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Evolution of the Wireless PAN and LAN standards

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Abstract

In the forthcoming fourth-generation (4G) all-IP mobile communications era, apart from the cellular/mobile networks, Wireless Personal Area Networks (PANs) and Local Area Network (LAN) are expected to fulfil the "anywhere and anytime" ubiquitous services' requirement. Users will request forming "ad hoc" personal area networks to enable personal devices to autonomously inter-communicate, while Wireless LANs will enable communication with colleagues at work, at conferences, at "hot spots", at home, or on the move. In parallel, advanced sensor devices of the surrounding environment will recognize the user and provide for added value services. In order to achieve this, open standard interfaces and interoperability between devices and manufacturers are mandatory. In this paper, we describe the most important, mature Wireless PAN and LAN standards, and introduce some evolving new standards.

Keywords: Wireless Personal Area Networks; Wireless LAN; Bluetooth; DECT; IEEE 802.11; IEEE 802.15.3

Abbreviations: AES, Advanced Encryption Standard; BPSK, Binary Phase Shift Keying; CCK, Complementary Code Keying; CSMA/CA, Carrier Sense Multiple Access with Collision Avoidance; CTM, DECT/Cordless Terminal Mobility; ETSI, European Telecommunications Standards Institute; DCF, Distributed Coordination Function; DCSA, Dynamic Channel Selection and Allocation; DECT, Digital Enhanced Cordless Telecommunications; DLC, Data Link Control; DSSS, Direct-Sequence Spread Spectrum; FHSS, Frequency Hopping Spread Spectrum; GAP, Generic Access Profile; GIP, DECT/GSM Interworking Profile; GPS, Global Position System; HCI, Host Control Interface; IIP, DECT/ISDN Interworking profile; IP, Internet Protocol; IR, Infrared; ISDN, Integrated Services Digital Network; LAN, Local Area Network; L2CAP, Logical Link Control Adaptation Layer Protocol; LLC, Logical Link Control; MAC, Medium Access Control; MC, Multicarrier; OFDM, Orthogonal Frequency-Division Multiplexing; PAN, Personal Area Networks; PDA, Personal Digital Assistant; PWT, Personal Wireless Telecommunications; QAM, Quadrature Amplitude Modulation; QoS, Quality of Service; QPSK, Quadrature Phase Shift Keying; RAP, DECT/Radio Local Loop Access Profile; RF, Radio Frequency; RFCOMM, RF Communication; RLC, Radio Link Control; SDP, Service Discovery Protocol; SIG, Special Interest Group; SOHO, Small Office/Home Office; TCM, Trellis Coded Modulation; TCS, Telephony Control Specification; TDD, Time Division Duplex; TDM, Time Division Multiplexed; TDMA, Time Division Multiple Access; WEP, Wired Equivalent Privacy; WESA, Wireless Ethernet Compatibility Alliance; Wi-Fi, Wireless Fidelity; WLAN, Wireless LAN; WPAN, Wireless PAN; WRS, Wireless Relay Station.

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1. Introduction

Wireless mobile is a very attractive market. It has sparked extensive development and deployment of powerful standards for various mobile applications over the last decade. In the forthcoming forth-generation (4G) mobile/wireless era, however, apart from the cellular/mobile networks, Wireless Personal Area Networks (PANs) and Local Area Network (LAN) are expected to fulfil the "anywhere and anytime" ubiquitous services' requirement. As it is shown in Fig. 1, the Wireless LAN, the Wireless PAN and the cellular technologies are complementary as far as the bandwidth, the mobility/coverage and the deployment cost are concerned. Though, overlapping may occur in some areas or applications, in the general case they target complementary market segments.

The scenario that is foreseen for wireless/mobile communications is shown in Fig. 2. Users will request forming wireless, "ad hoc", personal area networks, centred on the individual. PAN networks will include any collection of devices that belong to or are carried by a networked user (e.g. cell phone, laptop, earphones, GPS navigator, palm pilot, beeper, portable scanner, etc.) and form his/her personal "PAN bubble". The bubble may expand or shrink dynamically depending on user's environment and needs. For example, it may connect to environment sensors or actuators. Such access is important when the mobile user enters into a new location and aims to quickly sense and control the environment (e.g. gain access/connectivity, control the temperature, adjust the lighting) or get recognized by the environment sensors (e.g. welcome message, uninterrupted communication, automatic selection of a background music, personalised sales messages, etc.).

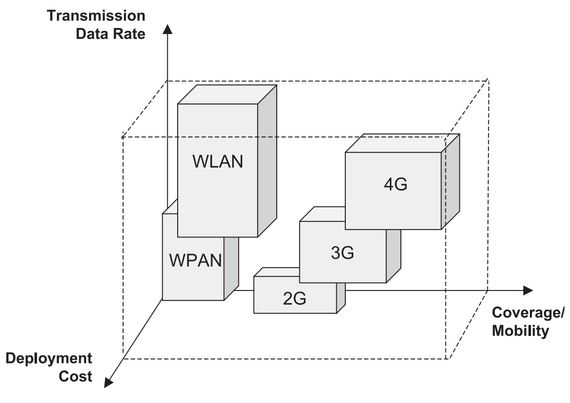

Fig. 1. Wireless LAN, PAN, cellular technologies comparison.

The PAN will gain access to the IP Core Network and the Internet, or communicate with other PANs either directly or via Wireless LANs or 3G/4G Cellular Networks. In the near future, Wireless LANs may be established practically everywhere, from public "hot spots" (e.g. stations, conference centres, malls, corporate environments) to the home [1]. In all cases, in order to achieve seamless communication, open standard interfaces and interoperability between devices and manufacturers are mandatory.

In this paper, we describe the most important, mature and efficient WPAN and WLAN standards, and introduce some evolving new standards in these areas. In Section 4, we recapitulate and provide a comparison between the different standards.

2. Wireless Personal Area Network standards

A Wireless PAN is a human centred network, connecting personal communication devices in a spontaneous architecture, within a short-range, "personal" or "body" space. Data may be exchanged between devices carried by the same person (e.g. phone, watch, PDA), between persons while in contact (e.g. during handshaking, business cards may be exchanged) or between the user and the environment (e.g. the car may recognize its driver, and start the engine). Various technologies have been proposed for PAN networks [2]. The dominant communication method is the RF technology and Bluetooth is the ad hoc standard.

IEEE has started standardizing the Wireless PANs technologies in the IEEE 802.15 working group. In more details, the IEEE 802.15 has defined the following working subgroups:

- *802.15.1*, which is almost identical to Bluetooth standard;
- *802.15.2*, which works towards overcoming the interference between 802.11 WLANs and PANs operating at the 2.4-GHz band;
- *802.15.3*, which provides higher data rates ad hoc networks; and
- *802.15.4*, which studies lower data rate and lower cost versions, e.g. sensor networks.

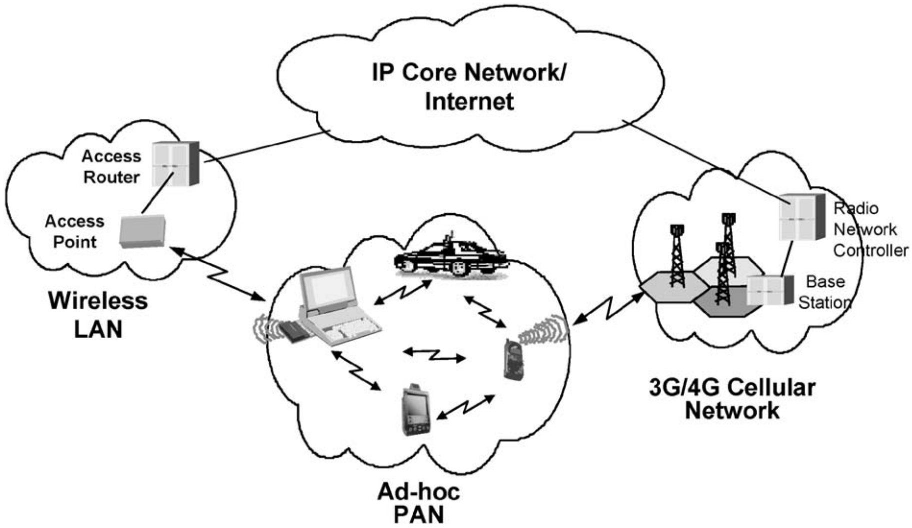

Fig. 2. Foreseen wireless/mobile communications scenario.

In this paragraph, we focus on the Bluetooth and its evolution, and on the IEEE 802.15.3 standard.

2.1. Bluetooth

Bluetooth [3] intends to serve as a universal, low-cost, air interface, which will replace the plethora of proprietary interconnect cables between personal devices. Bluetooth is a short-range (10 cm to 10 m) Frequency Hopping Spread Spectrum (FHSS) wireless system providing up to 1 Mbps in the unlicensed 2.4-GHz band.

Within Bluetooth specification communication is based on ad hoc networking. This means that there is no base station or access point, but mechanisms and messages for Bluetooth devices to discover each other and establish point-to-point and point-to-multipoint communication links. After initial communication, however, Bluetooth standard establishes a star network topology called "piconet". When a Bluetooth device initiates a communication, it defines a new piconet cell having the device as the centre of the cell (master device) and all devices in this cell are considered slave devices. Due to a three-bit identity field, one master device may communicate with up to seven active slave devices. If more slave devices are located within the same piconet, they are inactive and no resources are allocated to them. During the lifetime of a piconet, the master device may change dynamically. Piconet cells may be combined to form a "scatternet" (Fig. 3.). In a scatternet, one or more Bluetooth devices are members of more than one piconet, acting as master device in one cell and slave device on another.

The Bluetooth protocol stack is shown in Fig. 4. The Baseband layer provides the functionality required for air interface packet framing, establishment and maintenance of piconets and link control. The Link Manager is responsible for link setup and control including authentication, encryption control, physical parameters control, etc. The Host Control Interface (HCI) provides for a mechanism whereby the higher layers of the protocol stack can delegate the decision on whether to accept connections to the link manager and whether to switch on filters at the link manager. The Logical Link Control Adaptation Layer Protocol (L2CAP) provides connection-oriented and connectionless data services to higher layer protocols. Finally, Service Discovery Protocol (SDP) allows Bluetooth devices to discover what services are available on a device, RFCOMM provides an emulation of serial ports, and Telephony Control Specification (TCS) provides an adaptation layer that enables Q.931 call control services.

Bluetooth is ideal for both mobile office workers and small office/home office (SOHO) environment [4]. However, the low bandwidth capability permits only limited and dedicated usage, and inhibits Bluetooth from multimedia networking.

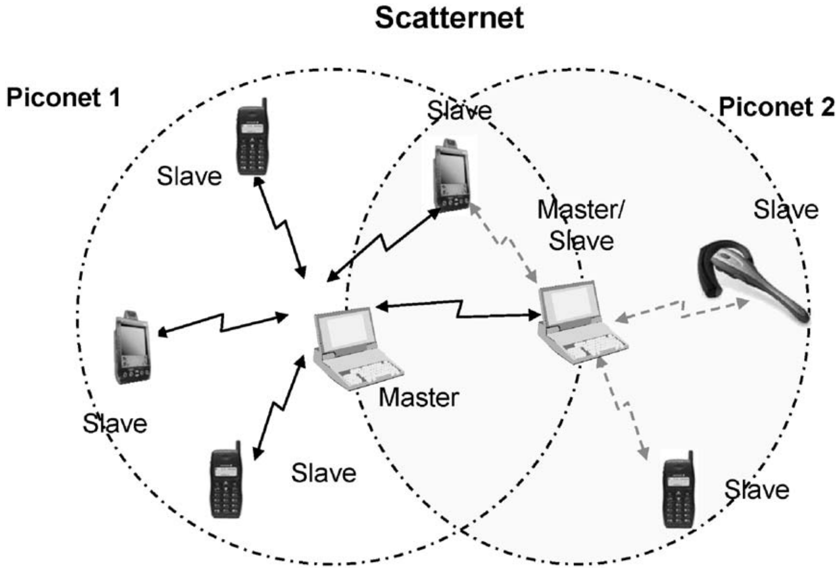

Fig. 3. Bluetooth scatternet architecture.

2.2. Bluetooth 1.1 and 2.0

Bluetooth 1.0 was intended to serve as a universal, low-cost, wireless cables replacement. Throughput, interoperability and security had never been among the initial requirements; however, during the maturing phase of the standard, new requirements have appeared that evolved to Bluetooth version 1.1.

Interoperation between devices from different vendors was one of the main issues. For security reasons, Bluetooth devices communicate via encrypted links. During the establishment of a new link, the devices exchange public keys in order to confirm their identities. The Bluetooth 1.0 specification leaves important details open to manufacturers' interpretation. As a result, Bluetooth 1.0 compliant devices from different manufacturers may fail to negotiate the initial link establishment. The problem appears if both devices believe that they are the master communication devices. Bluetooth 1.1 solves this initial interoperability problem by requiring the slave devices to acknowledge to the master device and confirm their role as slaves.

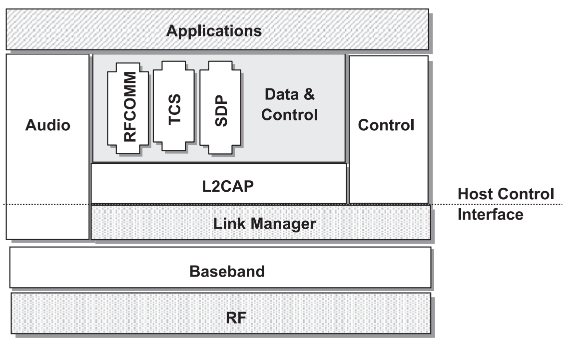

Fig. 4. Bluetooth protocol stack.

Another important interoperability problem was related to the protocol frame structure. Bluetooth 1.0 supports optionally up to five slots per packet to achieve the maximum data transfer rate of 720 kbit/s per channel. In a Bluetooth v 1.0 communication, if the master transmits more slots per packet than the slave can support, the communication will fail. Bluetooth 1.1 specifies a control protocol to inform the master device on slaves communications' capabilities and on the maximum number of slot they can support.

Bluetooth 1.0 had also to assure worldwide operation and compliance with all countries' frequency plan. Bluetooth defines a frequency hopping pattern with 79 hops in the unlicensed 2.4-GHz band. This frequency band is recognized by international regulatory agencies, such as the FCC (USA), ETSI (Europe), and the MKK (Japan) for unlicensed radio operations. For more details, the worldwide frequency allocations for unlicensed operation in the ISM band are summarized in Table 1.

However, some countries, including Japan, France, and Spain, utilize part of the 2.4-GHz frequency for noncommercial purposes. In order to extend coverage in these countries, a different hopping pattern with 23 hops was defined. However, Bluetooth devices that use the 79-hop pattern are incompatible with those that follow the 23-hop pattern. To overcome this interoperability issue, the Bluetooth Special Interest Group (SIG) managed to gain worldwide permission for the 79-hop pattern equipment. In this way, the 23-hop option was removed, and Bluetooth 1.1 compliant devices use only the 79-hop pattern.

The success of Bluetooth 1.1 initiated Bluetooth 2.0 specification, which will be able to transfer up to 20 Mbps in ranges of up to 50 m. Moreover, the direct integration of Bluetooth 2.0 chips into mobile terminals (e.g. PDAs and phones) will offer the users the capability to use interchangeably the local Bluetooth connections wherever available or roam to the third-generation (3G) and 2.5G mobile networks. This will enable greater flexibility introducing the wide availability of Personal Access Networks (PAN).

2.3. IEEE 802.15.3

The 802.15.3 [5] is a new specification designed from scratch in order to support ad hoc networking and multimedia QoS guarantees. IEEE 802.15.3 operates in the unlicensed frequency band of 2.4 GHz and is designed to achieve data rates from 11 to 55 Mb/s, targeting distribution of high-definition video and high-fidelity audio. IEEEE 802.15.3 (Fig. 5) uses five types of modulation formats: trellis coded Quadrature Phase Shift Keying (QPSK) at 11 Mpbs, uncoded QPSK at 22 Mb/s, and 16/32/64-Quadrature Amplitude Modulation (QAM) at 33, 44 and 55 Mb/s, respectively (TCM) [6]. The base modulation format

Table 1
Global spectrum allocation at 2.4 GHz

Region	Allocated spectrum (GHz)
US	2.4000–2.4835
Europe	2.4000–2.4835
Japan	2.4710–2.4970
France	2.4465–2.4835
Spain	2.4450–2.4750

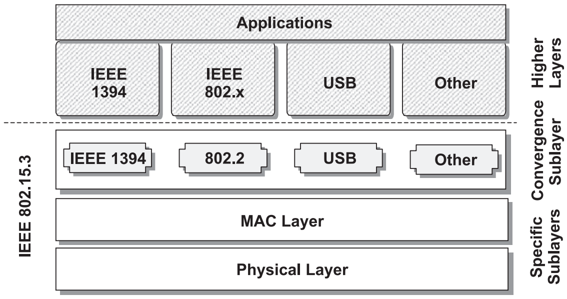

Fig. 5. IEEE 802.15.3 protocol stack.

is QPSK (differentially encoded). Depending on the capabilities of devices at both ends, the higher data rates of 33–55 Mb/s are achieved by using 16/32/64-QAM schemes with eight-state 2D trellis coding. Finally, the specification includes a more robust 11 Mb/s QPSK TCM transmission as a dropback mode to alleviate the well-known hidden node problem. The 802.15.3 signals occupy a bandwidth of 15 MHz, which allows for up to four fixed channels in the unlicensed 2.4-GHz band.

IEEE 802.15.3 is optimized for short-range transmission limited to 10 m, enabling low cost and integration into small consumer devices, e.g. a flash card or a PC Card. The PHY layer also requires low current drain (less than 80 mA) while actively transmitting or receiving data and minimal current drain in the power save mode. Finally, the selection of the 2.4-GHz band is highly important, since the 5-GHz band is prohibited for outdoor usage in many countries worldwide, including Japan.

3. Wireless LAN network standards

Wireless LAN standards will also play an important role in the evolution of personal communications. They are expected to cover local areas, generate pico-cells and provide interconnectivity between Wireless PANs and broadband wireless/mobile networks. Moreover, Wireless LANs in cooperation with higher layer protocols standardization efforts are expected to solve the interoperability problems and offer an unprecedented opportunity to increase the networking customer base beyond the satiated corporate environment [7]. In this section, we highlight the most important, mature and evolving Wireless LAN (WLAN) standards.

3.1. Digital Enhanced Cordless Telecommunications (DECT)

Digital Enhanced Cordless Telecommunications (DECT) is a flexible digital radio access standard for cordless communications in residential, corporate, and public environment. In Europe, DECT utilizes the 1880–1900 MHz frequency range. In other parts of the world, frequencies between 1900 and 1930 MHz may be used. Moreover, the North American Personal Wireless Telecommunications standard (PWT) and its extension (PWT/E) are based on DECT. PWT operates in the US unlicensed band 1910–1920 MHz, while PWT/E into the licensed bands 1850–1910 and 1930–1990 MHz.

DECT was introduced by ETSI for cordless telecommunications, mainly focusing on the telephony and the ISDN access [8]. After the first version of the standard was released in 1992, the DECT standardization work concentrated on the definition of standard interworking profiles. In 1994, the Generic Access Profile (GAP) was completed. GAP is the basis for all other DECT speech profiles, and contains the protocol subset required for the basic telephony service in residential cordless telephones, business wireless PBX, and public access applications. Other interworking profiles available today are the DECT/GSM interworking profile (GIP), the DECT/ISDN interworking profile (IIP), the DECT/Radio Local Loop Access Profile (RAP), the DECT/Cordless Terminal Mobility (CTM) Access Profile (CAP), and multiple Data Service Profiles. The second version of the DECT standard was released in 1995, incorporating all extensions and enhancements to the DECT base standard. Some examples of these extensions are as follows: inclusion of emergency call procedures to aid acceptance of DECT for public access applications, definition of the Wireless Relay Station (WRS) as a new system component to enable more cost-efficient infrastructures, and description of the optional, direct, portable-to-portable communication feature for DECT.

Currently, DECT is supported and promoted by the DECT Forum, with representatives in all the major geographical regions around the world. DECT contains many forward-looking technical features and profiles. DECT systems' efficiency is based on the following mechanisms and operational characteristics:

- *Access method*. The DECT radio interface is based on the Multicarrier/Time Division Multiple Access/Time Division Duplex (MC/TDMA/TDD) radio access methodology. Basic DECT frequency (1880–900 MHz) is allocated to 10 carrier frequencies, and the time is organized in frames. Each frame lasts for 10 ms and consists of 24 timeslots separated in two fixed parts. The first part is used for the base station to the terminal transmission (downlink) and the second for the reverse direction (uplink).
- *Dynamic Channel Selection and Allocation*. In order to increase the frequency allocation efficiency, capacity and QoS, DECT utilizes a continuous Dynamic Channel Selection and Allocation (DCSA) mechanism. The DCSA mechanism aims to set up the radio links on the least interfered available channel.
- *Mobility and handover*. Mobility functions in DECT architecture provide the ability to the terminals to freely roam through a (multi-)cellular DECT infrastructure. Wireless users with authorized access to the network can initiate and receive calls at any location within the DECT coverage area and roam between DECT pico-cells when in active communication.
- *Diversity*. In order to face very fast channel fades, DECT base station can be equipped with antenna diversity. In this case, the terminal utilizes a special signaling protocol to control the base-station's antenna diversity.
- *Security*. DECT provides a security mechanism sufficient for all commercial, personal and in-home communications. The DCSA mechanism is combined with effective subscription and authentication protocols to prevent unauthorized access. Moreover, an advanced ciphering concept provides protection against eavesdropping.

DECT is the default standard for cordless phone communications. For data transmission purposes, throughput rates up to 552 kbit/s in 24 kbit/s steps can be achieved, with full security and very low bit error rate (10^{-9}). With eight-level modulation, the maximum data rate (unidirectional) may be up to 2 Mbps.

3.2. IEEE 802.11

IEEE 802.11 [9] is the most mature wireless protocol in the unlicensed band of 2.4 GHz for Wireless LAN communications, tested and deployed for years in corporate, enterprise, private and public environments. Definition of the IEEE 802.11 started in 1990 and the first version of the standard was almost finalized by mid 1996. In 1997, the IEEE validated the initial 802.11 specifications as the standard for Wireless LANs. The first version of 802.11 provided for 1–2 Mbps data rates, fundamental signalling methods and services. The major drawback of this version was the limited throughput. In 1999, IEEE enhanced the 802.11 to 802.11b standard, which is able to support transmissions of up to 11 Mbps, comparable to the wired 10 Mbps Ethernet (10BaseT).

As all IEEE 802 × protocols, IEEE 802.11 covers the lower layers of the OSI model, and specifies the Physical and the Medium Access Control Protocol (MAC). Moreover, the IEEE 802.2 Logical Link Control (LLC), 48-bit addressing and the upper layers of the protocol stack remain unchanged as other 802 LANs, allowing for very simple bridging from wireless to IEEE wired networks, (Fig. 6).

The 802.11 standard defines three types of physical layer specifications: Direct-Sequence Spread Spectrum (DSSS), Frequency Hopping Spread Spectrum (FHSS), and infrared (IR). In practice, only the first two, DSSS and FHSS, are present in the market.

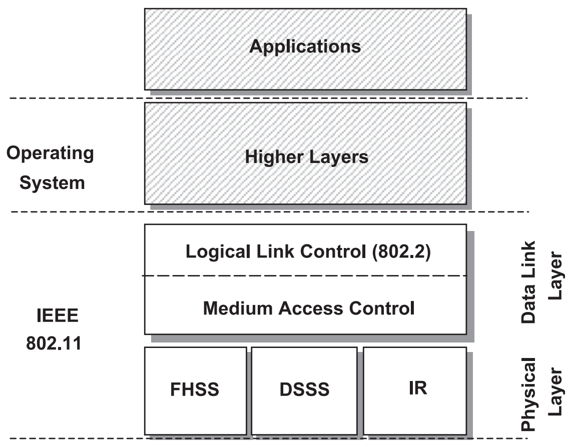

Fig. 6. IEEE 802.11 protocol stack.

In the DSSS technique, the 2.4-GHz band is divided into 14 channels of 22 MHz each. Adjacent channels partially overlap one another, and only three are completely nonoverlapping. Data is sent across one of the channels without hopping to other channels. The user data are modulated by a single, predefined wideband-spreading signal. The receiver knows this signal, and is able to recover the original data.

In the FHSS technique, the 2.4-GHz band is divided into a large number of subchannels. Just like Bluetooth, the number of subchannels differs between geographical regions, i.e. 79 frequencies in US/Europe and 23 in Japan. However, in IEEE 802,11, the peer communication endpoints agree on the frequency hopping pattern, and data is sent over a sequence of the subchannels. The transmitter sends data over a subchannel for a fixed length of time (dwell time), then changes frequency according to the hopping sequence and continues transmission. As the dwell time is rather long, the transmitter can send multiple symbols at the same frequency. FHSS techniques allow for a relatively simple radio design, but are limited to speeds of no higher than 2 Mbps. This limitation driven primarily by FCC regulations that restrict subchannel bandwidth to 1 MHz leads to hopping overhead.

The 802.11 MAC, like the 802.3 Ethernet MAC, has to support multiple users on a shared medium. In order to avoid collisions in the wired Ethernet, the terminal transmits and listens at the same time using the Carrier Sense Multiple Access with Collision Detection (CSMA/CD) protocol. In radio systems, however, the terminal is not able to transmit and receive simultaneously, thus it is not able to detect a collision. Thus, 802.11 uses a modified protocol, called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) or Distributed Coordination Function (DCF) [10]. CSMA/CA attempts to avoid collisions by using explicit packet acknowledgment (ACK), which means that an ACK packet is sent by the receiving station to confirm that the data packet arrived integral.

3.3. IEEE 802.11b

The main enhancement of 802.11b was the standardization of a physical layer, able to support higher speeds of 5.5 and 11 Mbps [11]. As 802.11 FHSS systems cannot support the higher speeds without violating current FCC regulations, DSSS technique was selected as the exclusive physical layer technique. In this way, 802.11b is backwards compatible and can interoperate at 1 and 2 Mbps only with the 802.11 DSSS systems, and not with FHSS systems. To increase the data rate, 802.11b specifies an advanced coding technique called Complementary Code Keying (CCK). CCK consists of a set of 64 code words, 8-bit long, which can be distinguished by the receiver even in the presence of noise or interference. The CCK encodes 4 bits per carrier to achieve data rate 5.5 Mbps, and 8 bits per carrier to achieve 11 Mbps. Both speeds use QPSK modulation and 1.375 Msps symbol rate. The differences between the 802.11 physical layers are shown in Table 2.

The 802.11b provides 11 Mbps in distances up to 300–400 m in open, outdoor environment and 30–50 m in indoor environment with low noise. To support noisy environments as well as extended range, 802.11b uses dynamic rate degradation. When the terminal moves beyond the optimal range or if substantial interference emerges, 802.11b degrades transmission at lower speeds, falling back to 5.5, 2, and finally 1 Mbps. Vice versa, if the terminal returns within the optimal range or the source of interference disappears, the connection will automatically accelerate.

3.4. IEEE 802.11a

IEEE 802.11a [12] is a very promising evolution of IEEE 802.11b. It is similar to 802.11b, but provides wireless data speeds up to 54 Mbps in distances up to 50 m, and uses the 5-GHz spectrum range, which has less interference than the 2.4-GHz spectrum.

Table 2
802.11 Physical layers differences

Physical layer	Data rate (Mbps)	Bits/symbol	Code	Modulation	Symbol rate (Msps)
802.11	1	1	Barker Sequence	BPSK	1
802.11	2	2	Barker Sequence	QPSK	1
802.11b	5.5	4	CCK	QPSK	1.375
802.11b	11	8	CCK	QPSK	1.375

The physical layer of IEEE 802.11a is a multicarrier system, based on Orthogonal Frequency-Division Multiplexing (OFDM). OFDM is very efficient in time-varying environments, where the transmitted radio signals are reflected from many points, leading to different propagation times before they eventually reach the receiver. It uses 52 carriers: 48 data carriers and 4 are pilot carriers, for synchronization and control. IEEE 802.11a uses various modulation schemes, namely BPSK, QPSK, 16-QAM, and 64-QAM with 1/2 or 3/4 error-correcting code overhead. According to the modulation, each one of the data carriers may transmit raw data rates from 125 kbps to 1.5 Mbps, so the total raw bandwidth may vary from 6 to 72 Mbps. Assuming that 64QAM is used for maximum bandwidth (72 Mbps) reduced by 3/4 error-correction code overhead, IEEE 802.11a may achieve up to 54 Mbps useful traffic.

IEEE 802.11a uses a MAC protocol almost identical to IEEE 802.11b and it is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). An IEEE 802.11a terminal must initially sense the medium for a specific time interval and if the medium is idle it can start transmitting the packet. If the medium is not idle, the terminal begins a backoff process and wait for a time interval (min 34 μs). When the backoff time has expired, the terminal can tray to access the medium again. As collisions in wireless environment cannot be detected, a positive acknowledgement is used to notify that a frame has been successfully received.

IEEE 802.11a products are already available. However, there are certain barriers before the worldwide acceptance. First of all, the coverage range is very short. Also, the 5-GHz frequency band is not available worldwide. Japan, for example, permits the use of a smaller band, containing half the channels. In Europe, the standard does not comply with various EU requirements. Moreover, IEEE 802.11a does not provide any QoS mechanisms. Thus, Europe is promoting the High Performance Radio Local Area Network Type 2 (HiperLAN2) standard, as it guarantees QoS. A step into the direction of wide establishment of IEEE 802.11a is the creation of a multivendor interoperability certification for 802.11a products. Since 29 November 2002, Wireless Ethernet Compatibility Alliance (WECA) provides Wi-Fi equivalent certification for IEEE 802.11a products.

3.5. IEEE 802.11g

IEEE 802.11g is another important extension of IEEE 802.11b. Just like IEEE 802.11a, IEEE 802.11g extends the OSI Model Physical Layer of 802.11b, by adopting either single-carrier, trellis-coded, eight-phase shift keying modulation or OFDM schemes and achieves data rates higher than 22 Mb/s (theoretically up to 54 Mbps). However, IEEE 802.11g has two advantages over 802.11a: it operates at the 2.4-GHz band, which is now available worldwide, and it is backwards compatible with the existing installed 802.11b products. In order to achieve the latter, IEEE 802.11g drops the data rate to 11 Mbps (or even lower), while the IEEE 802.11a uses the 5-GHz radio frequency and thus it is not interoperable with the 802.11b devices.

The IEEE 802.11g is defined by the 802.11g Task Group, which was formed in September 2000 and consists of more than 100 members from various companies, consultancies, and academic institutions. Currently, IEEE 802.11g is still in draft version. It is expected that after comments from the sponsor group, it will reach version 9.0 in late 2003. IEEE 802.11g pre-products already achieve up to 24 Mb/s within 100 m in the 2.4-GHz band. However, interoperability between vendors cannot be established, as the standard has not yet been finalized.

3.6. Future evolution of IEEE 802.11

The wide acceptance of IEEE 802.11/802.11b initiated new versions and enhancements of the specification. Various IEEE task groups aim to enhance specific areas of the 802.11 standard.

- *802.11d* task group works towards 802.11b versions at other frequencies, for countries where the 2.4-GHz band is not available. Since 2002, most countries have released this band.
- *802.11e* task group works towards the specification of a new 802.11 MAC protocol in order to accommodate additional QoS provision and security requirements over legacy 802.11 PHY layers.
- *802.11f* task group aims to improve the handover mechanism in 802.11 so that users can maintain a connection while roaming between access points attached to different networks.
- *802.11h* aims to enhance the control over transmission power and radio channel selection to 802.11a, in order to be acceptable by the European regulators.
- *802.11i* aims to enhance 802.11 security. Instead of the Wired Equivalent Privacy (WEP), a new authentication/encryption algorithm based on the Advanced Encryption Standard (AES) is under preparation.
- *802.11j* is working towards IEEE 802.11a and HiperLAN2 interworking.
- *802.11m* is proposed as an IEEE 802.11 maintenance task group. The group's job will be to maintain previously published amendments, like 802.11b, 802.11g, etc.

3.7. Wireless Fidelity (Wi-Fi)

In parallel to the standards bodies, in order to ensure interoperability and compatibility across all market segments, IEEE 802.11 product manufactures have agreed on a compliance procedure called Wireless Fidelity (Wi-Fi) standard. Moreover, a Wireless Ethernet Compatibility Alliance (WECA) has been formed in order to certify Wi-Fi interoperability of new products, to certify cross-vendor interoperability and compatibility of IEEE 802.11b wireless networking products and to promote IEEE 802.11b for the business and the home applications. Members of WECA include WLAN semiconductor manufacturers, WLAN providers, computer system vendors, and software makers, such as 3Com, Aironet, Apple, Breezecom, Cabletron, Compaq, Dell, Fujitsu, IBM, Intersil, Lucent Technologies, AVAYA, No Wires Needed, Nokia, Samsung, Symbol Technologies, Wayport, and Zoom. Since 29 November 2002, WECA also provide Wi-Fi equivalent certification for IEEE 802.11a products.

3.8. HIPERLAN/2

HIPERLAN/2 is a flexible radio LAN standard designed to provide high-speed access to a variety of networks including 3G mobile core networks, ATM networks, and IP-based networks, and also for private use as a Wireless LAN system. It is the European proposition for a broadband Wireless LAN operating with data rates up to 54 Mbps at PHY on the 5-GHz frequency band.

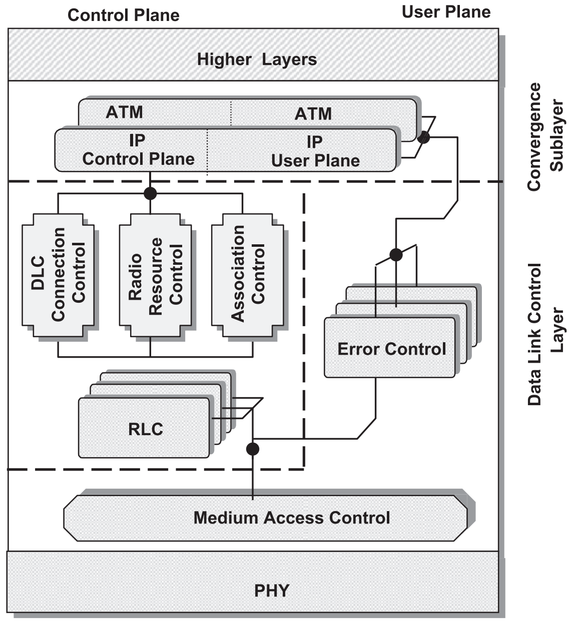

Fig. 7. HiperLAN/2 protocol stack.

HiperLAN/2 is a connection-oriented Time Division Multiplexed (TDM) protocol. Data is transmitted on connections that have been established prior to the transmission using signaling functions of the HiperLAN/2 control plane. This makes straightforward to implement support for QoS. Each connection can be assigned a specific QoS, for instance, in terms of bandwidth, delay, jitter, bit error rate, etc. It is also possible to use a more simplistic approach, where each connection can be assigned a priority level relative to other connections. This QoS support in combination with the high transmission rate facilitates the simultaneous transmission of many different types of data streams, e.g. video, voice, and data.

The HiperLAN/2 protocol stack is shown in Fig. 7 [13]. At the physical layer, HiperLAN/2 uses OFDM to transmit the analogue signals. Above the physical layer, the MAC protocol is built from scratch implementing a type of dynamic TDMA/TDD scheme with centralized control. The MAC frame appears with a period of 2 ms. The Error Control is responsible for detection and recovery from transmission errors on the radio link. Moreover, it ensures in-sequence delivery of data packets. In the Control Plane, the Radio Link Control (RLC) Sublayer provides a transport service to the DLC User Connection Control, the Radio Resource Control, and the Association Control Function. Finally, a convergence sublayer is provided for each supported network.

4. Technologies comparison

Wireless PAN and LAN standards are expected to contribute in fulfilling the “anywhere and anytime” ubiquitous services’ requirement. However, in order to achieve seamless communication, open standard interfaces and interoperability between devices and manufacturers are mandatory. In this paper, we presented some of the most important wireless technologies. Among the Wireless LAN technologies, IEEE 802.11b as an established, proven and mature technology and the broader IEEE 802.11g are expected to capture in short- to mid-term the maximum share of the

Table 3
Comparison of wireless LAN and PAN technologies

	Bluetooth 2	802.15.3	DECT	802.11	802.11b	802.11a	802.11g	HiperLAN2
Frequency band	2.4 GHz	2.4 GHz	1.8–1.9 GHz	2.4 GHz	2.4 GHz	5 GHz	2.4 GHz	5 GHz
Technology	FHSS	OFDM	GFSK	DSSS	DSSS	OFDM	DSSS/OFDM	OFDM
Max range	10 cm–10 m	10 m	80 m	150 m	150 m	50 m	100 m	80 m
Power	very low	medium	medium	medium	medium	high/medium	medium/high	medium
Complexity	1 ×	1.5 ×	1.2 ×	1.2 ×	1.2 ×	4 ×	~ 3.5 ×	2.5 ×
QoS	yes	yes	yes	Inherited only in 802.11e. Backwards compatibility is questionable.				yes
Thoughput								
Physical	≤ 10 Mbps	11–55 Mbps	≤ 2 Mbps	2 Mbps	11 Mbps	54 Mbps	54 Mbps	54 Mbps
Effective	≤ 6 Mbps	≤ 30 Mbps	≤ 1 Mbps	≤ 1 Mbps	≤ 7 Mbps	≤ 31 Mbps	≤ 22 Mbps	≤ 31 Mbps
Reg. support	worldwide					US/Asia	worldwide	Europe/Japan
Promoters	2000 +	~ 50	3000 +	100 +	100 +	~ 100	~ 100	< 50

market. The major limitation of IEEE 802.11 is the lack of QoS and isochronous transmission slots, which will be provided by IEEE 802.11e. In the Wireless PAN era, Bluetooth has already established new communications standards in personal communications networks, while IEEE 802.15.3 is also expected to cover the multimedia requirements. Table 3 provides a comparison of Wireless LAN and PAN technologies, underlining the major differences and competitive advantages.

Wireless LAN and PAN technologies have already captured a large market segment as they provide a simple, efficient, and user-friendly, alternative private networking system. Due to their market success and wide adoption, these technologies have also moved into the public sector, focusing on "hot spots" (e.g. airport, train station, conference centre, hotel) with large concentration of mobile enabled users, mostly travelling businessmen, who are equipped with mobile devices (e.g. PDAs, laptops) and want to gain instant access to their corporate Intranet and the Internet. In the future, seamless and robust universal mobility between heterogeneous Wireless LANs, PANs, and cellular networks is expected to be an indispensable feature of the wireless networks beyond IMT-2000 [14]. Future wireless networks will combine multi-vendor, multi-technologies networks in order to cover a specific geographical location. Each network (cellular, LAN, or PAN) may comply with different specifications and standards, and encompass different number of "cells", while overlapping is expected. Coverage, frequency band, licensed/unlicensed operation, terminals' density, and transmission characteristics may drastically vary. However, integration and interoperability of all these diverse technologies, along with new truly broadband wireless innovations and intelligent, user-oriented services will lead towards a new generation of heterogeneous wireless networks, which has already been called "fourth-generation" systems.

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