and a filter before the phone device. The splitter divides the signal received from the line into high and low frequencies, while the filter blocks the high frequency bands to allow voice reception in the phone (Figure 3.2).

A widely deployed DSL technology was the High-bit-rate DSL (HDSL) [HUM 97]. HDSL is unidirectional, as it cannot send and receive data simultaneously, thus it needs two wire pairs to perform bidirectional transmission. Moreover, telephone calls are not possible, as all the available bandwidth is used for data transmission. Furthermore, HDSL is symmetric, which means that both downstream (from the SP to the customer) and upstream (from the customer to the SP) traffic streams have the same data rate, in this case up to 2Mbps [HUM 97] using 2B1Q modulation with a signal range of up to 4.5Km. This technology can be used for private networks, LAN-to-LAN connection and private branch exchange (PBX), among others. In fact, HDSL is useful in scenarios where the traffic flows in both directions (e.g. clients and servers in the same network). Symmetric DSL (SDSL) is similar to HDSL (same data rate for downstream and upstream traffic), but SDSL only uses a wire pair for the transmission, with a maximum data rate of 2Mbps [HUM 97] and a range of about 3Km. SDSL can be used for small to medium businesses and branch offices [CIS 10].

One of the most popular DSL technologies is the Asynchronous DSL (ADSL) [CHO 03]. Differently from HDSL and SDSL, ADSL uses Frequency Division Multiplexing (FDM) for separating the basic telephone service and the upstream and downstream frequency bands [CIS 10]. Besides, ADSL is an asymmetric technology, because it provides a higher bandwidth for the downstream traffic (up to 8Mbps), and only 650Kbps for the upstream traffic, for a distance of up to 5.8Km. Such a design is mainly adapted for World Wide Web navigation, because the upstream traffic consists mainly on control information, while the downstream traffic is used multimedia data transmission (text, audio, images, video, etc.) [HUM 97]. Other potential applications of ADSL are Internet/Intranet navigation, Video on Demand (VoD), and remote LAN access [CIS 10]. An extension of ADSL is the very-high-data-rate DSL (VDSL), which was designed to not be dependent on the underlying physical medium. As a result, VDSL is able to run over the existing copper infrastructure and over other physical media, such as optical fibre. Moreover, VDSL provides both types of transmissions, asymmetric and symmetric [G.993]. On the one hand, the asymmetric transmission allows up to 50Mbps for the downstream traffic and 6.4Mbps for the upstream traffic. However, the delivered data rate depends highly on the length of the link, as the maximum downstream rate may be reached only in the first 300m of wire (short line) [CIS 10]. Moreover, if the distance between the clients and the service providers is up to 1.5Km (long line), the downstream rate is smaller than 13Mbps and the upstream rate is smaller than 1.6Mbps. Still, such data rates are higher than the maximum values given by ADSL. On the other hand, the symmetric transmission can reach up to 25Mbps in short lines and to 6.5Mbps in long lines [PAL 04]. VDSL has been seen as a very appropriate candidate for providing high definition TV (HDTV).

Notice that the asymmetry of ADSL and VDSL eliminates the phenomenon known as the near-end crosstalk [CIS 10]. Crosstalk are interferences produced in the communication channel due to the electromagnetic coupling between the signal lines. There are two types of crosstalk: near-end crosstalk or NEXT (interference between signals in opposite directions, at the end of the communication) and far-end crosstalk or FEXT (interference between signals in the same direction, during the communication). ADSL and VDSL solves the near-end crosstalk by separating the two transmission bands into non-overlapping intervals using Frequency Division Multiplexing (FDM) [COO 99][ZEN 01]. Moreover, VDSL defines an upstream power back-off (UPBO) to mitigate far-end crosstalk, by providing a spectral compatibility between the loops of different lengths in the same blinder [G.993]. However, the next generation of DSL technologies will need to provide higher data rates in order to responds to the growing demand of multimedia services [SON 02], and the increase of speed causes significant electromagnetic coupling, that in turn generates crosstalk [CEN 04]. Moreover, the incompatibility between the different DSL services (different types of services having different symbol rates), as well as the diversity of the DSL service providers (signals from different modems are completely asynchronous), will make the crosstalk problems in the copper wires difficult to solve [ZEN 01][SON 02].

The next generation DSL technologies is evolving towards IP-core networks [DSL 09]. In the Broadband Forum, previously known as the DSL Forum, the current efforts include interoperability plans for the ADSL2, ADSL2plus and VDSL2 technologies. These technologies add improvements for a better management of the system. First, ADSL2 has been developed to increase both the ADSL maximum data rate and reachable distance. In fact, the data rate can reach up to 12Mbps for the downstream traffic and up to 1Mbps for the upstream traffic, while the reachable distance is increased up to 7Km in the “ADSL2 Annex L”, or Reach-Extended ADSL2 (ReADSL2). ADSL2 increases the data rate by using a Trellis codification and a quadrature amplitude modulation (QAM), instead of the FDM and DTM used by ADSL. Moreover, ADSL2 adds diagnostic capabilities to check the state of the line (noise, attenuation, signal-to-noise ratio (SNR)). These features can be used by the service providers to perform real-time performance monitoring and, therefore, to give the opportunity for deployment services that requires a specific and guaranteed quality of service (QoS). Besides, ADSL2 transceivers can modify their behaviour to use a power saving mode. In order to allow this, ADSL2 defines two low-power modes, L2 and L3. In the L2 power mode, the data rate is decreased, so the power consumption is lower, while in the L3 power mode, the transceiver is turned to a sleeping mode, in which the power consumption is minimal. The full-power mode (L0) is the normal behaviour of a traditional ADSL transceiver, always working at the maximum data rate, and, consequently, using the same energy whatever the bandwidth used for transmission at a given time. An ADSL2 transceiver can switch from L0 to L2 power mode when the Internet traffic over the ADSL connection decreases, and to L3 when the user is not on-line. To prevent the crosstalk problems, ADSL2 defines the seamless data adaptation (SRA), that varies the data rate based on the probability of crosstalk [AWA02].

Another approach to increase the throughput of ADSL is increasing the frequency range. ADSL2plus (or ADSL2+) extends the download frequency range up to 2.2MHz (1.1MHz is used by ADSL and ADSL2), to reach a downstream data rate of 24Mbps, while the upstream data rate is kept to 1Mbps. The likelihood for interferences grows when the used spectrum is increased, but ADSL2plus can mask frequencies below 1.1MHz, reducing the crosstalk [AWA02]. Furthermore, ADSL2plus is backward interoperable with ADSL and ADSL2, and provides the capability to be used in conjunction with Rate-Adaptive Profiles [BFT08]. This feature makes possible to allocate a given data rate to services requiring guaranteed QoS (i.e. IPTV, VoIP), while maintain a variable data rate for the best effort services (i.e. Internet). As a consequence, the variable data rate can be adjusted to support a high number of services with poor quality, or to deliver the best quality affordable with traffic prioritization. Finally, the maximum speed can be increased by using the capability known as ADSL2+ bonding. This characteristic increases the total bandwidth by deploying various ADSL2 or ADSL2plus lines. For example, in case of two ADSL2plus lines of 24Mbps each one, the maximum data rate is increased from 24Mbps to 48Mbps (2x24Mbps). These and other features make ADSL2plus a strong candidate to impulse IPTV in digital home networking [BFT08].

Lastly, an enhancement to VDSL, known as VDSL2, supports asymmetric and symmetric transmission at a bidirectional (the sum of upstream and downstream rates) data rate of up to 200 Mbps on twisted pairs [G.993.2]. The underlying modulation code is the same as ADSL and ADSL2plus, enabling backwards compatibility with ADSL. Besides, this standard includes many of the features and functionality contained in ADSL2plus, including advanced diagnostics and a common management interface. As a result, VDSL2 is a serious contender for the provisioning of Triple-play services: voice, video, data, high-speed Internet access and HDTV. Note that VDSL2 reaches higher data rate values than ADSL2plus only in the first 1.6Km, approximately. After this distance, the data rate values for both technologies are similar.

To conclude, xDSL technologies over copper pair allow a low-cost deployment as they use an existing infrastructure (previously used by the POST service). However, the signal degradation in such lines is highly dependent on the distance between the customer's home and the central office. Moreover, the stability of the line can be affected by neighbor lines (i.e. noise, interferences), and by the quality of the copper wires used for the transmission. These factors makes difficult to achieve very high data rates. As a consequence, the market of DSL has decreased during the last years with respect to other broadband technologies such as FTTH [BRO 09].

3.2.3. FTTH

The growing bandwidth demand cannot be fulfilled by the traditional technologies working over copper wires (i.e. xDSL), due to the inherent characteristics of the cables. Specifically, the wide deployment of bandwidth-intensive services (e.g. HDTV, interactive gaming, joint video editing) in residential and business environments is increasing, as well as the number of services requiring very high resource utilization and bringing new business opportunities. Fiber-to-the-Home (FTTH) is the only technology that can provide higher bandwidth and higher reliability at a relative low cost of maintenance, in a short period of time, to support high quality streaming applications (i.e. broadcast video, VoIP). Moreover, FTTH increases the upstream data rates to values higher than the previous technologies, which is necessary for adequately supporting symmetric services (i.e. real-time systems, remote collaboration, VoIP) [CIS 07].

The market of FTTH shows a growth of the number of customers during the last years [FTT 10a]. The global FTTH market grew by 16 percent, to almost 41 million subscribers, at the end of 2009, with respect to the end of June 2009. Furthermore, it is expected that, by the end of 2014, there will be around 306 million homes using FTTH around the world [ITU 10]. Nevertheless, its ratio of penetration in Europe is very low when compared to the United States or Japan.

FTTH is a communication architecture that uses fibre cables, instead of using the traditional copper infrastructure (xDSL) or coaxial cable (CATV). The fibre cable provides higher speeds more efficiently than the previous mechanisms [CIS 07]. The optical fibre is made of four basic elements: core, cladding, buffer and jacket, where the core is surrounded by the cladding. The data are sent to the core using light pulses.

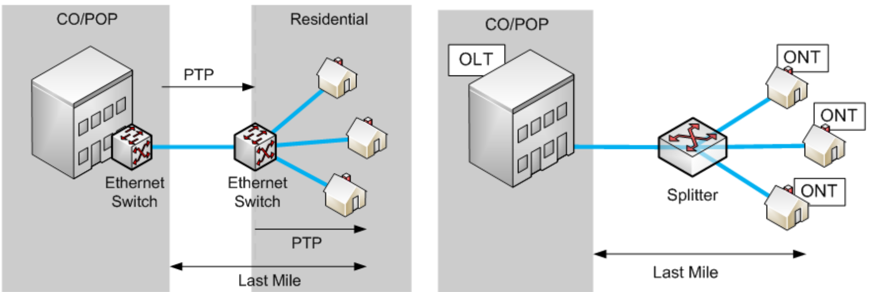

Figure 3.3. *(a) Active Optical Network (AON)*
(b) Passive Optical Network (PON)

The light is totally reflected in the cladding material, which is chosen with a low index of refraction (i.e. glass or plastic material). The buffer protects the cladding and the core from external perturbations (i.e. wetness), and the jacket is the final encapsulation, typically of plastic material. Moreover, the optical signal is carried by using a single wavelength for each one: downstream and upstream traffic. However, using the Wavelength Division Multiplexing (WDM) technology allows the multiplexing of both signals in the same fiber [BAN 05].

For the fiber infrastructure, there are three different topologies for the communication between the central office (CO), known as headend or point of presence (POP), and the customer's equipment [FTT 09]. First, the point-to-point (P2P or PTP) topology builds a dedicated fiber from a central office to each subscriber. Besides, as the POP is usually connected to more than one customer, this structure is also known as the star topology. Second, the Point-to-Multipoint (P2MP) topology allows the sharing of the optical fiber between various customers, resulting in a tree structure. Third, in the Ring topology, a predefined sequence of optical fiber paths builds a closed loop that the terminal manages. The PTP and Ring topologies should be implemented by using the Ethernet technology, and are commonly deployed in Europe [CIS 07]. In contrast, the Passive Optical Networks (PON), a particular case of P2MP [FTT 09], is widely deployed in the United Stated and in Japan. Besides, in Europe the interest of PON networks has being growing in the last years [FTT 10b]. Note that Ethernet point-to-point and PON are the most used topologies, and for this reason they will be further discussed in the next paragraphs [FTT 10b].

To implement Ethernet PTP networks for FTTH there are two options. The simplest solution is to directly connect the POP and the customer's premises using a dedicated fiber. The deployment costs of this solution are quite high, mainly due to the amount of fiber optic needed to set up the network infrastructure. Another solution is to connect the POP to a remote aggregation point (switch or router), and then using a dedicated fiber from this point to each house (cf. Figure 3.3a) [FTT 10b]. This approach is also known as Active Optical Networks (AON) [KEY 08]. Unlike PONs (explained in the next paragraph), AONs use active processing equipments in the network (e.g. Ethernet switches), instead of passive elements (e.g. unpowered optical splitters) that simply split the signal. Specifically, the use of active elements as switches and routers allows the CO to ultimately send the signal to a specific destination, without broadcasting. One disadvantage is that the active equipment must be powered, thus AONs are inherently less reliable than PONs [LAR 09].

Regarding PONs, they define their own elements for the communication infrastructure. In PON FTTH networks, the central office has an Optical Line Termination (OLT), while the home (or more generically premise) has an Optical Network Termination (ONT), which can be situated just outside or inside (Figure 3.3b). Moreover, between both elements there is a passive optical splitter, used for distributing the optical signal from the central office up to 32 homes [LIN 06]. The total bandwidth is delivered over an uniquely fiber from the CO to the splitter, where the signal is send up to 32 fibers (1:32), each of them directed to an ONT. The downstream traffic is broadcasted to each home by the splitter. However, for the upstream traffic, time-sharing protocols are used to control the access of multiple subscribers to the shared fibre in order to avoid collisions [FTT 10b]. Each ONT knows the time slots during which its transmission is allowed [LIN 06]. Thanks to bandwidth sharing, PON infrastructures requires less fiber to be deployed than PTP networks, so the overall cost for deploying the infrastructure is less costly in PONs than in PTPs. Furthermore, the dynamic bandwidth allocation capabilities also allows capital and operational cost savings [FTT 10b] and, at the same time, gives the ability to offers higher bandwidth to customers when the network is not overloaded, as well as dynamic bandwidth allocation according to traffic priorities. Finally, this architecture supports both Ethernet and ATM protocols [CIS 07].

There are diverse access protocols defined to work over the aforementioned architectures. The FTTH Council has highlighted two protocols using the Ethernet PTP topology, known as Ethernet in the First Mile (EFM) and Ethernet over P2P (EP2P), and three protocols using PON, the Broadband PON (BPON), Ethernet PON (EPON) and Gigabit PON (GPON) [FTT 09]. Nevertheless, taking into account their status of deployment, the most representative of these protocols are the PON-based protocols. Concretely, BPON and their predecessor, APON are deployed in Japan, while GPON is used in Europe and the United States, and, finally EPON is widely used in Asia (Japan, China, Korea)[IEE 06a].

ITU recommendations for FTTH comprise G.983 (APON and BPON) and G.984 (GPON), ratified in 1995 and 2000 respectively. ATM-PON (APON) was the first standard defined for PONs, and was designed to use ATM as its signaling protocol at the data link layer. To extend the number of services offered by the technology, APON was improved to support Ethernet access, video distribution and AES security [LIN 06], and was renamed to Broadband PON (BPON)[HTT]. BPON (G.983.1 Amendment 2) defines two types of transmission, symmetric and asymmetric, with a maximum symmetric data rate of 622.08Mbps, or asymmetric data rates up to 1244.16Mbps for downstream data and 622.08 for upstream data [G.983.1]. On the other hand, Gigabit-Capable PON (GPON) was developed to increase efficiency in the transmission of Ethernet-based traffic over the PON. To this purpose, GPON defines the GPON Encapsulation Method (GEM) protocol, which uses flexible frame sizes to transport data and also frame fragmentation [LIN 06]. Moreover, GPON increases the number of customers to 128 (split ratio 1:128), and the maximum data rate up to 2.4Gbps and 1.2Gbps for downstream and upstream data respectively in asymmetric mode, and 2.4Gbps for symmetric connections [G.984.1]. Future ITU recommendations will be able to include XG-PON [FTT 10b], supporting maximum data rates of up to 10Gbps and 2.5Gbps for downstream and downstream data in asymmetric mode and up to 10Gbps in symmetric transmissions [TRO 08][FTT 10b].

IEEE standards for FTTH includes 802.3ah (EPON) and 802.3av (10G-EPON) specifications, approved in 2004 and 2009 respectively. Ethernet PON (EPON), also known as Gigabit Ethernet (GEPON) or Ethernet in the First Mile (EFM), uses a Passive Optic Splitter (POS) and an Optical Network Unit (ONU) in each home. The structure of an EPON is able to provide users with a set of services that are available through the OLT. Moreover, such services can come from specific networks connected to the OLT, such as PSTN, IP or CATV networks. The ONU is the user side equipment in the EPON, which converts the fiber optic signal into the electric signal and offers the different services to the customer (i.e. VoIP, HDTV, and video conferences). EPON achieves a maximum data rate of up to 1Gbps in both directions, while proprietary EPON products reach up to 2Gbps for the downstream data rate [FTT 10b]. More recently, 10G-EPON improves such values, achieving a maximum downstream data rate of 10Gbps and 1Gbps for the upstream traffic, or 10Gbps in both directions (symmetric). 10G-EPON is the evolution of the EPON technology and was developed with the aim to offer advanced video services, e.g., bandwidth-intensive downstream and upstream services, and support for more subscribers [IEE 06a].

Current trends in access technologies are focused on achieving higher upstream data rates. In fact, there is a growing consumer demand for applications and services that require high upstream data rates (e.g. massively multiplayer online games, distributed cooperation and collaboration). The tendency is toward symmetric bandwidth usage, and the higher upstream bit rate of the PON gives FTTH operators a competitive advantage over DSL providers [FTT 10b].

3.2.4. Third generation technologies (3G)

Until recent years, cellular technologies were built around the provision of voice services and, as the fixed plain old telephone networks, were based on a circuit switched approach with dedicated resources for each call. However, the global demand for new types of services made upgrades mandatory and finally led to a new evolution. 3G systems are the third generation of cellular technologies which bring together mobile communications and high-speed data services, including access to the Internet and other sources of broadband data. The term 3G does not refer to only one technology, but to a range of standards which fulfill the requirements defined by the International Telecommunication Union (ITU), known as International Mobile Telecommunications 2000 (IMT-2000) systems. The IMT-2000 systems allow the simultaneous use of speech and data services, and typically provide a minimum of 2 Mbps for stationary or walking users, and 384 kbps for higher-speed moving users.

The data wave has deeply penetrated the recent mobile systems and changed the value chain [KOR 03]. The user is no longer restricted to the options offered by its service provider, but by the global Internet access. 3G systems provide an open service architecture and the convergence of mobility, personal and multimedia services. They enable ubiquitous access to data services, immediacy of relevant information (such as pertinent alerts), location-based services (e.g. traffic data, nearby restaurants, businesses or people) and support a guaranteed quality of service (QoS) to fulfill the heterogeneous requirements of a wide range of applications.

Users can benefit from on-the-go video applications (e.g. videoconference and home IPTV surveillance), access to home and office networks, remote synchronization of portable devices with information held on the home server, real-time interactive gaming, and other innovative high-quality applications. Apart from user's mobility and everywhere access to digital home services, 3G systems are also an option to provide direct Internet connectivity to home devices and can be an option to provide Internet access to the in-home LAN. This approach is especially appealing to homes without a fixed phone, with sporadic access to Internet services (i.e. where the maintenance of a fixed line is not convenient) or in rural areas where wired-based high speed technologies are not available.

Several technologies fulfill the requirements of IMT-2000 systems. In fact, in 1999 ITU approved 5 proposals and there have been later others incorporated into the list. A recognized 3G technology is the CDMA2000 system, which is based on the second generation IS-95 infrastructure developed by 3GPP2. The system has undergone several revisions, and the initial 'single carrier evolution-data only' (1xEV-DO) specifications were completed in 2001 and provide up to 2.4 Mbps in the downlink, 153 Kbps in the uplink channel, but requires a separate 1.25 MHz channel for data. The CDMA2000 'single carrier evolution and voice' (1xEV-DV) provides up to 3Mbps data rate and introduces an all-IP architecture and new radio techniques. The current last release 'EV-DO Rev B' provides peak rates of 14.7 Mbps in the downlink. The Mobile WiMAX technology was also approved as an IMT-2000 system by ITU in 2007, but as a late member of the family, it actually exceeds the general requirements and it is expected to be recognized as a 4G technology in the near future.

However, the most widely adopted 3G technology is the Universal Mobile Telecommunications System (UMTS) [3GP 10] which is based on the Global System for Mobile communications (GSM) standards. The family of technologies based on GSM is the dominant cellular system which, in August 2010, stands at 89.7% share of the global mobile market and serves 4.45 billion subscribers worldwide. The maintenance and development of the GSM technical specifications is managed nowadays by the Third Generation Partnership Project (3GPP), a partnership of Standards Development Organizations whose main partners are the European Telecommunications Standards Institute (ETSI), the USA Alliance for Telecommunications Industry Solutions (ATIS), the China Communications

Standards Association (CCSA), the Japanese Association of Radio Industries and Businesses (ARIB), the Korean Telecommunications Technology Association (TTA) and the Japanese Telecommunications Technology Committee (TTC).

In the 1990s, the early GSM systems were focused on voice services and provided a data rate of 9.6 Kbps, later upgraded to 14.4 kbps, but inadequate for high speed data services. The introduction of GPRS, considered as 2.5G, was able to provide up to 140 Kbps with typical rates of 56 Kbps. The last update of the second generation called 'GSM EDGE' features an effective data rate of up to 180 Kbps and is presently approved as an IMT-2000 system, although it is an upgrade of the second generation and it is not typically referred to as 3G.

The introduction of UMTS significantly enhanced the performance of GSM systems for data services. Due to the increasing demand for high speed mobile networks, the evolution of broadband cellular specifications follows a tight schedule. 3GPP introduces new revisions to the original GSM technology in the form of releases which define a new set of features. The 384 kbps download peak rate of the original UMTS was further enhanced with the definition of the HSPA technology upgrade to 14.4 Mbps in specifications Releases 5 and 6. The Evolved HSPA (HSPA+) introduced in Release 7 is expected to provide up to 84 Mbps download data rate. The family of UMTS-HSPA technologies, known as generation 3.5G, is widely being adopted. In August 2010 [SUP 10], 98.8% of 3G/W-CDMA networks have already been upgraded to HSPA and the number of HSPA devices has increased of 48% since October 2009. From an estimated 452 million subscribers of UMTS-HSPA at the end of 2009, it is expected to reach 677 million in 2010 and 2 billion by 2013. More than two thousand devices are commercially available, including smartphones, notebooks, personal media players and cameras, as well as USB modems and wireless routers to provide Internet access to the LAN.

This technology is also known as W-CDMA (due to its most widely adopted air interface), FOMA (due to the original Japanese implementation of UMTS by the NTT DoCoMo service provider) or directly marketed as 3G. UMTS offers voice and SMS services, as well as 'bearer' services which provide the capability of transfer data and to access worldwide data services. The characteristics of a bearer service can be renegotiated at any time during the establishment and management of a session. UMTS is able to fulfill QoS requirements for four types of traffic: conversational class (e.g. voice, video conference), streaming class (e.g. video on demand, multimedia), interactive class (e.g. gaming, web browsing) and background class (e.g. downloading and email). These capabilities have a cost, as UMT has a higher power consumption than the previous GSM systems (with an impact on battery life of mobile devices), and the mobile high speed access to worldwide networks is usually more expensive than in-home wired solutions.

There are three options regarding the air interface, also known as the UMTS Terrestrial Radio Access (UTRA). They include the UTRA-TDD HCR (a) which can be deployed in thin frequency bands and uses the same frequency band for the downlink and uplink; and the TD-SCDMA (b) air interface developed in China which requires even narrower frequency bands. However, most UMTS systems are based on Wideband Code Division Multiple Access (W-CDMA) (c) which provides a good balance between performance, cost and capacity. W-CDMA requires 5MHz wide channels, support FDD and TDD transmission modes, and allows multiple types of handover (i.e. the process of transferring the control of a call or data session without interruption) including soft handover and hard handover.

UMTS systems require the allocation of new frequency bands, a complex and costly process in the already crowded electromagnetic spectrum, which is usually controlled by the governments. As a consequence, the situation is not homogeneous around the globe. Table 3.3 shows the most common bands and their regions. The most widespread alternative being UMTS2100, however there is a wide range of options and some of them overlapped in the same region. The bids for 3G licenses have reached exorbitant prices. In Europe, telecommunication operators have spent more than 150 billion Euros in licenses which have an impact on the commercial cost of these services, although the effect should decrease in the future.

Band	*UE Trans. (MHz)*	*UE Recep. (MHz)*	*Region*
2100	1920-1980	2110-2170	Europe, Africa, Asia, India, Australia, Brazil
1900	1850-1910	1930-1990	North America, South Amarica
1700	1710-1785	1805-1880	North America
850	824-849	869-894	North America, South America, Asia, Australia
900	880-915	925-960	Europe, Asia, Australia, Venezuela

Table 3.3. *Widespread UMTS frequency bands*

UMTS defines a complete network system which includes the user equipment (UE), the terrestrial radio access network (UTRAN) and the core network (CN). Relevant entities of UTRAN are the base station which communicates with the UE, known as Node-B, and the control equipment for the base stations, called Radio Network Controller (RNC). Under the Node-B responsibilities are the air interface transmission, the CDMA coding, modulation/demodulation and error handling. Each RNC controls the resources allocated in one or more node-Bs and is responsible for channel allocation, power control settings, encryption, and handover decisions.

The same core network can support both UTRAN and GSM radio access. In the original UMTS architecture (Release 99), the CN is divided in to two domains. On one hand, the circuit switch (CS) domain, mainly oriented towards voice communications and to connectivity between fixed PSTN and ISDN networks. On the other hand, the packet switch (PS) domain, that provides data services and packet connectivity. The later Releases 4 and 5 define the IP Multimedia Subsystem domain which implements an all-IP network and allows the handling of voice and data services as IP packets, thus turning the PS and CS domains obsolete. The all-IP architecture opens the cellular environment to the large ecosystem of all IP applications and provides a uniform transport technology that reduces deployment costs. Furthermore, in the all-IP approach, data is transferred through fewer entities in the network, minimizing latency and enhancing the user experience.

3.2.5. WiMAX

An emerging and promising technology and one of the main candidates to be approved as a 4G technology is WiMAX. In 2001, the WiMAX Forum [FOR 10] was formed by key industry players, with the goal of developing a fixed wireless alternative to DSL and cable that improves the performance of proprietary approaches and provides an open and interoperable standard. This technology enables the delivery of wireless broadband access to enterprise and residential customers as a cost effective solution. It is commonly known as “last mile broadband” because is able to fill the gap between the core network of the service provider and the end user premises, and to avoid the deployment of a wired infrastructure.

WiMAX technology is based on the IEEE 802.16 [BRO 10] standard. Although in the early stages, the initial IEEE 802.16-2004 focused on this fixed broadband alternative (therefore known as “Fixed WiMAX”), the latter IEEE 802.16e-2005 amendment included mobility capabilities, thus providing a support for dynamic users using laptops or handheld devices on-the-go, later leading to “Mobile WiMAX”. Apart from the mobility features (i.e. support for soft and hard handovers), this update also provides several enhancements, such as the support for SOFDMA schemes, multiple input multiple output (MIMO) antenna schemes, advanced antenna diversity and adaptive systems. The expected IEEE 802.16m revision will significantly enhance the technology data rates and the spectral efficiency, potentially enabling WiMAX as a real 4G technology.

Although the term “WiMAX” is commonly and loosely used to refer to the IEEE 802.16 standard itself, not every aspect of the standard is considered by the WiMAX Forum [PAR 06]. The standard is comprehensive and complex, so only a subset of the standard is considered in the WiMAX profiles and in the interoperability and conformance tests. In order for a product to be WiMAX certified, it must fulfill the tests specified by the WiMAX Forum, which ensure that the product or module satisfies a specific set of requirements and, therefore, that products of different vendors will be interoperable.

In a nutshell, WiMAX enables a coverage range of up to 48 Km and peak speeds up to 72 Mbps, while the upcoming IEEE 802.16m revision is expected to offer up to 1Gbps. However, it must be taken into account that both features cannot be fulfilled at the same time. In other words, the higher speeds are reached by the subscriber stations closer to the base station, and the throughput degrades almost linearly with the distance. WiMAX accommodates licensed and unlicensed frequency bands. Unlicensed bands at 2.4 GHz and 5.8 GHz can be used by independents parties to provide local services for hotspots while licensed bands are allowing service providers to deploy high-quality networks. A global and uniform spectrum for WiMAX has not been licensed, but WiMAX profiles specify three options at 2.3 GHz, 2.5 GHz and 3.5 GHz. Furthermore, WiMAX is approved as an IMT-2000 technology, therefore a WiMAX equipment is allowed to make use of the frequency bands licensed for this set of standards. Moreover, WiMAX features high spectral efficiency, allowing the transmission at 3.7 bits/Hz, as well as robust and adaptive scheduling mechanisms which make the most of the available RF environment and actual physical conditions. Its design also defines advanced medium access control mechanisms (namely OFDMA) and advanced antenna technologies such as MIMO which enhances robustness and throughput by using several antennas for transmission and reception. Added up to the support of QoS features and services, such as IP connectivity and VoIP, turns WiMAX into a very appealing technology.

WiMAX advantages [AND 07], based on its technical features, will be further explained. First of all, WiMAX is an IP-based architecture where services are delivered end-to-end based on this model. This design allows the use of the applications and services already available for IP, while reducing the communication processing costs. At the same time, it seamlessly interoperates with other network types such as 3G mobile, wireless and wired networks, so it does not loose existing infrastructure investments. Furthermore, the Quality of Service (QoS) capabilities included in WiMAX allows the handling of a wide range of traffic flows with different QoS requirements. Real-time and non real-time traffic, as well as constant and variable bit rate data traffic, can coexist to manage delay-sensitive voice and multimedia services along with regular downloads. WiMAX also provides strong security mechanisms accommodating several user credential alternatives (such as digital certificates and smart cards) in its flexible authentication architecture, advanced key-management protocols and strong symmetric-key encryption based on the Advanced Encryption Standard (AES).

At the lower level, WiMAX also introduces several characteristics which boost its performance. A basic concept in this area is the Orthogonal Frequency Division Multiplexion (OFDM) used by WiMAX at the physical level. OFDM is a multi-carrier modulation scheme where a high bitrate stream is divided in to several lower bitrate streams and each one is transmitted using a different subcarrier. This approach allows minimizing intersymbol interference and increasing the duration of each transmitted symbol, so reducing the impact of signal spread delay. OFDM improves the spectral efficiency by a smart selection of subcarriers (i.e. each orthogonal to the others) which does not require non-overlapping transmission channels. This multi-carrier approach degrades smoothly when the signal delay spread increases. The scheme is also robust against interferences which can affect part of the subcarriers and allows the permutation of the used subcarriers if required. Moreover, it can be easily implemented based on Fast Fourier Transforms (FFT). The latter OFDMA multi-access scheme also allows allocating different subcarriers for multiple users, therefore improving bandwidth exploitation and system capacity.

In fact, WiMAX can modify the per user resource allocation in a dynamic and flexible way. This can be done in three domains: in frequency, as previously explained with OFDMA; in time, based on Time Division Multiplexing (TDM) schemes, and in space, with multiple antenna techniques. This resource allocation can be modified in real-time by the base station. WiMAX also supports adaptive modulation and coding, so that it uses spectral efficient modulation techniques in favorable environmental conditions, and is able to switch to more robust (but slower) schemes when signal-to-noise ratios degrade, making the RF environment as available as possible. These low level features, combined with the scalable data rate and bandwidth support provided by WiMAX, make this technology a great choice as a wireless broadband option to provide the interconnection between the Internet and digital home services.

Considering the layer model of WiMAX, the IEEE 802.16 standard only defines the two lowest layers of the architecture (i.e. the Data Link Layer and the Physical layer) which can be integrated in other network models, in most the TCP/IP stack. The Data Link Layer is divided into two sublayers: the Logical Link Control (which usually applies the IEEE 802.2 standard), and the Medium Access Control (MAC). The MAC layer is split in to three sublayers [NUA 07]: the Convergence Sublayer, which receives higher-layer data, process them if required and classify them to choose the right QoS mechanism; the Common Part Sublayer, which establishes and maintains the connection between both sides, and provides multiple access, frame construction and bandwidth allocation; and the Security Sublayer, which handles key management, authentication, encryption and data integrity. Last but not least, the Physical Layer manages data transmission through the air interface by handling the type of signal used, the modulation and all physical characteristics. Although the IEEE 802.16 standard defines five physical interfaces, only two of them (OFDM and OFDMA) are included in WiMAX. The underlying concept of these schemes, as well as the advantages introduced by the WiMAX physical data communication design, have been presented previously.

Regarding network topology, WiMAX allows two possible cases: a Point-to-Point (PMP) topology and a Mesh topology. PMP is a centralized topology where the base station (BS) is the centre of its own network of subscriber stations (SS), which are only allowed to communicate with their BS. On the other side, in a mesh topology, each SS can communicate with any other SS and, if required, can communicate with the BS through several hops of SSs, thus extending the range of the BS. Nowadays, a user can find in the market subscriber units as WiMAX-enabled laptops, handsets or mobile phones, and a wide range of consumer electronic devices are expected to arrive. These devices will be directly connected to the WiMAX network deployed by their service provider in order to access the Internet. As in 2010, Wi-Fi is a much more widespread technology embedded in consumer devices, although a WiMAX gateway with integrated WiFi access can be used as a bridge between the WiMAX Internet connectivity and the WiFi or Ethernet LANs already available in the user's digital home.

WiMAX has the potential to play an important role in providing high quality Internet access for digital home environments. It provides an alternative to fixed cable and DSL for the last mile broadband access, as well as high-speed services for mobile and handset devices. This technology can be used alone or as a backup alternative in the case of service outage, providing a home or business continuity. WiMAX can be the technology selected to connect home services to the main networks in areas with complex geography where the deployment of a wired infrastructure would be expensive, in areas of low population density or in developing countries where the existing wired infrastructure is limited, because of the lower cost and the easier deployment of its infrastructure.

3.2.6. Long Term Evolution (LTE)

Long Term Evolution (LTE) is a new cellular radio standard which defines the next-generation evolution of the Universal Mobile Telephone System (UMTS). As discussed in the presentation of UMTS, the GSM family of technologies is the dominant cellular systems with about 90% of the global market share in 2010. The development of the LTE specifications is managed by 3GPP [3GP 10] which introduces the upgrades and evolutions of the GSM technology in the form of “releases” (i.e. revisions to the previous standards).

As a 40x-100x increase in mobile broadband traffic is expected in the near future and as Internet-friendly mobile devices are becoming widespread, LTE is now the main cellular industry direction. Although a feasibility study of LTE appeared in 3GPP's Release 7, it was not until December 2008 that the technology specifications provided in Release 8 were complete. In 2010, the LTE ecosystem is being built and several suppliers (including Nokia, LG, Infineon, Qualcomm, Samsung and Toshiba) have already announced heterogeneous types of devices including routers, handsets, notebooks, USB modems and dongles, as well as chipsets which will embed the LTE connectivity in a variety of computer and consumer electronic devices. Even if LTE starts the race for high-speed mobile broadband networks a little bit later than WiMAX, it has the support of the GSM technologies presented previously. LTE has global acceptance by leading operators worldwide, there is spectrum available to support initial deployments and infrastructure systems are being installed. As of August 2010, there are two LTE systems launched in Sweden and Norway [SUP 10], up to 22 LTE networks expected to be in commercial service by the end of 2010, at least 45 LTE networks by the end of 2012 and 80 more network commitments in 31 countries.

The goal of LTE [KHA 09] is to design a packet-optimized radio-access technology with a simplified network architecture which provides higher data rates, a reduced cost per bit, low latency and low power consumption, flexible use of frequency bands and high spectral efficiency. LTE provides increased peak data rates. The downlink, based on OFDMA (discussed in the presentation of WiMAX technology) and several modulation schemes, can reach up to 326 Mbps with a typical user speed of 5-50 Mbps; on the other hand, the uplink, based on SC-FDMA (Single Carrier Frequency Division Multiple Access), which is better suited for transmission from hand-held devices while reducing power consumption, will support several modulation schemes and provides up to 86 Mbps with a typical user upload rate of 5-50 Mbps. The latency for the transmission of a packet from the network to user equipment has been reduced under 10 ms, and to less than 5 ms in case of small IP packets. LTE accepts a wide range of carrier bandwidths from 1.4 MHz to 20 MHz, both for uplink and downlink, while the widest bandwidth is required for the highest speeds. Despite the maximum technical speeds, the specification defines several User Equipment categories with lower levels of performance which are required for practical reasons in order to enable a range of implementation choices for system deployment. In UE categories, downlink/uplink peak rate ratios range from 10/5 Mbps in Cat. 1 to 300/75 Mbps in Cat. 5, all of them using a 20 MHz bandwidth and multi-antenna configurations from 2x2 MIMO to 4x4 MIMO.

Regarding the frequency bands used by LTE around the world, several options are available. 2.6GHz will be the key band in Europe, Asia, Middle East and Africa as it has been acquired already in several locations and licenses have been granted in countries such as Germany, Sweden, Denmark and China. However, 1.8 GHz is also considered promising as its coverage area is two times larger than 2.6GHz, it is already available in Europe and it enables the possibility to reuse antenna of GSM 1.8GHz and UMTS 2.1 GHz. LTE based on 1.8 GHz is estimated to be ready for mass market in 2012. Last, but not least, as a result of the switchover to digital terrestrial TV, the Digital Dividend spectrum in 700-800 MHz has been freed up and is being considered for LTE deployment. The Digital Dividend spectrum provides very good propagation characteristics which would enable extending mobile broadband to rural areas.

As a standard oriented to mobile broadband networks, LTE performance has been optimized for low speeds (i.e. 0-15 km/h), with high performance at 15-120 km/h and even still providing a functional support at 120-350 km/h, while 350-500 km/h is under consideration. As LTE has focused on high-speed data services, voice services were not initially considered, but the Voice over LTE (VoLTE) initiative presented in November 2009 works to implement voice and SMS, as well as roaming over LTE.

The complete LTE system architecture has undergone a redesign known as System Architecture Evolution (SAE) which was standarized in 3GPP Release 8. The architecture is based on the GSM/UMTS core network, but it has been optimized to simplify the architecture, its operations and to provide a cost-efficient deployment. The result is the Evolved Packet System (EPS) which is the correct term for the overall system, although it is commonly known as LTE/SAE or LTE. The EPS consists of three parts: the Evolved Packet Core (EPC) which is a new all-IP packet core network; the Evolved UTRA (E-UTRA) based on the previous UMTS Terrestrial Radio Access (UTRA) which defines the user equipment and air interface; and the Evolved UTRAN (E-UTRAN) based on the old UTRAN, which used to define the Radio Network Controller (RNC) and Node B (i.e. 3G femtocells). However, in the simplified architecture of the new version, RNC is eliminated from the data path and Node B is substituted by eNodeB. The complex functionality which used to implement RNC is distributed in E-UTRAN between eNodeB, the Serving Gateway and Core Network MME entities.

The new LTE/SAE system [LES 08] is a flat architecture optimized for packet-switched traffic where the core network has moved towards an all-IP architecture. There is only one packet domain which supports all services. The system provides efficient support for IP-based non-real-time services, but the resource management scheme has also been designed to support real-time services regarding transfer delay and bit rate. The SAE architecture supports circuit-like services providing constant bit rate transmission and constant delay, as well as interoperability towards traditional PSTN networks, and maintains voice call continuity. In contrast with the previous UTRAN which allowed the allocation of both high-speed shared channels and dedicated radio resources to guarantee bit rate services, the new approach introduces a fully shared radio allocation scheme in order to maximize resource usage. The system provides seamless mobility between heterogeneous access networks including non-3GPP access technologies. It should be pointed out that other high-speed wireless technologies such as WiFI or WiMAX only define the physical and data link layers, but do not consider the higher layers. The complete networking framework provided by the SAE system can potentially accommodate these alternative access technologies. In fact, 3GPP Release 9 published in December 2009 specifies the interoperability between LTE,UMTS and WiMAX.

LTE is making its way to be recognized as a 4G technology, the next generation of global broadband mobile standards. The Working Party 5D of the International Telecommunications Union (ITU) is responsible for specifying the features that a 4G technology must fulfill. The ITU denotes these next generation systems as International Mobile Telecommunications-Advanced (IMT-Advanced) systems, an evolution of the IMT-2000 recommendations which guided the development of 3G technologies ten years before. While LTE and WiMAX where being designed, the IMT-Advanced framework had not been yet defined, so these technologies are commonly referred to as 3.9G technologies.

In 2008, ITU published the IMT-Advanced technical requirements [ITU 08a][ITU 08b], as well as their evaluation and submission guidelines. As a consequence, in September 2009 the 3GPP Partners formally submitted LTE Release 10 as a candidate 4G technology. As defined by ITU-R, the overall features of IMT-Advanced are:

– High degree of commonality and functionality worldwide while retaining the flexibility to support a wide range of services and applications in a cost efficient manner.

– Compatibility of services within IMT and with fixed networks.

– Capability of interworking with other radio access systems.

– High-quality mobile services.

– User equipment suitable for worldwide use.

– User-friendly applications, services and equipments.

– Worldwide roaming capability.

– Enhanced peak data rates to support advanced services and applications (100 Mbit/s for high and 1 Gbit/s for low mobility were established as targets for research).

LTE Advanced is expected to fulfill (and partially exceed) 4G requirements and be backward compatible with LTE Release 8. In 2010, LTE Advanced is expected to provide a download peak rate of 1Gbps in low mobility and 100 Mbps in high mobility, an improved uplink peak rate up to 500 Mbps, and to support bandwidth up to 100 MHz and 8x8 MIMO multiantenna configurations as well as reduced latency. As peak data rates do not match the experience of the typical user, IMT-Advanced (as opposed to the previous IMT-2000) has also defined goals for average performance which turn out to be very challenging targets, but expected to be fulfilled by LTE's improved spectrum efficiency.

3.2.7. Comparison of broadband technologies

	DSL	*FTTH*	*UMTS*	*WiMAX*	*LTE*
Media	Copper pair	Optical Fiber	Wireless	Wireless	Wireless
Download (Max.)	50Mbps Announced: 250Mbps	10 Gbps	42Mbps Announced: 84Mbps	72Mbps Announced: 1Gbps	326Mbps Announced: 1Gbps
Download (Typical)	2-10Mbps	20-100Mbps	3.6-7.2Mbps	5-15Mbps	5-50Mbps

Upload (Max.)	25Mbps Announced: 100Mbps	10Gbps	11.5Mbps Announced: 23Mbps	72Mbps (shared)	86Mbps Announced: 500Mbps
Frequency band	25kHz-30MHz	-	850/900/1700/1900/2100 MHz	2.3/2.4/2.5 /3.5/5.8GHz +IMT-2000 Bands	2.6GHz, 700/800MHz +UMTS bands
Bandwidth	1.1-30MHz	-	5-10MHz	3.5-10MHz	1.4-20MHz
Range	7Km	20Km	100Km	50Km	100Km

Table 3.4. *Technical characteristics of broadband technologies*

Table 3.4 compares the relevant characteristics of the broadband technologies. The 'Max.' data rates refer to the maximum theoretical data rate to be reached by current and announced revisions of the given technologies. As the maximum rates deeply differ from the most typical data rates offered to the end user, the latter data is also provided. It must be taken into account that even the provided data rates are 'up to' speeds and that the final user experienced data rate may (and will) vary. In the fixed broadband technologies, the range refers to the wire length from the active transmission equipment deployed by the network operator to the user's home. In the wireless technologies, the range refers to the maximum distance from the cell base to the (mobile) user equipment.

Whenever an adequate wire-based infrastructure is available, fixed broadband technologies are usually the best option in order to provide Internet access to the digital homes, as they typically offer the best performance/cost ratio. Mobile broadband technologies are usually a better option in rural, geographically complex, and underdeveloped areas where the cost of deploying fixed infrastructures is excessive. It is also the case in homes which are too far from the broadband active transmission equipment or when the quality is not adequate and in scenarios where mobility capabilities are also required. Considering the fast evolution of mobile broadband networks, if the final user cost is moderate, they can also be considered a proper alternative in areas usually dominated by fixed technologies. In fact, in July 2009, the proportion of fixed broadband lines was almost six times more than the number of mobile broadband lines with dedicated devices (e.g. service cards, modems and keys) according to the European Commission [BRO 09]. However, the penetration of the mobile alternatives had increased a 50% in only six months.

Between the fixed broadband solutions, DSL technologies are a widespread alternative representing four out of every five fixed lines in Europe. The DSL technologies allow reusing the copper pair infrastructure already available from the POTS. It reduces the installation cost to a fraction of the cost of the FTTH deployment while providing adequate broadband speeds for current applications. However, DSL technologies present several limitations compared to other alternatives. First of all, the maximum data rate decrease abruptly with the distance from the home to the active equipment installed by the service provider. As a consequence, the end-user typically receive a fraction of the “up to” advertised speed. Secondly, the performance is subject to noise, interference, line stability and copper line characteristics which further influence the final user experience. Last but not least, the technology is reaching the bandwidth limits of the old copper lines. As the bandwidth requirements of the digital home increase due to new applications such as high quality video streaming, multitasking and online backups, DSL technologies could suffer from scalability issues and turn out to be insufficient. Another popular fixed alternative is the Hybrid Fiber Coax (HFC) technology presented in the introduction. It requires the deployment of a new network usually carried out by cable TV companies. HFC is able to provide data rates up to 340-440Mbps in the downlink and 120Mbps uplink according to the last DOCSIS 3.0 and EuroDOCSIS 3.0 specifications. However, these data rates require to bond up to 8 channels (which are sacrificed from the TV offer). Moreover, the combined channel is shared by more subscribers increasing contention and reducing the throughput.

On the other side, FTTH technologies are foreseen as the upcoming path for fixed broadband networks. Although current penetration around the world is still reduced, it has increased of more than a 30% during the last year and the number of FTTH/B subscribers could attain all other fixed broadband technologies in the following few years [APA 10]. FTTH provides the highest bandwidth capabilities, including the uplink (typically limited in other solutions). Moreover, the technology is far from its limit, providing a scalable solution for the future digital home requirements. In contrast with DSL technologies, data rate remains stable within the operative distance range. These features added to high network reliability lead to a better user experience. However, FTTH infrastructures require installing a fiber connection to each home/building along with expensive transmission equipments. As a result, deployment cost becomes very high and this is the main reason why DSL technologies are still the most widespread alternative.

As previously introduced, mobile broadband technologies are a relevant option for areas without fixed infrastructure, as well as a convenient 'last mile' alternative as they do not require the costly deployment to each building or individual home. As current and upcoming versions will be able to satisfy the requirements of most digitals homes, they are expected to conquer part of the fixed broadband market. However, there are new factors that must be considered in the mobile alternatives. The network performance obtained are affected by the weather conditions (e.g. raining reduces the performance) and by the position of the mobile equipments and antennas in the building. Moreover, network congestion becomes a more relevant aspect. In fact, network operators are limited to use the costly licensed frequency ranges. The frequency bandwidth available must be shared by all users which has an impact on the reliability and throughput of the network, especially during peak times. As a result, service providers apply fair use policies which limit the range of applications (e.g. P2P and VoIP applications) or the amount of bandwidth consumption (e.g. reducing the data rate if the threshold is exceeded). All these factors may have an impact on the digital home experience and should be considered.

As presented in the subsections of the respective technologies, 3G networks are extensively deployed and available all around the world, while WiMAX technology adoption has recently started and LTE is still in its very beginning. Compared to 3G/UMTS, emerging pre-4G technologies support new schemes which exploit multiuser and frequency diversity and provide flexible and dynamic adaptation to the current RF environment. The latest releases of 3G/UMTS have incorporated advanced features and should provide a performance and throughput similar to the initial pre-4G versions. However, the emerging technologies have been designed since the beginning as an all-IP architecture and include advanced technical features such as MIMO multi-antennas configurations, elements which have been add-ons to the initial 3G/UMTS technology. The new technologies will continue to improve and bring many features such as a higher spectral efficiency, peak data rates, greater system capacity, flexibility and throughput.

Considering the upcoming 4G technologies, the contenders come from two different perspectives: WiMAX was designed by the computer industry, while LTE has been defined by the cellular industry. Although both can be adopted in the digital home, this origin may have an impact in their deployment and final features. WiMAX is able to use both the licensed and unlicensed frequency spectrum, while LTE is limited to the first range. As a result, a proprietary WiMAX network can be deployed, while LTE options are limited to the deployments by local network operator. WiMAX hit the market before LTE, and, as a consequence a higher number of networks and a wider range of devices are currently available. However, LTE has the support of the widespread GSM industry which will boost the number of network deployments around the world and its adoption in manufacturers' product catalogs. The 'mobility' provided by WiMAX is usually reduced to the area(s) where the operator has deployed its network, while LTE will potentially provide national mobility and roaming capabilities (at an extra cost). Affordable WiMAX-based Internet access options are becoming popular, while the cost of LTE-based alternatives needs to be settled.

Regarding their technical capabilities, both technologies share several radio-interface attributes. Both provide flexible bandwidths, support MIMO antenna configurations, OFDMA access methods in the downlink and FDD/TDD multiplexing, while they differ in the uplink access method (i.e. OFDMA in WiMAX and SC-FDMA in LTE). The performance and data rates announced in their next revisions are similar. Whether 802.16m or LTE Advanced will be a better option will be determined by the real performance and market penetration of these two new technologies.

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