High-Speed Wireless Mobile LAN Communications:

Improved Error Control Mechanisms for Real-Time Services

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Resumo

Esta dissertação foca o tema do aperfeiçoamento de esquemas de controlo de erros para as comunicações digitais sem fio de alto débito. O objectivo principal é conseguir um melhor suporte da qualidade dos serviços em tempo real, como o vídeo, quando usados em redes digitais móveis sem fio.

Presentemente, as comunicações nas redes móveis sem fio de alto débito têm que suportar consideráveis variações nas condições de transmissão e nos requisitos dos serviços, precisando frequentemente de complexas modulações rádio e de códigos concatenados para controlo de erros.

No que respeita às funções de controlo de erros, é habitual implementar-se mecanismos de “Forward Error Correction” e de “Automatic Repeat reQuest” (ARQ), respectivamente, nas camadas “Physical” e “Data Link Control” (DLC) do modelo de referência OSI. Mesmo assim, os requisitos de comunicação dos serviços em tempo real de média/alta qualidade poderão ser difíceis de atingir quando as condições de transmissão forem desfavoráveis.

Para ultrapassar esta limitação, imposta principalmente pelo uso de algumas clássicas metodologias na caracterização e transporte do tráfego, propõe-se um novo conjunto de mecanismos de controlo de erros. Estes baseiam-se principalmente no uso de esquemas ARQ Híbridos e em modos de transmissão com diferentes níveis de robustez perante os erros. Neste sentido, a implementação destas novas técnicas permite, significativamente, uma melhor utilização de algumas das capacidades oferecidas pelas modernas redes locais (LANs) sem fio. Um desafio acrescido é saber como enquadrar estes mecanismos no actual contexto das LANs sem fio de alto débito e como quantificar os aperfeiçoamentos atingidos para diversas condições de transmissão rádio.

Para obter estes resultados tornou-se necessário, por um lado, acompanhar algumas das actividades de normalização em curso de modo a avaliar e caracterizar os mecanismos de controlo de erros propostos. Por outro lado, foi necessário desenvolver um modelo para a simulação do sistema, assim como diversas outras ferramentas computacionais. Estas
ferramentas de simulação servem para analisar a “performance” dos mecanismos propostos para diferentes tipos de implementação e/ou de modificação de protocolos, para ajustar a nova técnica a diferentes meios e aplicações e, por último, para fazer a comparação com os sistemas existentes. Para este efeito, foram feitas análises para diversas condições do canal de rádio, incluindo modelizações AWGN e Gilbert-Elliot, com múltiplas parametrizações, que serão aqui apresentadas.

Os resultados alcançados potenciam, assim, o desenvolvimento de esquemas ARQ de alta “performance” adaptados à camada DLC de uma LAN sem fio de alto débito, nomeadamente a ETSI/BRAN HIPERLAN Tipo 2. As simulações apresentadas mostram que estes métodos melhoram consideravelmente a “performance” dos serviços em tempo real, necessitados de altos débitos e exigindo atrasos limitados.
Abstract

This dissertation focuses on improved error control schemes for high-speed wireless digital communications. The main objective is a better quality support for real-time services, such as video, when using wireless mobile digital networks.

At present, communications in high-speed wireless mobile networks have to deal with considerable varying transmission and service requirement conditions, often needing complex radio modulations and concatenated error control functions.

In what the error control functions are concerned, it is usual to implement Forward Error Correction and Automatic Repeat reQuest (ARQ) mechanisms in, respectively, the Physical and the Data Link Control (DLC) layers of the OSI reference model. Even so, the communication requirements of medium/high quality real-time services may be hard to meet under hostile transmission conditions.

To overcome this limitation, mainly set by the use of some legacy methodologies in the traffic characterization and transport, a new set of error control mechanisms is proposed. These new mechanisms rely mainly in the use of Hybrid ARQ error control schemes and differentiated error robustness transmission modes. In this sense, when implementing these new techniques, some of the capabilities offered by modern wireless Local Area Networks (LANs) are significantly better utilized. An extra challenge is how to implement it in the current high-speed wireless LANs framework and how to quantify the achieved improvements under diverse radio conditions.

In order to achieve these results it became necessary, on one side, to follow some ongoing standardization activities to fully evaluate and characterize the proposed error control mechanisms. On the other side, it was necessary to develop a model for system simulation, as well as several other computational tools. These simulation tools are required to analyze the performance of the proposed mechanisms for different architectural implementations and/or protocol modifications, to tune the new approach in different environments and applications and finally to compare it with existing systems. Analysis for diverse radio channel conditions,
from AWGN modeling to Gilbert-Elliot modeling with multiple parameterization choices were also done and will be presented.

Achieved results are applied to develop high performance ARQ schemes to be used at the DLC layer of a high-speed wireless LAN, namely the ETSI/BRAN HIPERLAN Type 2. Simulations presented show that these methods greatly improve the performance of real-time services demanding high data rates and requiring limited delays.
Résumé

Cette dissertation est centrée sur le thème du perfectionnement de schémas de contrôle d'erreurs pour les communications numériques sans fil de haut débit. Le principal objectif est celui d'atteindre un meilleur support de la qualité des services en temps réel, tel que la vidéo, toutes les fois qu'ils sont utilisés dans des réseaux numériques mobiles sans fil.

En ce moment, les communications dans les réseaux mobiles sans fil de haut débit doivent supporter de considérables variations dans les conditions de transmission et des services requis, nécessitant souvent de complexes modulations radios et de fonctions de concaténation de contrôle d'erreurs.

En ce qui concerne les fonctions de contrôle d'erreurs, d’habitude on procède à l’implémentation des mécanismes “Forward Error Correction” et “Automatic Repeat request” (ARQ), respectivement, dans les couches “Physical” et “Data Link Control” (DLC) du modèle de référence OSI. Malgré cela, les conditions requises de communication des services en temps réel de qualité médiane ou supérieure peuvent être difficiles à atteindre quand les conditions de transmission sont hostiles.

Pour dépasser cette limitation, imposée surtout par l’utilisation des certaines méthodologies classiques dans la caractérisation et transport du trafic, de nouveaux mécanismes de contrôle d'erreurs sont proposés. Ceux-ci se basent surtout sur l’utilisation de schémas ARQ Hybrides et sur des modes de transmission disposant de différents niveaux de résistance devant les erreurs. Ainsi, l’implémentation de ces nouvelles techniques permet, significativement, une meilleure utilisation de quelques capacités offertes dans les modernes réseaux locaux (LANs) sans fil. Un défi extra consiste à savoir comment encadrer ces mécanismes dans l’actuel contexte des LANs sans fil de haut débit et comment quantifier les perfectionnements obtenus sous diverses conditions de transmission-radio.

Pour parvenir à ces résultats il a fallu acompanner quelques activités de normalisation en cours afin d’évaluer et de caractériser les mécanismes de contrôle d’erreur proposés. Par ailleurs, il a été nécessaire de développer un modèle de simulation du système, ainsi que
plusieurs autres outils de l'ordinateur. Ces outils de simulation servent à analyser la “performance” des mécanismes proposés pour différents types d'implémentation et/ou de modification de protocoles, à régler la nouvelle technique à différents environnements et applications et, finalement, servir à faire la comparaison avec les systèmes existants. A cet effet, l'analyse pour diverses conditions du canal radio, inclus modèle AWGN et Gilbert-Elliot avec paramétrisations multiples, est ainsi présenté.

Les résultats obtenus servent à développer des méthodes ARQ de haute “performance” qui seront utilisées dans la couche DLC d'un LAN sans fil de haut débit, nommé ETSI/BRAN HIPERLAN Type 2. Les simulations présentées montrent que ces méthodes améliorent considérablement la performance de services en temps réels nécessitant de hauts débits de données et exigeant des retards limités.
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<td>Association Control Function</td>
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<tr>
<td>ACH</td>
<td>Access feedback CHannel</td>
</tr>
<tr>
<td>AMPS</td>
<td>Advanced Mobile Phone System</td>
</tr>
<tr>
<td>AP</td>
<td>Access Point</td>
</tr>
<tr>
<td>ARQ</td>
<td>Automatic Repeat reQuest</td>
</tr>
<tr>
<td>ASCH</td>
<td>ASsociation control CHannel</td>
</tr>
<tr>
<td>ATM</td>
<td>Asynchronous Transfer Mode</td>
</tr>
<tr>
<td>AWGN</td>
<td>Additive White Gaussian Noise</td>
</tr>
<tr>
<td>BCCH</td>
<td>Broadcast Control CHannel</td>
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<tr>
<td>BCH (codes)</td>
<td>Bose, Chaudhuri and Hocquenghem</td>
</tr>
<tr>
<td>BCH</td>
<td>Broadcast CHannel</td>
</tr>
<tr>
<td>BMB</td>
<td>Bit Map Block</td>
</tr>
<tr>
<td>BMN</td>
<td>Bit Map block Number</td>
</tr>
<tr>
<td>BPSK</td>
<td>Binary Phase Shift Keying</td>
</tr>
<tr>
<td>BRAN</td>
<td>Broadband Radio Access Networks</td>
</tr>
<tr>
<td>BWA</td>
<td>Broadband Wireless Access</td>
</tr>
<tr>
<td>CAI</td>
<td>Cumulative Acknowledgement Indicator</td>
</tr>
<tr>
<td>CBR</td>
<td>Constant Bit Rate</td>
</tr>
<tr>
<td>CC</td>
<td>Central Controller</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CEPT</td>
<td>European Conference of Postal and Telecommunications Administrations</td>
</tr>
<tr>
<td>CL</td>
<td>Convergence Layer</td>
</tr>
<tr>
<td>CM</td>
<td>Centralized Mode</td>
</tr>
<tr>
<td>CPE</td>
<td>Customer Premises Equipment</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
</tr>
<tr>
<td>C-SAP</td>
<td>Control Service Access Point</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier Sense Multiple Access/Collision Avoidance</td>
</tr>
<tr>
<td>CT</td>
<td>Cordless Telephone</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
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</tr>
<tr>
<td>DCCH</td>
<td>Dedicated Control CHannel</td>
</tr>
<tr>
<td>DCF</td>
<td>Distributed Coordination Function</td>
</tr>
<tr>
<td>DCS (1800)</td>
<td>Digital Communication System</td>
</tr>
<tr>
<td>DECT</td>
<td>Digital Enhanced Cordless Telecommunications</td>
</tr>
<tr>
<td>DES</td>
<td>Data Encryption Standard</td>
</tr>
<tr>
<td>DFS</td>
<td>Dynamic Frequency Selection</td>
</tr>
<tr>
<td>DiL</td>
<td>Direct Link</td>
</tr>
<tr>
<td>DLC</td>
<td>Data Link Control</td>
</tr>
<tr>
<td>DLCC</td>
<td>DLC Connection</td>
</tr>
<tr>
<td>DM</td>
<td>Direct Mode</td>
</tr>
<tr>
<td>DSSS</td>
<td>Direct Sequence Spread Spectrum</td>
</tr>
<tr>
<td>EC</td>
<td>Error Control</td>
</tr>
<tr>
<td>ERC</td>
<td>European Radiocommunications Committee</td>
</tr>
<tr>
<td>ERMES</td>
<td>European Radio Messaging System</td>
</tr>
<tr>
<td>ERO</td>
<td>European Radiocommunications Office</td>
</tr>
<tr>
<td>ETSI</td>
<td>European Telecommunications Standards Institute</td>
</tr>
<tr>
<td>FCC</td>
<td>Federal Communications Commission</td>
</tr>
<tr>
<td>FCCH</td>
<td>Frame Control CHannel</td>
</tr>
<tr>
<td>FCH</td>
<td>Frame CHannel</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FHSS</td>
<td>Frequency Hopping Spread Spectrum</td>
</tr>
<tr>
<td>GE</td>
<td>Gilbert-Elliott (model)</td>
</tr>
<tr>
<td>GF</td>
<td>Galois Field</td>
</tr>
<tr>
<td>GFSK</td>
<td>Gaussian Frequency-Shift Keying</td>
</tr>
<tr>
<td>GMSK</td>
<td>Gaussian Minimum-Shift Keying</td>
</tr>
<tr>
<td>GPRS</td>
<td>General Packet Radio Service</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>HL/2</td>
<td>HIPERLAN type 2</td>
</tr>
<tr>
<td>HIPERLAN</td>
<td>High PErformance Radio Local Area Network</td>
</tr>
<tr>
<td>HSCSD</td>
<td>High Speed Circuit Switched Data</td>
</tr>
<tr>
<td>IEEE</td>
<td>Institute of Electrical and Electronics Engineers</td>
</tr>
<tr>
<td>IMT(-2000)</td>
<td>International Mobile Telecommunications</td>
</tr>
<tr>
<td>ISM</td>
<td>Industrial, Scientific and Medical</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Full Form</td>
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<tr>
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</tr>
<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
</tr>
<tr>
<td>ITU-R</td>
<td>International Telecommunication Union - Radio Sector</td>
</tr>
<tr>
<td>ITU-T</td>
<td>ITU - Telecommunication Sector</td>
</tr>
<tr>
<td>LAN</td>
<td>Local Area Network</td>
</tr>
<tr>
<td>LCCH</td>
<td>Link Control CHannel</td>
</tr>
<tr>
<td>LCH</td>
<td>Long transport CHannel</td>
</tr>
<tr>
<td>(N)LOS</td>
<td>(Non) Line Of Sight</td>
</tr>
<tr>
<td>MAC ID</td>
<td>MAC IDentity</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MAN</td>
<td>Metropolitan Area Network</td>
</tr>
<tr>
<td>MPEG</td>
<td>Moving Pictures Experts Group</td>
</tr>
<tr>
<td>MSS</td>
<td>Mobile Satellite Service</td>
</tr>
<tr>
<td>MT</td>
<td>Mobile Terminal</td>
</tr>
<tr>
<td>NET ID</td>
<td>NETwork IDentity</td>
</tr>
<tr>
<td>NMT</td>
<td>Nordic Mobile Telephone system</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OSI</td>
<td>Open Systems Interconnection</td>
</tr>
<tr>
<td>PAN</td>
<td>Personal Area Networking</td>
</tr>
<tr>
<td>PBX</td>
<td>Private Branch Exchange</td>
</tr>
<tr>
<td>PCF</td>
<td>Point Coordination Function</td>
</tr>
<tr>
<td>PCS</td>
<td>Personal Communication Services</td>
</tr>
<tr>
<td>PDA</td>
<td>Personal Digital Assistant</td>
</tr>
<tr>
<td>PDU</td>
<td>Protocol Data Unit</td>
</tr>
<tr>
<td>PHS</td>
<td>Personal Handyphone System</td>
</tr>
<tr>
<td>PN</td>
<td>Pseudo Noise (code sequences)</td>
</tr>
<tr>
<td>POS</td>
<td>Personal Operating Space</td>
</tr>
<tr>
<td>PPM</td>
<td>Pulse Position Modulation</td>
</tr>
<tr>
<td>(D)PSK</td>
<td>(Differential) Phase Shift Keying</td>
</tr>
<tr>
<td>PSTN</td>
<td>Public Switched Telephone Network</td>
</tr>
<tr>
<td>PT</td>
<td>Payload Type</td>
</tr>
<tr>
<td>(M-)QAM</td>
<td>(M-ary) Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>QOS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>(O)QPSK</td>
<td>(Offset) Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<td>--------------------------------------------------</td>
</tr>
<tr>
<td>RACH</td>
<td>Random Access Channel</td>
</tr>
<tr>
<td>RBCH</td>
<td>RLC Broadcast Channel</td>
</tr>
<tr>
<td>RCH</td>
<td>Random Channel</td>
</tr>
<tr>
<td>RES</td>
<td>Radio Equipment and Systems</td>
</tr>
<tr>
<td>RFCH</td>
<td>Random access Feedback Channel</td>
</tr>
<tr>
<td>RG</td>
<td>Resource Grant</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>RR</td>
<td>Resource Request</td>
</tr>
<tr>
<td>RRC</td>
<td>Radio Resource Control</td>
</tr>
<tr>
<td>RS</td>
<td>Reed-Solomon (codes)</td>
</tr>
<tr>
<td>RSS</td>
<td>Received Signal Strength</td>
</tr>
<tr>
<td>SAP</td>
<td>Service Access Point</td>
</tr>
<tr>
<td>SCH</td>
<td>Short transport Channel</td>
</tr>
<tr>
<td>SDU</td>
<td>Service Data Unit</td>
</tr>
<tr>
<td>SMS</td>
<td>Short Messaging Service</td>
</tr>
<tr>
<td>SN</td>
<td>Sequence Number</td>
</tr>
<tr>
<td>SWAP</td>
<td>Shared Wireless Access Protocol</td>
</tr>
<tr>
<td>TACS</td>
<td>Total Access Communications System</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time Division Multiple Access</td>
</tr>
<tr>
<td>TPC</td>
<td>Transmit Power Control</td>
</tr>
<tr>
<td>UBCCH</td>
<td>User Broadcast Channel</td>
</tr>
<tr>
<td>UDCH</td>
<td>User Data Channel</td>
</tr>
<tr>
<td>UMCH</td>
<td>User Multicast Channel</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunication System</td>
</tr>
<tr>
<td>UNI</td>
<td>User Network Interface</td>
</tr>
<tr>
<td>U-PCS</td>
<td>Unlicensed PCS</td>
</tr>
<tr>
<td>U-SAP</td>
<td>User Service Access Point</td>
</tr>
<tr>
<td>UTRA</td>
<td>UMTS terrestrial radio access</td>
</tr>
<tr>
<td>VBR</td>
<td>Variable Bit Rate</td>
</tr>
<tr>
<td>WLANs</td>
<td>Wireless Local Area Networks</td>
</tr>
<tr>
<td>WMANs</td>
<td>Wireless Metropolitan Area Networks</td>
</tr>
<tr>
<td>WPANs</td>
<td>Wireless Personal Area Networks</td>
</tr>
</tbody>
</table>
Glossary of terms

Access Feedback Channel (ACH): A HIPERLAN/2 (HL/2) transport channel where the results of access attempts made in the random access phase of the previous MAC frame is conveyed.

Access Point (AP): A device that is responsible for the centralized control of the resources in a radio cell. It is usually connected to a fixed network.

Association Control Channel (ASCH): A HL/2 logical channel in the uplink that conveys new association and re-association request messages.

Association Control Function: A group of control functions that use the services of the RLC. These functions are responsible for the handling of the association between MT and AP.

Broadcast Channel (BCH): A HL/2 transport channel that broadcasts control information.

Broadcast Control Channel (BCCH): A HL/2 logical channel that broadcasts control information relevant for the current MAC frame.

Central Controller: Provides control functionality equivalent to that of an access point but is not necessarily attached to a fixed network. This term is normally used if central controller and MT functionality are located in a single device. It mainly involves direct mode communication.

Centralized Mode: In centralized mode, all data transmitted or received by a mobile terminal must pass the access point or the centralized controller, even if the data exchange is between mobile terminals associated to the same access point or centralized controller.

Direct link phase: Part of a MAC frame that only contains the data exchanged directly between MTs using direct mode communication methods.

Direct Mode: The data exchange between MTs associated with the same AP or CC takes place without passing but under control of the access point or the central controller.

DLC connection: A connection oriented communication path at DLC layer. A DLC connection carries user or control data and is identified by a DLC connection identifier. A connection has a set of properties for the transfer of data agreed upon between the MT and the AP or between MT's and a CC.

DLC User Connection Control: A group of control functions that uses the services of the RLC. It is responsible for the handling of DLC user connections.
**DLC User Connection:** A DLC user connection is uniquely identified by the DLC connection ID and a MAC ID.

**Downlink phase:** Part of the Downlink transmission of a MAC Frame during which user and control data is transmitted from the access point or central controller to mobile terminals. The data transmitted can be user as well as control data in unicast, broadcast and multicast modes.

**EIRP mean power:** Mean EIRP power is defined as the average RF power delivered without interruption when measured in a period that is long compared to the lowest frequency component of the transmitted signal.

**Encryption Function:** A function that is responsible for keeping user data and part of RLC signaling secret between communication devices.

**Error control (EC):** The error control is responsible for detection of transmission errors and, where appropriate, for the retransmissions. It is assumed that one error control instance is provided per DLC connection.

**Frame CHannel (FCH):** A HL/2 transport channel that is broadcast and which carries the frame control channel.

**Frame Control CHannel (FCCH):** A HL/2 logical channel that contains the information defining how the resources are allocated in the current MAC frame. Its content changes in general dynamically from frame to frame.

**Logical channel:** A generic term for any distinct data path. A set of logical channel types is defined for different kinds of data transfer services. Each logical channel type is defined by the type of information it carries. Logical channels can be considered to operate between logical connection end points.

**MAC Frame:** The periodical structure in time that appears on the air interface and that determines the communication of wireless devices.

**Mobile Terminal (MT):** A device that communicates with an access point or with each other via a radio link. It is typically a user terminal.

**PDU train:** A sequence of transport channels delivered to and received from the physical layer.

**PHY burst:** sequence of OFDM symbols created by PHY layer to deliver a PDU train.

**PHY mode:** A PHY mode corresponds to a signal constellation (Modulation alphabet) and a code rate combination.
Radio cell: A radio cell is the area covered by an access point or central controller. It is sometimes used as a term to describe an AP or CC and its associated terminals.

Radio Link Control sublayer: A control plane of the DLC which offers transport services for the radio resource control, association control function and the DLC user connection control.

Radio Resource Control: A group of control functions that use the services of the RLC. It controls the handling of radio resources.

Random access Feedback Channel (RFCH): A HL/2 logical channel where the result of the access attempts to the random channel made in the previous MAC frame is conveyed.

Random Access Phase: The period of the MAC Frame where any MT can try to access the system. The access to this phase is based on a contention scheme.

Random Channel (RCH): A HL/2 transport channel in the uplink of the MAC that carries the logical channels random access channel and association control channel. A contention scheme is applied to access it.

Resource Grant: Allocation of transmission resources by an access point or a central controller.

Resource Request: A message from a terminal to an access point or central controller in which the current buffer status is conveyed to request for transmission opportunities in the uplink or direct link phase.

Sector antenna: The term is used to describe if an access point or central controller uses one or more antenna element.

Transport Channel: A basic element to construct PDU trains. Transport channels describe the message format.

Uplink phase: Part of the MAC frame in which data is transmitted from mobile terminals to an access point or a central controller.
Chapter 1

Introduction

1.1. Framework

Error control is one of the most important functions in a modern digital communication system. The two classical ways to implement such control are the Forward Error Correction (FEC) and the Automatic Repeat reQuest (ARQ) mechanisms. The choice of one of these two methods is traditionally related to the kind of application in terms of delay tolerance, error sensitivity and the availability of a feedback channel. FEC is normally used for delay-constrained communications such as real-time audio and video services; ARQ is more suitable for delay-tolerant communications such as typical data services.

Wireless mobile digital communications are strongly affected by errors caused by the joint effects of fading and multipath signal propagation. Fading effects are felt only at minor percentages of time, but multipath effects can be more persistent, depending on the location of the mobile terminal. When too many errors occur one says the radio channel is in a bad condition; otherwise the radio channel is considered to be in a good condition.

For these fading and multipath environments, a traditional FEC mechanism represents a lack of efficiency since FEC doesn't adapt to variable error channel conditions: either a waste of bandwidth may occur when the radio channel is in a good condition, or insufficient error protection may exist when it gets bad.
An ARQ mechanism is by far more adaptable to the variable radio channel conditions than FEC. This happens because the ARQ amount of redundancy (ratio between retransmissions and transmissions) is not fixed as in FEC codewords. Nevertheless, in the presence of a low-speed short-range wireless network, or in a high-speed long-range radio link, an ARQ mechanism presents prohibitive time delays for delay-constrained communications, such as those carrying real-time audio and video. This limitation is mainly due to the cumulative delays originated by the packet framing, packet transmission, protocol execution and propagation time from transmitter to receiver, making the allowable number of retransmissions almost null.

With recent and further on-going development of high bit rate Wireless Local Area Networks (WLANs) standards, as the IEEE 802.11 version “a” [1] and the High Performance Radio Local Area Network Type 2 (HIPERLAN/2) [2], the ARQ mechanisms are, again, being strongly considered even for delay-constrained applications. This is now possible due to the high-speed and short-range communication characteristics.

![Diagram of Wireless LANs User Plane Protocol Reference Model](image)

**Figure 1. Wireless LANs User Plane Protocol Reference Model.**

From a user plane protocol layering perspective, these WLANs do not differ from other LANs. They only implement wireless specific layers enclosing appropriated functions and
mechanisms for the radio medium. Figure 1 shows some important wireless specific layers within a typical user plane protocol reference model.

Regarding the error control mechanisms, the high bit rate WLANs, operating at 5 GHz bands, normally use a FEC technique in the wireless Physical (PHY) layer and associated with an Orthogonal Frequency Division Multiplexing (OFDM) modulation scheme [3]. Beyond FEC, an ARQ mechanism can also be used in the wireless Logical Link Control (LLC) sublayer to further improve the communication link quality.

In fact, as radio link speed increases and distance between transmitter and receiver decreases, the sum of packet transmission delay and propagation delay becomes small enough to consider ARQ as a viable solution. An evidence of this is the recent publication of several works supporting this idea [4, 5].

This ARQ approach will enable scenarios with real-time multimedia terminals using Wireless LANs both in infrastructure and ad hoc modes. A representation example is shown in Figure 2. More specific examples of the intended use of mobile broadband digital communications can be found in [6, 7].

![Figure 2. Multimedia terminals using wireless LANs.](image-url)
Perhaps even more important than publications is the recent adoption by the ETSI/BRAN project* of a basic set of error control modes, implemented in the Data Link Control (DLC) layer of its HIPERLAN/2 standard [8]. The motivation behind this approach is trying to fulfill, as much as possible, the quality requirements of any kind of service, be it real-time or not.

That basic set of error control modes is composed of the so-called “acknowledged”, “repetition” and “unacknowledged” modes. They differ mostly in reliability terms and their use depends also on the connection type (unicast, multicast or broadcast). The “acknowledged” mode is the only one applying an ARQ technique, but in a restricted “pure detection and plain retransmission” scheme.

A common characteristic, set intrinsically or through some extra mechanism, is that all HIPERLAN/2 error control modes have means to achieve low latency transmissions, but efficiency and/or global quality may be significantly low when used by some demanding real-time services and radio operating conditions are not favorable.

1.2. New contributions

In spite of the general satisfactory performance that can be achieved with the acknowledged/ARQ mechanism (performance that is eventually enough for low quality real-time audio/video services), there is still room for some improvements both in terms of efficiency, lower delay and lower packet dropping.

These improvements, even if obtained at the expense of more complex protocols, can definitely drive the up-coming wireless LANs techniques to meet the more quality demanding (semi-) professional applications, where the impact of terminal cost is less sensitive than in pure personal communications. On the contrary, very low packet loss, low delay and high useful bit rate are major requirements when aiming at higher quality standards.

* ETSI stands for “European Telecommunications Standards Institute” and BRAN is the acronym of “Broadband Radio Access Networks”.
The work presented in this thesis has evolved from the current general "acknowledged" error control mode defined for HIPERLAN/2. From this point on several work assumptions were established and developed by the author. Major ones are related with ARQ mechanism improvements and the way they are implemented either using current protocol specifications or proposing minor changes [9].

1.3. Thesis organization

After this first introductory chapter the thesis is organized in 7 chapters that cover the following aspects:

- In chapter 2 a global presentation of some important data networking radio frequency bands is done. The different types of current wireless data networks are presented, along with their relevant characteristics.

- In chapter 3 the general IEEE 802.11 standard is presented along with its high-speed versions for the 2.4 GHz band and the 5 GHz band.

- In chapter 4 the ETSI/BRAN HIPERLAN Type 2 standard is explained giving details about its physical and DLC main layers, not forgetting the error control modes.

- In chapter 5 a review of the ARQ schemes including conventional, as the one used by HIPERLAN Type 2, and Hybrid ones are first presented. An overview of the proposed Hybrid ARQ mechanisms is described next, followed by the definition of the differently coded PDU formats. The novel Hybrid ARQ mechanisms, when using a high-speed WLAN such as HIPERLAN/2, are then fully described.

- In chapter 6 information is given about the system modeling and the simulators developed by the author. The main developed blocks and tools and the methodology used to test and compare current and proposed error control mechanisms are presented. The corresponding simulation results obtained using the developed simulation system are also shown.

- The thesis ends with the conclusions in chapter 7 and the bibliographic references in chapter 8.
Chapter 2

Wireless data networks

2.1. Background

After the consolidation and global widespread of major personal telecommunication services, like voice, fax and, more recently, intranet and internet data, users of these services see as most valuable a possible evolution from wired accesses to wireless ones. In fact, the desire for free movement, firstly, and to be in contact anywhere and anytime, secondly, has been always on the mind of telecommunication service users.

The move for massive use of personal wireless devices started some decades ago, in the area of control, with the large diffusion of infrared remote controls for electronic devices. Approximately by the same time, the area of personal communications saw the appearing of the first cordless phones, acting only as an extension of the wired phone line, enabling a free movement around a house or an office.

After a period of some co-existence of cordless phones' proprietary solutions, causing serious problems of inappropriate call billing, communication privacy and radio interference in neighbor's systems, the European Conference of Postal and Telecommunications Administrations (CEPT) has finally regulated the use of cordless phones. The set of devices object of CEPT recommendation was named Cordless Telephone-first generation (CT-1). It used analog technology for the voice transmission but it already set identification codes, to be
periodically interchanged between the fixed and mobile parts of the system, in order to increase the communication privacy.

CT-1 devices had an operating range of 20-50 meters in indoor environments and up to 200 meters in an open space. The established operating frequencies were set in the 914-915 MHz band for the mobile parts and in the 959-960 MHz band for the fixed parts, providing 40 communication channels. CT-1 devices already had a channel-free automatic selection mechanism. More recently, CEPT Recommendation relative to CT-1 devices was further specified and converted into an Interim-European Telecommunication Standard (I-ETS) [10]. The next version of cordless telephony was the Cordless Telephone-second generation (CT-2) using digital technology and operating in the frequency band 864.1 MHz to 868.1 MHz [11].

The most recent standard for cordless telephony is named Digital Enhanced Cordless Telecommunications (DECT) and enables modes for data transmission, besides voice channels [12]. The voice telephony is provided over slotted 32 kbit/s bearer channels. For data transmission higher bit rate bearers can be provided depending on the modulation scheme. The basic DECT modulation is the 2-level Gaussian Frequency-Shift Keying (GFSK) but new backwards compatible 2-level (π/2-DBPSK), 4-level (π/4-DQPSK) and 8-level (π/8-D8PSK) modulation options are already specified.

For the 2-, 4- and 8-level modulation schemes DECT provides gross bit rates of, respectively, 1152, 2304 and 3456 kbit/s. Using a 2-level modulation and normal full slots (there are also half and double slots), unidirectional user bit rates can be up to 552 kbit/s or 736 kbit/s for, respectively, protected or unprotected asymmetric connections. For symmetric (protected) connections the bi-directional user bit rate can be up to 2×288 kbit/s. Using the 8-level modulation the corresponding bit rates can be up to 1729.6, 2208 and 2×902.4 kbit/s.

A primary and protected frequency band is available European wide for DECT systems between 1880 MHz and 1900 MHz [13]. Power output and other restrictions limit the maximum effective range to below five kilometers. If necessary, high traffic densities may be supported by DECT access networks through the close spacing of base stations, which is possible due to their dynamic channel selection feature.

In the field of radio (wireless) data networks a well-known example is the Aloha network [14]. This network was developed around 1970 in order to provide radio data communications between the central computer of the University of Hawaii and the several
data terminals distributed at its campuses. Based in a multiple access scheme to the radio medium, the first version of this network (pure Aloha) controls that multiple access in a time unslotted fashion. This latter fact causes some inefficiency due to packet collisions but pure/unslotted Aloha successor, the more popular slotted Aloha [15], made real improvements forcing network nodes to wait for a time slot boundary before each packet transmission.

After these first examples of wireless personal communications the big move was taken with cellular networks systems, offering paging services and voice services (using analog technologies first, then digital).

In Europe the Scandinavian countries were the first ones to start cellular services. Norway in 1981 and Sweden in 1982 are relevant examples of early cellular services implementation.

In North America, the first test of cellular service took place in the remote year of 1962. But only by the early 80's, the Federal Communications Commission (FCC) decided how to structure the cellular service. Two test systems were built in Washington, D.C., and Chicago. At the conclusion of successful testing in 1983, these two cities became the first to offer a commercial service.

From here on the "explosion" in the number of companies offering wireless services and in the respective number of users has been remarkable.

The success of wireless services and technologies, specially the cellular service, relies on the great convenience offered to users. They say they are more efficient, both professionally and personally. Feeling safer when using a cellular phone is also an aspect very appreciated by users.

2.2. Spectrum allocations

Radio spectrum use, as a precious common resource, is firmly regulated by some organizations. These ones are responsible for the right definition of each radio frequency bandwidth allocation. In North America that organization is the FCC and in Europe it is the European Radiocommunications Committee (ERC), which belongs to CEPT. Frequency band allocation for TV and radio broadcasting, telecommunication operators fixed links, military
radio-applications, aeronautical radio-navigation and mobile communication services are just some examples of allocations made by those organizations.

Normally, the use of a frequency band implies a negotiation with those organizations, which analyze among others, the radio-communication characteristics including radiated power and possible interference, the usage/service involved, type of equipment and the range/geographical coverage. Only later on they sell the right to use the frequency. This process is usually called a licensing process.

Aware of the difficulties that licensing processes imply for individual users when intending to use local radio communications, those organizations have allocated special frequency bands to be used in an easier way.

The most common bands with that purpose are called Industrial, Scientific and Medical (ISM) bands and have the relevant propriety of being unlicensed, that is, the user may utilize these bands without any registering or payment process. The most important ISM bands concerning wireless data networks are located at 900 MHz, 2.4 GHz and 5.8 GHz.

Subsequent sections refer only to the frequency bands relevant to wireless data network services. These include licensed, unlicensed and licensed-exempt bands. For the latter, the radio devices must strictly agree with respective approved radio operations standards, in spite of its unlicensed nature.

2.2.1. Frequency bands around 900 MHz

At 900 MHz there is an ISM band defined in North America. This band has a frequency bandwidth of 26 MHz covering the 902-928 MHz radio spectrum.

Many of the first commercially available wireless data products have chosen exactly this ISM band. This is explained by the simpler and less expensive cost of radio electronics. A large part of this type of products has now moved to the 2.4 GHz band, since it offers better performance results and is (by now) a little bit less polluted by other unlicensed devices.

The use of ISM bands (both 900 and 2400 MHz) implies the adoption of certain rules by corresponding radio devices. One of these rules is related with the maximum transmitted power. For the 900 MHz band FCC specifies a maximum power of 1 watt. Other rule
concerns the obligatory use of Spread Spectrum (SS) techniques. These techniques are normally applied using Direct Sequence (DS) or Frequency Hopping (FH) systems.

In Europe, the 900 MHz ISM band does not exist since these frequencies are reserved for the Global System for Mobile Communications (GSM) cellular networks. The amount of GSM reserved bandwidth equals 50 MHz (2 × 25 MHz). The exact frequency ranges are the 890-915 MHz and the 935-960 MHz, to be used, respectively, by mobile units and fixed base stations [16]. GSM systems operating in this band are also known as GSM-900, since there is other frequency band allocation at 1800 MHz (GSM-1800).

As an example of possible frequency allocations and licensing characteristics to cellular network operators, Table 1 shows the status of Portuguese cellular service on approximately December 31, 2001. Notice that national licensing bodies avoid to license the 914-915 and 959-960 MHz frequencies due to possible interference with CT-1 devices still in operation.

<table>
<thead>
<tr>
<th>Operator (GSM)</th>
<th>Service start</th>
<th>License expiry</th>
<th>Frequencies</th>
<th>Subscribers (thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMN</td>
<td>October 1992</td>
<td>March 2007</td>
<td>905.9-913.9 / 950.9-958.9 MHz (2 × 8 MHz) 1763.5-1766.7/1858.5-1861.7 MHz and 1770.1-1772.9/1865.1-1867.9 MHz (2 × 6 MHz)</td>
<td>3 275</td>
</tr>
<tr>
<td>Telecel</td>
<td>October 1992</td>
<td>October 2006</td>
<td>890.1-898.1 / 935.1-943.1 MHz (2 × 8 MHz) 1759.9-1763.1/1849.9-1858.1 MHz and 1772.9-1775.7/1867.9-1870.7 (2 × 6 MHz)</td>
<td>2 787</td>
</tr>
<tr>
<td>Optimus</td>
<td>August 1998</td>
<td>November 2012</td>
<td>898.1-905.9 / 943.1-950.9 MHz (2 × 7.8 MHz) 1775.7-1781.7 / 1870.7-1876.7 MHz (2 × 6 MHz)</td>
<td>1 916</td>
</tr>
<tr>
<td>Analogue</td>
<td></td>
<td></td>
<td>None</td>
<td></td>
</tr>
</tbody>
</table>

#### 2.2.2. Frequency bands within 1800-2200 MHz

Around the frequency of 2 GHz there are several distinct bands, mostly related with cellular mobile services. Regarding the Europe region there exist a second band for GSM, a band for DECT systems and bands for the third generation cellular service.
The allocated band for GSM-1800 comprises two slices of 75 MHz, namely, the 1710-1785 MHz and the 1805-1880 MHz ranges. These bands were first recommended by CEPT [17] and then formally decided by ERC [18]. The designation Digital Communication System (DCS) 1800 was formerly used when referring to these bands but now is more common to use the designation GSM-1800.

Concerning DECT systems its reserved frequency band covers the frequencies between 1880 and 1900 MHz [13], that is, it just follows the upper GSM-1800 band.

For the European third generation cellular service, known as Universal Mobile Telecommunication System (UMTS), the ERC decision on the UMTS frequency bands [19] designates the frequency bands 1900-1980 MHz, 2010-2025 MHz and 2110-2170 MHz to terrestrial UMTS applications. The UMTS satellite component applications are accommodated within the bands 1980-2010 MHz and 2170-2200 MHz.

The ERC decision on the terrestrial UMTS spectrum utilization [20] sets a harmonized UMTS spectrum scheme in order to allow an efficient use of the systems, in particular in border areas. Some rules set on that scheme are the following:

- The frequency band 1920-1980 MHz is paired with 2110-2170 MHz for Frequency Division Duplex (FDD) operation,
- The duplex direction for FDD carriers is mobile transmit within the lower band and base transmit within the upper band,
- The frequency bands 1900-1920 MHz and 2010-2025 MHz are unpaired bands for Time Division Duplex (TDD) operation,
- The frequency band 1920-1980 MHz may also be used for TDD operation.

The success of third generation mobile services implies the existence of a competitive market for those services. As a recognition of this fact, the ERC decision (00)01 [21] states that all 155 MHz bandwidth, of designated terrestrial UMTS bands, shall be made available by 1 January 2002 for International Mobile Telecommunications (IMT-2000) terrestrial systems family (already implemented in 19 European Administrations). Even so, the need for further substantial spectrum (approximately $2 \times 180$ MHz below 3 GHz) is foreseen for mass market.

In North America the main bands around the 2 GHz are related with the Personal Communication Services (PCS). For these last there are licensed and unlicensed bands. The
licensed bands consist in two slices of radio spectrum. The first covers the 1850-1910 MHz and the second the 1930-1990 MHz.

Even being thought as a free band to increase the development of wireless data communications, the setting of the unlicensed PCS (U-PCS) band has the concern of making possible the establishing of Isochronous communications besides the more “natural” Asynchronous ones. With this purpose two different spectrum allocations were made and specific rules defined to regulate the corresponding accesses. These rules are sometimes called the spectrum etiquette.

Concerning these U-PCS bands, for asynchronous communications two slices of 10 MHz were allocated, one at 1910-1920 MHz and the other at 2390-2400 MHz. For isochronous communications is reserved the 1920-1930 MHz band. Typical applications using asynchronous and isochronous communications are, respectively, wireless LANs and wireless Private Branch Exchanges (PBXs).

DECT - Digital Enhanced Cordless Telecommunication
GSM - Global System for Mobile Communications
IMT - International Mobile Telecommunications
MSS - Mobile Satellite Service
PCS - Personal Communication Services
PHS - Personal Handyphone System
UMTS - Universal Mobile Telecommunication System
U-PCS - Unlicensed PCS

Figure 3. Mobile services spectrum allocations at frequencies 1800-2200 MHz.
In Japan there is a band for the Personal Handyphone System (PHS) covering approximately the frequencies near the 1900-1920 MHz. The Japanese allocated bands for the third generation of mobiles are almost identical as the ones for European UMTS.

Figure 3 shows the major spectrum allocations for several wireless mobile services, for both terrestrial and satellite types of coverage.

### 2.2.3. The ISM 2.4 GHz band

One of the more popular radio frequency bands within many wireless operators is the 2400-2483.5 MHz ISM band. This popularity derives also from equipment vendors since this band is available internationally. This turns the radio equipment made for it a considerable large market.

This ISM band has been in use for other purposes for some time. As the name ISM suggests the operation of equipment as industrial microwave furnaces, some kinds of scientific and medical instrumentation, and even the common domestic microwave oven, gave off radiation at these frequencies. This phenomenon is inherent to the equipment characteristics and up to a few years ago there was no chance of using this band for radio communications without significant interference.

With the development of spread-spectrum techniques, which substantially ameliorate the interference problem, the use of ISM 2.4 GHz for communications purposes become possible. Nevertheless the problem of some interference remains. In great part due to this problem the ISM band was declared unlicensed for communications, allowing anyone to use this band as well.

On the other hand, the availability of this band for all these new users might increase again the radio interference. These last would appear not only from previous referred ISM equipment but also from other communications devices. As so, the operation in this band strictly imposes the use of spread spectrum technologies. The transmitted power level is also object of limitation. As shown in Table 2, the exact value for the maximum output power delivered by radio LAN devices depends if they are being operated in Europe, North America or Japan.
Table 2. Usage characteristics for the 2.4 GHz ISM band.

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency Range</th>
<th>Maximum Output Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe</td>
<td>2400-2483.5 MHz</td>
<td>100 mW (EIRP)</td>
</tr>
<tr>
<td>North America</td>
<td>2400-2483.5 MHz</td>
<td>1000 mW</td>
</tr>
<tr>
<td>Japan</td>
<td>2471-2497 MHz</td>
<td>10 mW</td>
</tr>
</tbody>
</table>

EIRP: Effective isotropic radiated power.

The advanced technical deployment of radio modulations and the setting of all these rules have given confidence to 2.4 GHz wireless network developers resulting in some affluent wireless network products and specifications.

Nevertheless the success of wireless networks at the 2.4 GHz band is somewhat threaded by the presence of incompatible protocols which can cause significant interference if run simultaneously in the same location.

In fact, several specific protocols were independently developed to support different usage models, hence having distinct requirements, like performance, power and cost.

The main three wireless network areas, using the 2.4 GHz ISM band, are concerned with local, home and personal environments. This corresponds, in a certain sense, to IEEE 802.11, HomeRF and Bluetooth developments. As shown in Table 3, the actual development stages of these protocols present different characteristics resulting, unfortunately, mutually incompatible.

Table 3. Characteristics of some independent wireless systems using the 2.4 GHz band.

<table>
<thead>
<tr>
<th></th>
<th>802.11b</th>
<th>HomeRF 1.0</th>
<th>Bluetooth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coded data rates</td>
<td>11 Mbit/s</td>
<td>1.6 Mbit/s</td>
<td>1.0 Mbit/s</td>
</tr>
<tr>
<td>End-user throughput</td>
<td>5.5 Mbit/s</td>
<td>0.8 Mbit/s</td>
<td>0.7 Mbit/s</td>
</tr>
<tr>
<td>Multimedia support</td>
<td>No</td>
<td>Audio</td>
<td>Audio</td>
</tr>
<tr>
<td>Low-power operation</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Range</td>
<td>50 m.</td>
<td>30 m.</td>
<td>10 m.</td>
</tr>
<tr>
<td>True network</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Supports roaming</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>
2.2.4. The 5 GHz bands

Due to the necessity of more radio spectrum to fulfill the new performance goals of latest generation of WLANs, a move to upper frequencies has occurred. The target radio bands envisaged by these novel WLANs are all located around the 5 GHz.

With that purpose radio regulation organizations have allocated radio spectrum around that frequency. Nevertheless, the amount of bandwidth and frequency bands is different in Europe, Japan and United States. Also different are the access rules to each of the allocated bands. The main characteristics of 5 GHz bands to be used in Europe, Japan and United States by WLANs systems are the following:

**Europe:**
- Name: HIPERLAN1/2,
- Total bandwidth: 455 MHz,
- Bands: 5.15-5.35 and 5.470-5.725 GHz,
- Access: license exempt.

**Japan:**
- Name: MMAC,
- Total bandwidth: 100 MHz,
- Band: 5.15-5.25 GHz,
- Access: sharing rule.

**United States:**
- Name: Unlicensed-National Information Infrastructure (U-NII),
- Total bandwidth: 300 MHz,
- Bands: 5.15-5.35 and 5.725-5.825 GHz,
- Access: unlicensed.

In Figure 4 is comparatively shown how spectrum allocation at 5 GHz is set in Europe, Japan and United States.
In 5 GHz bands higher bit rates are possible because of the availability of more bandwidth. Nevertheless, it is more difficult to operate in this frequency since the noise level is higher and obstacles, like walls and trees, become harder to transpose by radio waves. Also, a higher data rate needs an increased Signal to Noise Ratio (SNR), which implies a reduction in the range of action of the devices.

The details relative to radio spectrum usage established by FCC for the U-NII bands [22] and by ERC for HIPERLANs 5 GHz bands [23] are shown, respectively, in Table 4 and Table 5.

**Table 4. Usage characteristics for the 5 GHz Unlicensed-National Information Infrastructure (U-NII) bands.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Frequency Band</th>
<th>Maximum Output Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA (U-NII lower band)</td>
<td>5150-5250 MHz</td>
<td>50 mW or 4 dBm+10log₁₀B (lower value)</td>
</tr>
<tr>
<td>USA (U-NII middle band)</td>
<td>5250-5350 MHz</td>
<td>250 mW or 11 dBm+10log₁₀B (lower value)</td>
</tr>
<tr>
<td>USA (U-NII upper band)</td>
<td>5725-5825 MHz</td>
<td>1000 mW or 17 dBm+10log₁₀B (lower value)</td>
</tr>
</tbody>
</table>

B: emission bandwidth size mask at –26dB (MHz).
Table 5. HIPERLANs and ISM 5 GHz bands according to the European Radiocommunications Committee.

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Use</th>
<th>Maximum Output Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>5150-5250 MHz</td>
<td>HIPERLAN Type 1 / Type 2 for indoor systems only, licence exempt.</td>
<td>200mW (EIRP)</td>
</tr>
<tr>
<td>5250-5350 MHz</td>
<td>HIPERLAN Type 2 for indoor systems only, licence exempt.</td>
<td>200mW (EIRP)</td>
</tr>
<tr>
<td>5470-5725 MHz</td>
<td>HIPERLAN Type 2, licence exempt. Outdoor and indoor systems.</td>
<td>1W (EIRP)</td>
</tr>
<tr>
<td>5725-5875 MHz</td>
<td>Low power devices, unlicensed ISM.</td>
<td>25 mW (EIRP)</td>
</tr>
</tbody>
</table>

EIRP: Effective isotropic radiated power.

Note that only the 5150-5250 MHz frequency range has currently been agreed as an allocation to mobile services by the International Telecommunications Union - Radio sector (ITU-R). FCC and ERC radio regulation bodies have allocated other parts of the 5GHz spectrum only within respective areas of jurisdiction.

2.2.5. Frequency bands above 5 GHz

High-speed wireless data networking requires undoubtedly great amounts of radio spectrum. The frequencies up to 5-6 GHz have been occupied along the last century by diverse radio systems both for civil and military applications, turning very scarce the spectrum options for systems using large channel bandwidths.

Even when older radio systems become obsolete or are moved to others radio spectrum regions, the released frequencies are often reallocated for mobile systems. In fact the radio spectrum up to 5-6 GHz is very precious for mobile systems. This is due to the normal need of working on Non Line Of Sight (NLOS) conditions and also because phenomena like multipath and attenuation are not so adverse.

All these circumstances largely contribute to the fact that fixed wireless data systems, like Broadband Wireless Access (BWA) systems, have to use frequencies above 5 GHz. A detailed article related with the technical issues of fixed wireless access is presented in [24].
One of the systems envisaging the use of radio frequency bands above 5 GHz is the IEEE 802.16 working group on BWA standards. This working group intends to create a new generation of Wireless Metropolitan Area Networks (WMANs) standards.

IEEE 802.16 is considering millimeter wave frequencies as the target operational frequency band, specifically those above 10 GHz. At these frequencies, Line of Sight (LOS) communications is mandatory and are often limited to a few kilometers due to the radio technology (e.g., power and cost of RF amplifiers) and the susceptibility to rain attenuation.

As a modern two-way user interactive BWA system, the IEEE 802.16 Point-to-MultiPoint (PMP) deployment aims a moderate size cell radius in order to use small power levels, explore the frequency reusing technique (i.e., more global available bandwidth) and to grant the required user real-time interactivity. As so the limited geographical range is not a real problem.

Moreover, the use of frequencies above 10 GHz results in a major outcome which is the fact that channel bandwidths could be larger, hence enabling high bit rates with low to moderate modulation schemes.

The 802.16 working group air interface base document defines a Physical layer prepared to work in the 10-66 GHz radio spectrum. Besides this basic definition two enhancements are underway, one for 2-11 GHz licensed bands and other with a focus on 5-6 GHz license-exempt bands.

HIPERACCESS and HIPERLINK systems are other two BRAN European systems that envisaged the use of frequency bands above the 5 GHz.

HIPERLINK systems, which will acts as a fixed wireless infrastructure for indoor private networks, already has a designated frequency band [25]. This band, to be used in a license exempt regime, embraces the frequencies 17.1-17.3 GHz enabling HIPERLINK systems to achieve a rate of 155 Mbit/s. The radio link range will be about 150 meters in a point-to-point configuration. Notice that the work on HIPERLINK standardization has not started yet.

By its turn, HIPERACCESS (H/A) systems that are intended to offer fixed outdoor wireless access to ATM and IP networks are still looking for radio spectrum at various frequencies well above 5 GHz.
For the creation of H/A specifications the frequencies bands near the 40 GHz are the more sought, in particular a spectrum allocation in the 40.5-43.5 GHz band, which are by now being discussed in the relevant CEPT/ERC working groups.

Depending on the private or public nature of the service, it is expected that differentiated bands will be used in, respectively, license exempt or licensed radio regimes. With this purpose, extra frequencies bands namely below 20 GHz are also under consideration.

The H/A systems configuration will be a point-to-multipoint one. HIPERACCESS has also defined minimum bit rates around the 25 Mbit/s and distance ranges of 0.5-5 km.

2.3. Wide area networks

2.3.1. Background

Wireless wide area networking is almost a synonym of mobile cellular networking. In fact this type of networks is practically unique in offering wide area coverage for wireless data communications.

As previously referred, mobile cellular communications began in the early 80’s with the so-called 1st generation system. The main characteristic of this generation is the use of analog technologies to process and transmit the voice signals. These systems are now completely obsolete when compared with digital technologies and cellular operators are, in a great part, discontinuing them.

Examples of Europeans analog cellular systems are the (Scandinavian) Nordic Mobile Telephone system (NMT), with operating frequencies near the 450 MHz, and the Total Access Communications System (TACS) using frequency bands around 900 MHz. In North America the current analog cellular system is named Advanced Mobile Phone System (AMPS).

Pioneering countries like Norway and Sweden still run their analogue systems (in parallel with digital GSM) using an “old” 460 MHz frequency band with a modest $2 \times 4.5$ MHz bandwidth.
Some other European countries still running analogue systems, namely the TACS-900, are Austria, Denmark, Ireland, Italy and Spain. In the United Kingdom, where analogue cellular started in January 1985, the services ceased in 2001.

2.3.2. Second generation cellular systems

The second generation cellular systems, first introduced in the early 90’s, are characterized by the exclusive use of digital technologies. Two much important wireless radio access technologies employed in 2nd generation are the Code Division Multiple Access (CDMA), mostly used by North American cellular systems, and the Time Division Multiple Access (TDMA), which is used in systems such as the worldwide accepted Global System for Mobile Communications (GSM). In the following they are briefly described some of the GSM characteristics, as included in respective specifications [26, 27] published by the European Telecommunications Standards Institute (ETSI).

In GSM systems, the radio spectrum allocated to a certain operator is occupied by a group of radio frequency (RF) carriers whose separation is 200 kHz. For each RF carrier, the modulating symbol rate is equal to 270.833 ksymbol/s and the modulation formats can be the Gaussian Minimum Shift Keying (GMSK) or the 8-Phase Shift Keying (8PSK). If the common GMSK modulation is used that corresponds to a modulating bit rate of 270.833 kbit/s.

With reference to user information capability, GSM systems can transport eight basic channels (one per standard call) per each RF carrier (other formats than basic channels are also supported).

The TDMA scheme used in GSM systems is rather complex. In fact, GSM is organized around several levels of time frame structures leading, as a final point, in time slots occupied by the basic channels.

Concerning these time frame structures, the longest one is called hyperframe and has an approximated duration of 3 hours and 29 minutes. The hyperframe is divided in 2048 superframes (6.12 seconds), which is then divided in multiframes. There are four types of multiframes that are further subdivided in TDMA frames. The multiframe type used to carry
traffic channels (TCH) has a duration of 120 ms and is subdivided in 26 TDMA frames (24 of them used for traffic). Finally, the TDMA frames (≈ 4.615 ms) comprise eight time slots to be used by corresponding eight basic channels.

Each time slot has a time duration of ≈ 576.9 μs and is occupied by 114 symbols of coded information bits from a total of 156.25 symbols. When using the GMSK modulation this per slot transmission capacity corresponds to a gross rate of 22.8 kbit/s. This capacity is made available for full rate TCHs notwithstanding the speech or data nature of user information stream. For instance, a full rate TCH for circuit switched data at 14.5 kbit/s after the convolutional coding operation increases its bit rate to the referred 22.8 kbit/s.

Besides the circuit switched modes intended for speech and circuit switched data traffic, including the High Speed Circuit Switched Data (HSCSD) multislot configurations, there is another enhancement to existing GSM networks which consists in packet switched data transmissions.

This packet switched mode is designated as General Packet Radio Service (GPRS) and it enables users to be permanently logged on without having to pay for the connection time but only for the transmitted or received data traffic. GPRS only uses network resources and bandwidth when data is actually transmitted. For more information relative to the GPRS radio interface see [28].

2.3.3. Third generation cellular systems

Further to actual second generation mobile services it was felt a need to develop a new wideband wireless system with enhanced characteristics such as video, multimedia and flexible data services, not forgetting the universal coverage issue.

With this purpose in mind, extensive research work took place within diverse technical projects and programmes. Some examples of conducted and ongoing work derive from consecutive RACE, ACTS and IST Programmes of the European Commission.

Indeed, the development of third generation mobile systems has been ongoing for a considerable number of years. At worldwide level the ITU has been working on these systems
under the name International Mobile Telecommunications (IMT-2000). At the European level a vast amount of work has been done under the name Universal Mobile Telecommunications System (UMTS). For instance, the standardization work for UMTS started already in 1991 in ETSI.

The ITU IMT-2000 initiative, formerly known as Future Public Land Mobile Telecommunications System (FPLMTS), is providing a global definition for third generation mobile systems. UMTS development, as part of IMT-2000, is taking into account ITU recommendations. Accordingly, the UMTS minimum requirements are identical to those of IMT-2000, namely the ones concerning maximum user bit rates. These ones depend upon users current environment as follows:

- At least 144 kbit/s for rural/wide area coverage (maximum speed: 500 km/h),
- At least 384 kbit/s for suburban/local area coverage (maximum speed: 120 km/h),
- At least 2 Mbit/s for low range indoor/outdoor coverage (maximum speed: 10 km/h).

Despite some technical differences, the UMTS definition covers both terrestrial and satellite segments. For the latter, it is required a minimum data rate of 9.6 kbit/s.

Concerning the intended global definition for 3rd generation systems, major wireless cellular communities reached an agreement on a harmonized CDMA radio standard, consisting in three different modes for the radio access. This family of CDMA modes includes a Direct-Sequence mode and a Multi-Carrier mode intended for paired spectrum and a Time Division Duplex (TDD) mode intended for unpaired spectrum.

Regarding the key radio and multiple access technology selected by ETSI, for its 3rd generation cellular services, the main choice was the Direct-Sequence CDMA (DS-CDMA). In this mode the information is spread over a bandwidth of approximately 5 MHz, thus it is also referred as Wideband CDMA (WCDMA). A signal spreading over a bandwidth of 1.6 MHz is specified as well and frequently denoted as Narrowband CDMA [29].

As approved by ETSI, the UMTS terrestrial radio access (UTRA) is being developed with two modes of operation, namely, the Frequency Division Duplex (FDD) and the TDD modes. In UTRA TDD there is a TDMA component in the multiple access in addition to the DS-CDMA.
The UTRA FDD mode provides an efficient operation in many UMTS environments since it fits well into the symmetric traffic generated by voice applications. However, the TDD mode may allow operators flexibility in network deployment and may support the increasing traffic asymmetry in a more efficient way.

In fact, the expected traffic nature, to be carried by UMTS networks, will progressively change from a large majority of voice applications to a significant percentage of data applications using UMTS as an access network. Even that such predominant data use is not likely in the initial phase of UMTS deployment, so favoring the FDD mode, the future UMTS traffic behavior will require a considerable additional capacity in the downlink direction, hence making more appropriated the TDD mode.

Third generation networks will be initially deployed in areas with large density of users, typically urban centers and specific spots like airports, central train stations and convention/exposition areas. 3rd generation users starting to leave those spots will have to be transferred to 2nd generation networks. Hence, a kind of inter-generational roaming will have to take place, putting some challenging problems. Nevertheless, all are in agreement that the rapid deployment of 3rd generation cellular systems largely depends on their interaction with 2nd generation ones.

2.4. Local area networks

2.4.1. IEEE 802.11

The existence of Wireless Local Area Network (WLAN) products in a proprietary basis began in the early 90’s with the available unlicensed ISM bands. Much of first products to appear used the North American 900 MHz ISM band. Some time later they started to use the 2.4 GHz band and later on, approximately by the middle-late 90’s, the existence of products using the 5.8 GHz band was a reality.

The main problem of those proprietary wireless LAN solutions was the little acceptance in the market place since there was not an unique standard (or at least a major strong one), guaranteeing the desired compatibility between all devices.
Anticipating this difficulty the Institute of Electrical and Electronics Engineers (IEEE) created a working group in an effort to analyze the wireless networking issue and establish a standard for radio LANs. The name of this Working Group was set as IEEE 802.11.

A large majority of WLAN vendors have joined IEEE 802.11 in order to try to make the standard closer to the products they made. Due to the great importance of WLAN area market, each vendor pushed hardly its own technology within 802.11 committee, resulting in a standard that took a long time to complete.

Indeed, after several years of discussion, in 1997 the IEEE approved an international interoperability standard intended for wireless LAN communications, that is, the IEEE 802.11 standard [30].

802.11 standard covers the Physical (PHY) layer and the Medium Access Control (MAC) layer, that is, the layer 1 and a significant part of layer 2 of the Open Systems Interconnection (OSI) Basic Reference Model [31], as defined by the International Organization for Standardization (ISO). Besides MAC procedures, this standard specifies three different PHY layer variations. Two of the PHY layers are based on spread spectrum radio technologies and operate in the 2.4 GHz band. They are, respectively, the Frequency Hopping Spread Spectrum (FHSS) and the Direct Sequence Spread Spectrum (DSSS). The third PHY layer variation, to be used only in indoor environments, uses diffuse infrared light.

All these PHY layers support data rates of 1 and 2 Mbit/s. The modulation characteristics, as defined in IEEE 802.11 basic standard, for each PHY layer and data rate variation are the following:

- **FHSS:** Gaussian Frequency Shift Keying (GFSK) modulation:
  1 Mbit/s data rate uses two-level GFSK (i.e., 2GFSK),
  2 Mbit/s data rate uses four-level GFSK (i.e., 4GFSK).

- **DSSS:** Phase Shift Keying (PSK) modulation:
  1 Mbit/s data rate uses Differential Binary PSK (i.e., DBPSK),
  2 Mbit/s data rate uses Differential Quadrature PSK (i.e., DQPSK).

- **Infrared:** Pulse Position Modulation (PPM) with a time unit of 250 nanosecond:
  1 Mbit/s data rate uses 16-PPM (i.e., 4 bits mapped into a 16 position symbol),
  2 Mbit/s data rate uses 4-PPM (i.e., 2 bits mapped into a 4 position symbol).
In relation to the basic 802.11 MAC layer definition, there are two modes of operation named, respectively, Distributed Coordination Function (DCF) and Point Coordination Function (PCF). DCF mode is the principal and mandatory mode being PCF an optional extension.

In DCF mode, the multiple access to the radio medium is based in distributed functionalities and contention rules. More precisely, this mode is based in a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) channel access mechanism. The basic principles of CSMA/CA are “listen before talk” and “transmission contention”.

In PCF mode, the multiple access to the radio medium is based in centralized coordinated functions. The mechanism used to implement this mode is the “polling” one. With this technique the base station retains the total control over the medium channel, sending “poll” messages to trigger authorized transmissions by corresponding nodes.

The basic 802.11 MAC layer also implements Request To Send (RTS) and Clear To Send (CTS) procedures, as well MAC level packet retransmission in case of error and, if necessary, fragmentation/reassembly of higher layer packets.

After the release of the 1 and 2 Mbit/s IEEE 802.11 standard, another working group started on a higher rate extension to the same 2.4 GHz frequency band. The intent was to deliver Ethernet like speeds over 802.11 WLAN systems and still maintaining a backward compatibility with previous PHY layer specification. This group was then in charge of the production of the 802.11 “b” version.

After the evaluation of various modulation proposals such as M-ary BiOrthogonal Keying (MBOK), Pulse Position Modulation (PPM) and Orthogonal Frequency Division Multiplex (OFDM), the working group, in a very hard process, finally reached a consensus on a single modulation method. This method is called Complementary Code Keying (CCK). CCK was adopted in July of 1998 by 802.11 working group as the basis for the high rate physical layer extension at 2.4 GHz. The CCK modulation enables data rate modes of 5.5 and 11 Mbit/s.

One reason why this higher rate extension was adopted is because it easily provides a path for interoperability with the existing 1 and 2 Mbit/s networks. In fact, this enhancement is an extension of the DSSS basic PHY layer since it uses the same preamble and header in its packets and also because it maintains the same channel bandwidth.
The products compliant with IEEE 802.11b version, that is, incorporating the DSSS-CCK technology, use the same MAC layer as defined in basic 802.11 standard.

There is also a PHY layer extension for 5 GHz bands that is known as the “a” version of IEEE 802.11. The use of U-NII bands at 5 GHz enables a considerable higher bit rate when compared with systems working at 2.4 GHz.

The main characteristics of this 802.11a high speed PHY layer extension for 5 GHz are the following:

- Several data rate modes from 6 to 54 Mbit/s (support of 6, 12 and 24 Mbit/s is mandatory),
- 20 MHz channel spacing,
- Primary use of U-NII bands resulting in 8 channels in lower+middle U-NII bands and 4 channels in upper U-NNI band (adaptations for Europe are in study),
- Orthogonal Frequency Division Multiplexing (OFDM) modulation (offering a good multipath robustness),
- 52 OFDM subcarriers, with 48 subcarriers for data and 4 for pilot assisted coherent detection,
- BPSK, QPSK, 16-QAM or 64-QAM subcarrier modulations,
- 4 µs OFDM symbol duration (3.2 µs plus 0.8 µs of guard interval),
- Convolutional coding with rate and constraint length of, respectively, R=1/2 and K=7 (higher rates obtained by puncturing),
- Same MAC layer as basic 802.11,
- Coordinated development with ETSI HIPERLAN/2 and Japanese MMAC resulting in an almost identical PHY layer.

Not only has the 802.11 PHY layer been object of attention for successive enhancements. In fact, there is also a movement to enhance the 802.11 MAC layer, in response to increasing user needs. The two main reasons are related with the demand for Quality of Service (QoS) over 802.11 and the need for improvements in privacy and authentication aspects.
The first reason, which is demand for QoS, is explained by the need to support real-time services such as voice over IP, video and multimedia. In general, these demanded QoS mechanisms must support the priorities and classes of service implemented in higher network layers.

The second reason, that is, privacy and authentication aspects, is mainly due to the need and desire to implement different authentication mechanisms, in order to correspond to differentiated demanding security environments.

In September 1999 a MAC enhancements study group was formed to answer these MAC layer issues. From here, a Project Authorization Request (PAR) was generated to analyze the enhancements related to QoS, security, authentication and other internal MAC functions. The task group known by 802.11E would be in charge of the corresponding developments.

The PAR, approved in March 2000, defines the scope and purpose of the project IEEE 802.11E:

- To enhance the 802.11 Medium Access Control,
- To improve and manage Quality of Service,
- To provide classes of service,
- To provide enhanced security and authentication mechanisms,
- To consider efficiency enhancements in the areas of the Distributed Coordination Function (DCF) and Point Coordination Function (PCF).

Another enhancement planned for 802.11E is the addition of support for Dynamic Frequency Selection (DFS) and Transmit Power Control (TPC). This will result in an 802.11E to CEPT rules harmonization allowing 5 GHz 802.11 radio devices to operate in Europe. The full implementation of this enhancement will require corresponding changes to the 802.11 PHY layers.

The task group E, responsible for these “QoS extensions to 802.11 MAC”, will produce a supplement to the 802.11 standard, in the same way as what happened with the “a” and “b” versions of the IEEE standard.
2.4.2. HIPERLAN type 1

HIPERLAN type 1 is a high performance wireless LAN specification developed by ETSI. The working group responsible for the first edition of the standard, in 1996 [32], was the Sub-Technical Committee RES10 (Radio Equipment and Systems).

The main objectives behind the HIPERLAN/1 (HL/1) development were the provision of high bit rate wireless communications and the easy formation of ad hoc wireless networks. With this last purpose in mind it specifies ways to achieve extra coverage, beyond the radio range limitation of a single node, using a multihop relaying mechanism. To increase the flexibility experienced by moving wireless users it also supports node mobility.

HL/1 devices may be freely operated in Europe in the 5.15-5.25 GHz frequency band according to CEPT Recommendation T/R 22-06 [25] and ERC Decision (99)23 [23] (replacing the previous ERC Decision (96)03 [33]). Three HL/1 channels may be accommodated in the 5.15-5.25 GHz band.

The HIPERLAN Type 1 Functional Specification is contained in EN 300 652 [34]. HL/1 specifications encompass the Physical layer and the MAC layer of the OSI Basic Reference Model. Main characteristics of Physical layer may be summarized as follows:

- Data is transmitted in bursts containing a number of Frequency Shift Keying (FSK) modulated low rate bits and a Gaussian Minimum Shift Keying (GMSK) modulated high rate bit stream,

- A burst comprises a synchronization/training sequence of 450 bits and data blocks that are composed by 496 interleaved, BCH(31,26)-coded bits,

- The signaling rate for high rate transmission is 23.5 Mbit/s resulting in net data rates approximately up to 19.5 Mbit/s.

The MAC layer comprises management functions like network topology information maintenance, device control functions and Channel Access Control (CAC) functions. Other MAC layer characteristics are:

- Elimination Yield Non-Pre-emptive priority Multiple Access (EY-NPMA) as the channel access method,
- Presence of optional EY-NPMA features, allowing normal or enhanced implementations,

- NPMA operates in channel access cycles comprising in series the prioritization, contention resolution and data transmission phases; thanks to the prioritization mechanism of EY-NPMA, the support of multimedia applications is (almost) possible.

HIPERLAN/1 type approval requirements and protocol conformance testing specifications are covered in the ETS 300 836 series.

### 2.4.3. HIPERLAN type 2

HIPERLAN/2 is a flexible Radio LAN standard designed to provide wireless high-speed access both to private LAN systems and to different networks including UMTS core networks, ATM networks and IP based networks. HIPERLAN/2 specifications [2] are being developed by ETSI Broadband Radio Access Networks (BRAN) project.

The development of HIPERLAN/2 (HL/2) has been characterized by the use of combined technologies derived from broadband cellular short-range communications and wireless LANs.

HL/2 offers an ambulant mobility within the defined local area network and flexible high-speed rates that can go up to 54 Mbit/s (PHY layer). As a short-range mobile system, and depending on the chosen data rate, a HL/2 transmission has a typical range of 50 meters.

Basic applications include data, voice and video, with specific QoS parameters taken into account. HL/2 systems can be deployed in offices, classrooms, homes, factories, hot spot areas like exhibition halls and more generally where radio transmission is an efficient alternative or a complement to wired technology.

The radio spectrum that has been allocated for the HL/2 standard lies in the 5 GHz range [23]. Besides some differences, the same 5 GHz bands are allocated to wireless LANs worldwide. This fact, in conjunction with some technical primacy, may increase the HL/2 potential to enable the success of wireless LANs on a global basis.
As mentioned earlier, a HL/2 radio access network can be used with a variety of core networks. This is possible due to a flexible architecture, which defines Physical and Data Link Control layers independent of those core networks. In addition to these two layers, a set of specific Convergence layers is defined at the top of the DLC layer.

The main characteristics of Physical layer may be summarized as follows:

- Modulation: Orthogonal Frequency Division Multiplexing (OFDM),
- Number of used subcarriers: 52, where 48 subcarriers are used for data and 4 for pilots,
- Subcarrier modulation: BPSK, QPSK, 16QAM and optionally 64QAM,
- Channel Spacing: 20 MHz,
- Sampling rate: 20 Msample/s (50 ns),
- FFT size: 64,
- OFDM symbol duration: 4 µs default mode, 3.6 µs as an option,
- Guard interval: 800 ns default mode corresponding to 16 time samples; 400 ns as an option,
- Mandatory Forward Error Correction: a rate 1/2, constraint length 7 mother convolutional code (9/16 and 3/4 by code puncturing),
- Supported data rates: 6, 9, 12, 18, 27, 36, and 54 Mbit/s,
- Interleaving: Block interleaving with the size of one OFDM symbol.

Two main DLC layer specifications were set with the purpose of obtaining a clearly differentiation of functionalities relative to user plane and control plane.

The first one includes the basic data transport functions consisting in a Medium Access Control (MAC) protocol and an Error Control protocol. About MAC protocol it should be noted that the air interface of HIPERLAN/2 is based on dynamic Time Division Duplex (TDD) and Time Division Multiple Access (TDMA) schemes, resulting in a very elaborated MAC framing.

Besides the DLC basic data transport functions, the other main specification defines the Radio Link Control (RLC) sublayer. In this specification the functionalities of RLC sublayer and the way how data, relative to the control plane, is exchanged between an access point and a mobile terminal are established.
Furthermore, to these two principal specifications, other ones are developed relative to the specific DLC profiles of Home and Business environments.

The Convergence layers have two main functions:

- The first, to adapt service requests from higher layers to the services offered by the DLC,
- The second, to convert higher layer packets with fixed or variable size into fixed-size DLC Service Data Units (SDUs) that are used within the DLC.

Convergence layers have been in development for protocols and applications derived from cell based core networks like ATM and packet based core networks like Ethernet (IP based) and IEEE 1394. An access interface definition to the 3rd generation mobile, in cooperation with UMTS and 3GPP, is also already scheduled.

In an attempt to full harmonize the systems developed in the 5 GHz networking wireless area, BRAN project has worked closely with IEEE 802.11 working group and with Japanese MMAC High Speed Wireless Access Networks working group.

2.5. Personal and home area networks

2.5.1. General considerations

Besides the previously referred wide area and local area wireless networks there is a relatively new concept for wireless communications involving more restricted geographical areas.

This concept relates with the provision of wireless connectivity among devices within or entering a Personal Operating Space (POS). A POS is normally defined as the space about a person, typically extending up to 10 meters in all directions and enveloping the person whether stationary or in motion. Obviously, a POS includes devices that are carried, worn, or located near the body.
The implementation of this concept, through proper standard specifications, will enable the so-called Wireless Personal Area Networks (WPANs). The development of WPAN standards is specially taking into account the provision of mechanisms enabling the very low power consumption and low complexity of wireless devices, but maintaining the envisaged performance. Some examples of WPAN developments can be found in subsequent sub-sections.

This section ends with the issue of wireless networks specific for home environments. In this case there is only one significant representative named HomeRF. This is largely justified because the technology and characteristics of home area networks are approximately equal to others local area networks resulting in some overlapping. In fact, recent WLAN specifications also concerned with home traffic normally supply a specific profile for this kind of environments. A comprehensive article related with the home networking technologies (not just wireless) can be found in [35].

2.5.2. Infrared communications

Infrared technology has long been used for the development of low-cost, short-range wireless data links. This technology has found its way into several kinds of equipment such as TV remote controls, personal computers, personal digital assistants, handheld data loggers, medical equipment, etc.

Until 1993, the infrared (IR) data industry suffered from a lack of standardization. To counteract this problem, industry members worked together and formed a non-profit organization called Infrared Data Association (IrDA).

IrDA was established to create and promote infrared data interconnection standards supporting interoperable applications and low cost point-to-point communications. Those standards hold up a broad range of appliances, computing and communications devices.

The most important IrDA standard specification concerning infrared communications is called IrDA-Data. This standard is mostly used to enable wireless connectivity for devices that would normally use cables to establish such connectivity.
The major IrDA-Data standard characteristics are:

- Ad hoc data transmission standard,
- Designed for point-to-point cable replacement,
- Narrow angle (30 degree) cone, point-and-shoot style applications,
- Operation over a distance up to 1 meter (extended range up to 10 m is under development),
- Half-duplex operation,
- Versatile data rates from 9.6 kbit/s to 4 Mbit/s (16 Mbit/s is under development).

In IrDA specifications, each connection is set up as a master/slave relationship. The master is called the primary station and the slave is called the secondary station. The primary station sends command frames initiating connections and transfers. Once communication is started, the two sides take turns talking. The primary station leads off and the secondary station follows sending response frames. Sides cannot talk for more than 500 ms at a time. They must allow the other side to talk, even if just to say it has nothing to send for the moment. This process continues until the communication is completed.

The primary station is also responsible for the organization and control of the data flow. In fact, data link layer is based in other protocols, such as High-level Data Link Control (HDLC) and Synchronous Link Data Control (SDLC), but integrating appropriated extensions due to the particular characteristics of IR communications.

The framing schemes, used by IrDA standard, and corresponding defined speed connections are as follows:

- Asynchronous framing: 9.6 kbit/s to 115.2 kbit/s,
- Synchronous HDLC framing: 576 kbit/s and 1152 kbit/s,
- Synchronous 4-PPM modulation framing: 4 Mbit/s.

Over these and some other capabilities, IrDA-Data standard specifies also a Infrared LAN (IrLAN) protocol for connecting an IrDA-enabled device to a wired network. Nevertheless, IrDA requirements for line of sight and maximum distance of one meter are limitative factors to be taken into account when placing IrLAN access devices. Also, once an IrDA device is connected to the LAN, it must remain relatively stationary.
Concluding, it seems clear that even providing upper bit rates than direct competitors, the major drawbacks of infrared technologies, which are the very short distance, the need for Line of Sight (LOS) and the slow mobility, prevent IrDA standards to be considered a true answer for WPANs.

2.5.3. Bluetooth

Bluetooth* is a radio frequency specification for short-range, point-to-multipoint voice and data transfer, mainly intended to replace the cables connecting electronic devices. Bluetooth can transmit through solid, non-metal objects, not needing LOS as infrared does. It is based on a low-cost, low-power radio link facilitating ad hoc connections for stationary and mobile communication environments.

The general Bluetooth characteristics are the following [36]:

- Omni-directional radio, operating in the unlicensed 2.4 GHz ISM band,
- Frequency Hopping Spread Spectrum (FHSS) technique, dividing the frequency band into 79 or 23 (France and Spain) RF channels; during the connection, radio transceivers hop from one channel to another in a pseudo-random fashion,
- Nominal hop rate of 1600 hops/s,
- Gaussian-shaped binary Frequency Shift Keying (GFSK) modulation,
- Symbol rate equal to 1 Mbaud,
- Time slotted RF channel with a nominal slot length of 625 µs,
- Fast Time-Division Duplex (TDD) scheme, enabling master-slave full duplex transmissions,
- Support of both synchronous and asynchronous user channels; easy integration of TCP/IP for networking,
- Synchronous channels capacity of 64 kbit/s in each direction,

* The name Bluetooth honors a 10th-century Danish viking and king named Harald Blåtand (Bluetooth in English). Harald Blåtand united and controlled Denmark and Norway, hence the inspiration on the name: uniting devices through Bluetooth.
- Asynchronous data channels with capacities up to 433.9 kbit/s symmetric or up to 723.2 kbit/s asymmetric (57.6 kbit/s in reverse direction),
- Supporting of up to 8 active devices in the same piconet (two or more units sharing the same channel).

The Bluetooth nominal link range is from 10 cm to 10 m, but can be extended to 100 m by increasing the transmit power. Indeed, each device can be classified into three transmission power classes:
- Power Class 1: designed for long range (~100 m) devices, with a maximum output power of 100 mW (20 dBm),
- Power Class 2: for ordinary range devices (~10 m) devices, with a maximum output power of 2.5 mW (4 dBm),
- Power Class 3: for short-range devices (~10 cm) devices, with a maximum output power of 1 mW (0 dBm).

For the communication between master and slave(s) devices, different types of links can be established. Two link types have been defined:
- Synchronous Connection-Oriented (SCO) link,
- Asynchronous Connection-Less (ACL) link.

The SCO link is a symmetric, point-to-point link between a master and a single slave in a Bluetooth piconet. The SCO link is maintained by using reserved slots at regular intervals and can therefore be considered as a circuit-switched connection between the master and the slave. The SCO link typically supports time-bounded information like voice.

The ACL link is a point-to-multipoint link providing a packet-switched connection between the master and all active slaves participating in the piconet. In fact, in the slots not reserved for SCO link(s), the master can establish an ACL link on a per-slot basis to any slave, including the slave(s) already engaged in an SCO link. The ACL link can be symmetric or asymmetric.

Besides some link control packets common to both SCO and ACL links, the packet types used on Bluetooth piconets are related to these same physical link modes and to the number of time slots they are used in. For the SCO physical link, 4 different packet types are defined as shown in Table 6. The user payload mentioned represents the packet payload excluding FEC, CRC, and payload header.
Table 6. Bluetooth SCO packet types.

<table>
<thead>
<tr>
<th>Type</th>
<th>Slot occupancy</th>
<th>Payload header (bytes)</th>
<th>User payload (bytes)</th>
<th>FEC</th>
<th>CRC</th>
<th>Symmetric max. rate (kbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HV1</td>
<td>1</td>
<td>n.a.</td>
<td>10</td>
<td>1/3</td>
<td>no</td>
<td>64.0</td>
</tr>
<tr>
<td>HV2</td>
<td>1</td>
<td>n.a.</td>
<td>20</td>
<td>2/3</td>
<td>no</td>
<td>64.0</td>
</tr>
<tr>
<td>HV3</td>
<td>1</td>
<td>n.a.</td>
<td>30</td>
<td>no</td>
<td>no</td>
<td>64.0</td>
</tr>
<tr>
<td>DV</td>
<td>1</td>
<td>1 (Data part)</td>
<td>10+(0-9) Data</td>
<td>2/3</td>
<td>yes (Data p.)</td>
<td>64.0+57.6 Data</td>
</tr>
</tbody>
</table>

In the table, the HVn and DV type designations stand, respectively, for High-quality Voice and Data-Voice packets (n evokes the amount of user payload). Exception made to the data part of DV packet, SCO packets do not include a CRC field and are never retransmitted.

For the ACL physical link 7 different packet types are defined as shown in Table 7.

Table 7. Bluetooth ACL packet types.

<table>
<thead>
<tr>
<th>Type</th>
<th>Slot occupancy</th>
<th>Payload header (bytes)</th>
<th>User payload (bytes)</th>
<th>FEC</th>
<th>CRC</th>
<th>Symmetric max. rate (kbit/s)</th>
<th>Asymmetric max. rate (kbit/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Forward</td>
</tr>
<tr>
<td>DM1</td>
<td>1</td>
<td>1</td>
<td>0-17</td>
<td>2/3</td>
<td>yes</td>
<td>108.8</td>
<td>108.8</td>
</tr>
<tr>
<td>DH1</td>
<td>1</td>
<td>1</td>
<td>0-27</td>
<td>no</td>
<td>yes</td>
<td>172.8</td>
<td>172.8</td>
</tr>
<tr>
<td>DM3</td>
<td>3</td>
<td>2</td>
<td>0-121</td>
<td>2/3</td>
<td>yes</td>
<td>258.1</td>
<td>387.2</td>
</tr>
<tr>
<td>DH3</td>
<td>3</td>
<td>2</td>
<td>0-183</td>
<td>no</td>
<td>yes</td>
<td>390.4</td>
<td>585.6</td>
</tr>
<tr>
<td>DM5</td>
<td>5</td>
<td>2</td>
<td>0-224</td>
<td>2/3</td>
<td>yes</td>
<td>286.7</td>
<td>477.8</td>
</tr>
<tr>
<td>DH5</td>
<td>5</td>
<td>2</td>
<td>0-339</td>
<td>no</td>
<td>yes</td>
<td>433.9</td>
<td>723.2</td>
</tr>
<tr>
<td>AUX1</td>
<td>1</td>
<td>1</td>
<td>0-29</td>
<td>no</td>
<td>no</td>
<td>185.6</td>
<td>185.6</td>
</tr>
</tbody>
</table>

In the table, the DMn and DHn type designations stand, respectively, for Data-Medium rate and Data-High rate packets, n being the number of time slots occupied. Exception made to the AUX1 packet, all other ACL packets include a CRC field and are retransmitted if no acknowledgement of proper reception is received.

The main devices that can better explore the Bluetooth's power-efficient radio technology are portable devices such as phones, pagers, headsets, notebook computers, etc. Besides the
actual opportunities for rapid, ad hoc deliberate connections, in the future Bluetooth may deliver automatic, unconscious connections between devices.

The Bluetooth system has been supported by a very strong industrial consortium (the Bluetooth Special Interest Group) and its acceptance has been quite good. A second version of the specification, approaching now the 10 Mbit/s and supporting over than 100 piconet nodes, is expected in 2002.

2.5.4. IEEE 802.15

At the beginning of 1998 the IEEE 802.11 WLAN Working Group started to investigate the need for a supplemental wireless network standard specifically targeted to provide very low power consumption, low complexity, wireless connectivity among devices within or entering a Personal Operating Space. It was then formed the Wireless Personal Area Networks Study Group to be in charge of that investigation.

One of the conclusions of that study group is that there is nowadays an unfilled market need for a means of networking devices within POS. Indeed the power consumption, cost, and size optimization constraints prohibit the use of currently available standardized solutions.

That's why one year later (in 1999) the Study Group was converted into a Working Group within IEEE 802 LAN/MAN Standards Committee (LMSC) and given the designation 802.15.

The scope of 802.15 WPAN is to define PHY and MAC specifications for wireless connectivity with fixed, portable and moving devices within or entering a POS. One of the goals of 802.15 will be to achieve a level of interoperability which could allow the transfer of data between a WPAN device and an 802.11 device. The 802.15 project will also address the Quality of Service issue in order to support a variety of traffic classes.

To assist the WPAN standards development, the 802.15 Working Group has a Publicity Committee and 4 main Task Groups as listed below:

- Task Group 1 (TG1): WPAN/Bluetooth,
- Task Group 2 (TG2): Coexistence,
- Task Group 3 (TG3): WPAN High Rate,
- Task Group 4 (TG4): WPAN Low Rate.
The WPAN/Bluetooth TG1 is deriving a WPAN standard based on the Bluetooth v1.x Foundation Specifications. This will set a standard for low complexity, low power consumption and global interoperable wireless devices. The 802.15.1 specification is well advanced, the IEEE Standards Board approval being expected in the second quarter of 2002.

The Coexistence TG2 is developing recommended practices to facilitate coexistence of 802.15 WPANs and 802.11 WLANs devices. To help that purpose, TG2 is developing a coexistence model to quantify the mutual interference of a WLAN and a WPAN.

The WPAN High Rate (HR) TG3 is chartered to draft and publish a new WPAN standard for high bit rates (20 Mbit/s or greater). Very recently, the 802.15.3 task group selected a physical layer proposal for its HR standard. The PHY adopted by TG3 operates in the unlicensed 2.4 GHz band with a minimum raw data rate of 22 Mbit/s. There will be optional modes that could allow it to go as high as 66 Mbit/s, although the highest data rates will have coding that will decrease this rate. Table 8 shows the proposed Wireless PAN High Rate PHY characteristics.

Table 8. IEEE 802.15 Wireless PAN High Rate: proposed physical layer characteristics.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency range</td>
<td>2.4-2.4835 GHz</td>
</tr>
<tr>
<td>Symbol rate</td>
<td>11 Msymbol/s</td>
</tr>
<tr>
<td>Base modulation</td>
<td>OQPSK</td>
</tr>
<tr>
<td>RF bandwidth</td>
<td>&lt; 22 MHz</td>
</tr>
<tr>
<td>Transmit power</td>
<td>0 to 8 dBm</td>
</tr>
<tr>
<td>Range</td>
<td>10 meters</td>
</tr>
</tbody>
</table>

Table 9 shows the chosen modulation formats providing the 802.15.3 highest data rates. The coding for the higher modulations is to be defined. With these crucial inputs the beginning of 802.15.3 WPAN HR draft standard took place.

The WPAN Low Rate TG4 is chartered to investigate a low data rate solution with multi-month to multi-year battery life and ultra low complexity. Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation. The wireless communication raw data rate will be high enough (maximum of 200 kbit/s) to satisfy a set of
simple needs such as interactive toys, but scaleable down to the needs of general sensors and automation (10 kbit/s or below). Future WPAN Low Rate devices are intended to operate in an unlicensed, international frequency band.

Table 9. IEEE 802.15 Wireless PAN High Rate: proposed physical modulation formats.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding</th>
<th>Data rates</th>
</tr>
</thead>
<tbody>
<tr>
<td>OQPSK</td>
<td>none</td>
<td>22 Mbit/s</td>
</tr>
<tr>
<td>16 QAM</td>
<td>TBD</td>
<td>22-44 Mbit/s</td>
</tr>
<tr>
<td>32 QAM</td>
<td>TBD</td>
<td>33-55 Mbit/s</td>
</tr>
<tr>
<td>64 QAM</td>
<td>TBD</td>
<td>44-66 Mbit/s</td>
</tr>
</tbody>
</table>

The Publicity Committee is coordinating the 802.15 working group submissions to ensure that clearly defined messages concerning WPAN devices usage, WPAN marketplace and potential WPAN market overlap are conveyed to the public.

Very recently, the IEEE 802.15 defined the Study Group 3a (SG3a: WPAN Alternative High Rate PHY), which is working to define a project to provide a higher speed PHY enhancement amendment to 802.15.3 for applications involving Imaging and Multimedia.

2.5.5. HomeRF

HomeRF is a set of wireless networking specifications produced by an industry consortium, mostly supported by North American communication companies, known as the HomeRF Working Group.

One motivation behind the formation of this group, happened in March 1998, was the deployment of fairly inexpensive networking solutions for home or small office environments. With this purpose in mind, HomeRF* systems are designed to carry both voice and data traffic and to interoperate with the Public Switched Telephone Network (PSTN) and the Internet.

* HomeRF has also been known as the “Shared Wireless Access Protocol” (SWAP) but, nowadays, HomeRF Working Group prefers to use just the expression “HomeRF”.

They operate in the 2.4 GHz ISM band and use a digital frequency-hopping spread spectrum radio technology, yielding a maximum data rate of 1.6 Mbit/s.

The HomeRF technology is derived from extensions of existing cordless telephone (namely DECT) and wireless LAN technologies to enable a new class of home cordless services. It supports both a Time Division Multiple Access (TDMA) service to provide delivery of interactive voice and other time-critical services, and a Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) service for delivery of high-speed packet data.

The HomeRF specification acts like a low-cost intermediate solution in the 2.4 GHz band, competing with IEEE 802.11 whenever shorter distances are involved and slightly lower performances are acceptable.

Concerning the possible network topologies, a HomeRF system can operate either as an ad hoc network or as a managed network under the control of a Connection Point. In an ad hoc network, where only data communication is supported, all stations are equal and the control of the network is distributed between the stations.

For time critical communications such as interactive voice a Connection Point is required to coordinate the system. The Connection Point, which provides the gateway to the PSTN, can be connected to a PC via a standard interface such as USB that will enable enhanced voice and data services. The HomeRF system can also use the Connection Point to support power management for extended battery life by scheduling device wakeup and polling.

The network can accommodate a maximum of 127 nodes. These nodes can be a mixture of these four basic types:

- Connection Point, supporting voice and data communications,
- Voice Node, using only the TDMA service to communicate with a base station,
- Data Node, using the CSMA/CA service to communicate with a base station and other data nodes, and,
- Voice and Data Node, using both types of services.

In version 1 of the specification (HomeRF 1.0) the main system parameters are the following:

- Operating radio frequency: 2.4 GHz ISM band,
- Transmission power: 100 mW,
- Data Rate: 0.8 Mbit/s using 2FSK modulation and 1.6 Mbit/s using 4FSK modulation,
- Frequency hopping rate: 50 hops/second,
- Range: covering typical home/small office and yard,
- Supported stations: Up to 127 devices per network,
- Voice connections: Up to 6 full duplex conversations,
- Data security: Blowfish encryption algorithm (over 1 trillion codes),
- Data compression: LZRW3-A algorithm,

Most recently (2001), and following a FCC positive answer to HomeRF Working Group petition to increase the frequency-hopping bandwidth, this group has presented a 10 Mbit/s HomeRF version suitable to deliver high-speed, high-quality data, voice and streaming media.

This wideband version, named HomeRF 2.0, is based in the same technology but it assumes now a 5 MHz channel bandwidth instead of the previous 1 MHz. The major changes from HomeRF 1.0 to HomeRF 2.0 are:

- A maximum data rate of 10 Mbit/s with fallback modes of 5, 1.6 and 0.8 Mbit/s,
- An offer of up to 8 simultaneous near-wireline voice quality channels,
- A prioritized access for streaming media (up to 8 simultaneous active streams),
- Support for 128 bit data encryption,
- Tracking of interference channels and respective avoidance by frequency hopper.

As expected, HomeRF 2.0 guarantees the backward compatibility with previous versions of HomeRF.

2.6. Fixed broadband access networks

2.6.1. IEEE 802.16

Following a global need to start standardization processes in the area of Broadband Wireless Access (BWA) systems, a project authorization request (PAR) within IEEE 802
LAN/MAN Standards Committee was approved, in November of 1998, exactly with those purposes. The resulting unit was named IEEE 802.16 Working Group on Broadband Wireless Access Standards and its mission is to develop standards and recommended practices to support the development and deployment of fixed broadband wireless access systems.

In the same line of action as IEEE 802.11 and 802.15 Working Groups, which are creating a family of standards to, respectively, wireless LANs and wireless PANs, the IEEE 802.16 Working Group is engaged in the creation of a family of standards for wireless Metropolitan Area Networks.

As other IEEE 802.x Working Groups, IEEE 802.16 will focus in the specification of Physical (PHY) and Medium Access Control (MAC) layers. A special attention will be given to MAC layer specification in order to guarantee the existence of multiple PHY layers, independently of the used frequency band. The details of these multiple PHY layers are hidden from the MAC layer with the help of a Transmission Convergence sublayer located between PHY and MAC.

In fact, the IEEE 802.16 Working Group has been working in the production of an air interface document with a common, flexible MAC platform supporting various PHY layers. The base document, entitled IEEE 802.16, will include the basic MAC and the 10-66 GHz PHY. The amendment 802.16a will include enhancements for 2-11 GHz licensed bands and the amendment 802.16b will include enhancements for license-exempt operation.

The 802.16b amendment is under the responsibility of a recent 802.16 inner Study Group called Wireless High-Speed Unlicensed Metropolitan Area Networks (WirelessHUMAN). Its charter is to investigate the feasibility of providing high-speed MAN access using unlicensed or license-exempt bands, with a special focus on the 5-6 GHz bands.

None of the documents referred to above have been approved yet and some of them have only a draft development status. The information presented hereafter is thus only indicative of 802.16 plans for each of the MAC and PHY layers, and it is based on available contribution documents.

2.6.1.1. 10-66 GHz PHY layer specification

The current 802.16 PHY layer specification for 10-66 GHz is being designed to meet the functional requirements currently defined for BWA systems. In order to reuse existing
technology, hence improving the robustness of implementation and the reduction of equipment cost, it incorporates many aspects of existing standards [37] [38] [39].

As a supporting technology for interactive two-way services, 802.16 systems provide both downstream and upstream channels.

For the physical layer downstream channel two modes of operation have been defined, one targeted to support a continuous transmission stream (Mode A) and one targeted to support a burst transmission stream (Mode B).

Independently of downstream mode, the upstream channel is always targeted to support upstream burst transmissions and is based on the use of a combination of time division multiple access (TDMA) and a demand assigned multiple access (DAMA).

The duplexing scheme used to merge the downstream and upstream channels depends on which type of operation mode is currently taking place, that is, Mode A or Mode B.

**Continuous Downstream Transmission (Mode A):**

If Mode A is used then a Frequency Division Duplexing (FDD) technique is employed to permit simultaneous downstream and upstream channels through the use of different frequencies for downlink and uplink transmissions. In this mode of operation, upstream and downstream signals have no defined framing, which allows receiver stations to transmit on the upstream independently of what it is being transmitted on the downstream signal.

In Mode A the information to be conveyed is multiplexed using a time division multiplexing (TDM) technique, that is, the information for each receiver station is multiplexed into the same stream of data and is received by all stations located within the same receiving sector.

In Mode A the downlink bitstream is currently defined as a continuous series of 188-byte packets. The large packets coming from the MAC layer are formatted into these fixed size packets by the action of the Transmission Convergence (TC) sublayer.

The relevant characteristics of the PHY layer corresponding to 802.16 air interface Mode A downstream type of operation are presented in Table 10.
Table 10. IEEE 802.16 air interface: Mode A continuous downstream physical layer parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Randomization</td>
<td>$1 + X^{14} + X^{15}$</td>
</tr>
<tr>
<td></td>
<td>Initialization: 100101010000000</td>
</tr>
<tr>
<td>Reed-Solomon outer coding</td>
<td>(204,188) over GF(256), t=8 byte errors corrected</td>
</tr>
<tr>
<td>Interleaving</td>
<td>Convolutional with depth I=12</td>
</tr>
<tr>
<td>Convolutional inner coding</td>
<td>Selectable rates: 1/2, 2/3, 3/4, 5/6, 7/8 or 1 (disabled)</td>
</tr>
<tr>
<td>Differential encoding</td>
<td>Enabled/disabled (only enabled when convolutional coding is not employed)</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK, 16-QAM (optional) or 64-QAM (optional)</td>
</tr>
<tr>
<td>Spectral shaping (roll-off factor)</td>
<td>$\alpha = 0.15, 0.25$ or $0.35$</td>
</tr>
</tbody>
</table>

**Burst Downstream Transmission (Mode B):**

Going now to the Mode B type of operation it is worth mentioning that this mode is relatively more complex than Mode A. In fact, mode B is to be applicable not only in systems using Time Division Duplexing (TDD) but also in FDD systems supporting half duplex stations, in addition to full duplex ones. Fortunately, the use of burst transmission brings an advantage as well, which is the possibility of using adaptive modulation / FEC schemes to fulfill different performance requirements of receiving stations.

Systems using one of those duplexing techniques (TDD or burst FDD) require a burst type capability in the downstream channel, which imposes some constraints on several aspects of the physical layer. These constraints deal primarily with the phase recovery issue (due to the burst transmission) and with the allowable codeword lengths in the adaptive modulation / FEC schemes.

In order to simplify the phase recovery and the channel tracking a 1 ms framing structure is used (other allowable frame durations are 0.5 and 2 ms). At the beginning of every frame a preamble is transmitted in order to allow phase recovery and equalization training.

Because Mode B PHY layers support the capability to have different modulation / FEC formats on the same carrier, the downstream payload coming from the MAC layer can be
segmented into data blocks of non-constant size. The size of these data blocks has to be properly set in order to accommodate the intended codeword size after the TC sublayer bytes are added.

Each downstream modulation / FEC scheme has its own PHY parameters that are conveyed to corresponding receiving stations via MAC messages. Table 11 shows the relevant Modulation / FEC parameters corresponding to the 802.16 air interface Mode B downstream type of operation.

Note that adaptive modulation / FEC is supported with any of the duplexing techniques (TDD or burst FDD) defined for the Mode B burst downstream type of operation.

Table 11. IEEE 802.16 air interface: Mode B burst downstream PHY layer modulation / FEC parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation</td>
<td>QPSK, 16-QAM or 64-QAM (optional)</td>
</tr>
<tr>
<td>FEC coding</td>
<td>Selectable from the following options:</td>
</tr>
<tr>
<td></td>
<td>(1) Reed Solomon (RS) over GF(256)</td>
</tr>
<tr>
<td></td>
<td>(2) RS + inner rate 2/3 block convolutional code</td>
</tr>
<tr>
<td></td>
<td>(3) RS + inner parity check (optional)</td>
</tr>
<tr>
<td></td>
<td>(4) Block turbo code (optional)</td>
</tr>
<tr>
<td>RS information bytes</td>
<td>k = 6-255</td>
</tr>
<tr>
<td>RS error correction capability</td>
<td>t = 0-16</td>
</tr>
<tr>
<td>Block convolutional code type</td>
<td>(24,16)</td>
</tr>
<tr>
<td>Parity check code</td>
<td>(9,8)</td>
</tr>
<tr>
<td>Block turbo code - row type</td>
<td>(64,57) or (32,26) Extended Hamming</td>
</tr>
<tr>
<td>Block turbo code - column type</td>
<td>(64,57) or (32,26) Extended Hamming</td>
</tr>
</tbody>
</table>

Upstream Transmission:

The very last physical layer definition is concerned with the upstream channel. As referred to previously the upstream transmissions intend to use a burst modulation in the context of a TDMA based system. Accordingly, the upstream physical layer has been designed to support those features.
In the same way as Mode B downstream transmissions, the upstream physical layer presents a value-added functionality: the use of adaptive modulation allowing different users to be assigned with different modulation / FEC types.

The setting of the modulation type and other specific upstream channel parameters can be programmed by MAC layer messages coming from the base station. This can be done during the registration process in order to optimize performance for a particular deployment scenario. This way each upstream burst is designed to carry messages of variable lengths and with different levels of error protection. The relevant parameters of 802.16 air interface upstream PHY layer are presented in Table 12.

Table 12. IEEE 802.16 air interface: upstream physical layer parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission convergence layer</td>
<td>Selectable on/off. When enabled, the TC layer includes 1 pointer byte and 2 CRC checksum bytes for error detection.</td>
</tr>
<tr>
<td>Randomization</td>
<td>$1 +X^{14} +X^{15}$</td>
</tr>
<tr>
<td></td>
<td>Initialization seed: 15-bit programmable</td>
</tr>
<tr>
<td>FEC coding</td>
<td>Selectable from the following options:</td>
</tr>
<tr>
<td></td>
<td>(1) Reed Solomon (RS) over GF(256)</td>
</tr>
<tr>
<td></td>
<td>RS information bytes: $k=6-255$</td>
</tr>
<tr>
<td></td>
<td>RS error correction capability: $t=0-16$</td>
</tr>
<tr>
<td></td>
<td>(2) RS + Rate 2/3 block convolutional code</td>
</tr>
<tr>
<td></td>
<td>(3) RS + Parity check (optional)</td>
</tr>
<tr>
<td></td>
<td>(4) Block turbo code (optional)</td>
</tr>
<tr>
<td>Differential encoding</td>
<td>Selectable on/off</td>
</tr>
<tr>
<td>Preamble</td>
<td>Programmable length: 0-1024 bits</td>
</tr>
<tr>
<td></td>
<td>Programmable value</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK, 16-QAM (optional) or 64-QAM (optional)</td>
</tr>
<tr>
<td>Spectral shaping (roll-off factor)</td>
<td>$\alpha = 0.15, 0.25$ or $0.35$</td>
</tr>
</tbody>
</table>
2.6.1.2. MAC layer specification

In relation to the 802.16 MAC layer a major concern behind its characterization is the definition of a protocol optimized for point to multi-point BWA systems. Additionally to that optimization, the MAC protocol is being planned to be independent of the type of traffic carried and to support the QoS requirements of real-time traffic as well.

With these purposes in mind the MAC protocol was set as connection-oriented. This means that when mapping services to Customer Premises Equipment (CPE), and associating varying levels of QoS, all data communications are carried out in the logical connections context. These logical connections are provisioned when a CPE is installed in the system and set up over the air at CPE registration. Moreover, new connections may be established when customer’s service needs change.

In order to support different network protocols, these ones are interfaced with MAC layer via “network convergence sublayers”. Some of the convergence sublayers under development are for IPv4, IPv6, Ethernet and ATM networks. The functions of a convergence sublayer include:

- Assigning network packet flows to MAC connections,
- Mapping network protocol parameters to MAC parameters,
- Suppress payload headers (e.g., connectionless headers), etc.

Regarding the PHY-MAC interaction, the MAC layer is able to support both framed and non-framed physical layers. For a framed PHY layer, the MAC aligns its scheduling intervals with the underlying PHY layer framing. For an unframed PHY layer, the scheduling intervals are chosen by the MAC to optimize system performance.

The MAC protocol is more complex in the upstream channel since this is more demanding in terms of coordinated medium access (that is, multiple contenders to the same resource).

In fact, the 802.16 wireless link operates with a central base station in a point-to-multipoint topology. This means that, in the downlink, the base station is the only transmitter

* Recall that the PHY layer Mode B (TDD or Burst FDD) uses a framed PHY; Mode A (continuous FDD) has no explicit PHY layer framing.
operating in this direction, hence it can transmit without having to coordinate with other stations, except for the overall time division duplexing that divides time into upstream and downstream transmission periods. When receiving this central base station "exclusive" downstream channel the user station’s mission is to check the address in the received messages and retain only those addressed to it.

However, the user stations share the upstream period on a demand basis. Depending on the class of service used, the CPE may be issuing continuing rights to transmit, or the right to transmit may be granted by the base station after receipt of a request from the user. In this way, users must adhere to a transmission protocol which minimizes contention between users and enables the service to be tailored to the delay and bandwidth requirements of each user application.

The upstream MAC protocol is accomplished through five different types of upstream scheduling mechanisms which are implemented using unsolicited bandwidth grants, polling, and contention procedures. Each scheduling service is tailored to a specific type of data flow as described in Table 13.

Table 13. IEEE 802.16 air interface: upstream MAC services.

<table>
<thead>
<tr>
<th>Upstream service name</th>
<th>Main use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unsolicited Grant Service</td>
<td>Real-time services generating fixed size packets on a periodic basis; e.g., ATM CBR and T1/E1</td>
</tr>
<tr>
<td>Unsolicited Grant Service with Activity Detection</td>
<td>Real-time services having significant periods of inactivity; e.g., VoIP with silence suppression</td>
</tr>
<tr>
<td>Real-Time Polling Service</td>
<td>Real-time services generating variable size packets on a periodic basis; e.g., MPEG video</td>
</tr>
<tr>
<td>Non-Real-Time Polling Service</td>
<td>Non-real-time services requiring variable size data grants on a regular basis; e.g., high bandwidth FTP</td>
</tr>
<tr>
<td>Best Effort Service</td>
<td>General best effort traffic</td>
</tr>
</tbody>
</table>

These different upstream MAC services are designed to improve the efficiency of the polling/granting process. By specifying a scheduling service and its associated QoS parameters, the base station can anticipate the throughput and latency needs of the upstream traffic and provide polls and/or grants at the appropriate times.
Concerning the protocol data unit (PDU) used in MAC layer, both in uplink and downlink, this one is a variable length packet containing a fixed length generic MAC header and a variable length payload field.

The generic MAC-PDU headers are reduced to three formats. The first two formats correspond to headers that precede almost all MAC messages, including both management and information data. One of the formats is used for uplink transmissions, the other being used for the downlink. The third header format is used only in the uplink with the special purpose of requesting additional bandwidth. The use of this format results in a MAC-PDU with just the header (i.e., with no payload field).

To conclude the IEEE 802.16 air interface explanation it should be mentioned that due to the large amount of spectrum available in the 10-60 GHz region for point-to-multipoint operations, the baud rates and RF channel bandwidths have been left somewhat flexible. This policy fits better to the different regulatory requirements in various countries around the world and allows service providers the ability to maximize capacity for a given spectrum allocation.

It can be said that customer station equipment should support symbol rates that lie in the interval 10 Mbaud to 40 Mbaud for the downstream transmissions and 5 Mbaud to 30 Mbaud for the upstream ones (indicative figures).

### 2.6.2. HIPERACCESS

The HIPERACCESS Standard Area mission is to develop standards for broadband multimedia fixed wireless access. In this line of action a HIPERACCESS (HA) system is a type of long-range wireless high-speed access connecting to a large variety of core networks including ATM, IP-based and UMTS networks.

HA systems will support a minimum typical data rate of 25 Mbit/s in a point-to-multipoint topology mainly intended to be used by residential and small business users (HIPERLAN/2 might be used for distribution within customer premises).

The top priority for the HA group is to write a standard enabling broadband radio systems at millimeter (mm) wave frequencies (20-50 GHz). Indeed, HA is being optimized for
the 40.5-43.5 GHz band. Other interesting bands, selected by HA group, are the 24.5-26.5, 27.5-29.5 and 31.8-33.4 GHz.

The second priority for the HA group is to write a standard for one broadband radio system working at frequencies below 20 GHz. This specification should be based on the high frequencies standard. Appropriate variations should be made only to cope with the use of lower frequencies.

IEEE 802.16 and HA systems have similar goals. As such the technical solutions are also very alike. Nevertheless, the HA technical discussions and decisions leading to consistent draft specifications are a little bit more delayed than 802.16. Hence, technical details subsequently shown are based not on draft specifications but on decision lists of HA Working Groups.

The HA PHY layer will be based on a FDD scheme and takes into account the possible existence of both full and half-duplex terminals. With this concern in mind different modes of operation supporting both types of terminals will be included in the standard. For spectrum allocations not suitable for FDD schemes a TDD scheme whose definition will be also included in the HiperACCESS standard might be used. This TDD scheme is based on the technology specified for FDD.

Concerning HA physical layer modulations the single carrier M-ary Quadrature Amplitude Modulation (M-QAM) technique was chosen for both downlink and uplink. The HA radio channel bandwidth is defined to be 28 MHz, in both directions, enabling baud rates around 22 Mbaud.

As shown in Table 14, at present five downlink PHY modes are defined. They provide different levels of error robustness through combined modulation, outer coding and inner coding. The choice of downlink PHY modes will be adaptive on a terminal per terminal basis. The master station automatically selects the best combination for every terminal at the system start up.

All PHY modes use the same Reed-Solomon outer coding scheme, that is, they use the same RS primitive code over GF(256) with an error correction capability of t = 8 bytes. The final length of RS codewords, which can be 69 or 122 bytes, depends if they derive from single MAC-PDUs (supposedly 53 bytes long) or from two MAC-PDUs (≈106 bytes long).
Based on this a corresponding amount of code shortening is properly applied to the RS primitive code.

Table 14. HIPERACCESS Physical layer: downlink PHY modes.

<table>
<thead>
<tr>
<th>If codeword is based in one PDU:</th>
<th>Modulation</th>
<th>Outer code</th>
<th>Inner code</th>
<th>Concatenated code rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QPSK</td>
<td>RS (69,53)_{256}</td>
<td>Convolutional, rate 2/3</td>
<td>51%</td>
</tr>
<tr>
<td></td>
<td>QPSK</td>
<td>RS (69,53)_{256}</td>
<td>-</td>
<td>77%</td>
</tr>
<tr>
<td></td>
<td>16-QAM</td>
<td>RS (69,53)_{256}</td>
<td>Convolutional, rate 5/6</td>
<td>64%</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
<td>RS (69,53)_{256}</td>
<td>Convolutional, rate 3/4</td>
<td>58%</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
<td>RS (69,53)_{256}</td>
<td>-</td>
<td>77%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>If codeword is based in two PDUs:</th>
<th>Modulation</th>
<th>Outer code</th>
<th>Inner code</th>
<th>Concatenated code rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>QPSK</td>
<td>RS (122,106)_{256}</td>
<td>Convolutional, rate 2/3</td>
<td>58%</td>
</tr>
<tr>
<td></td>
<td>QPSK</td>
<td>RS (122,106)_{256}</td>
<td>-</td>
<td>87%</td>
</tr>
<tr>
<td></td>
<td>16-QAM</td>
<td>RS (122,106)_{256}</td>
<td>Convolutional, rate 5/6</td>
<td>72%</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
<td>RS (122,106)_{256}</td>
<td>Convolutional, rate 3/4</td>
<td>65%</td>
</tr>
<tr>
<td></td>
<td>64-QAM</td>
<td>RS (122,106)_{256}</td>
<td>-</td>
<td>87%</td>
</tr>
</tbody>
</table>

RS: Reed-Solomon (block code)

Up to now the reference codeword structure to be used in the HA dowlink is the one based in two MAC-PDUs. As this solution could be, in some situations, inefficient at DLC layer the possibility to dynamically change from “two PDUs” to “single PDUs” codewords is currently under investigation. The implementation of a versatile and efficient codeword shortening procedure can even change the default codeword to three MAC-PDUs (approximately 159 bytes long).
Table 15. HIPERACCESS Physical layer: uplink PHY modes.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Outer code</th>
<th>Inner code</th>
<th>Concatenated code rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>QPSK</td>
<td>RS (69,53)256</td>
<td>Convolutional, rate 2/3</td>
<td>51%</td>
</tr>
<tr>
<td>QPSK</td>
<td>RS (69,53)256</td>
<td>-</td>
<td>77%</td>
</tr>
<tr>
<td>16-QAM</td>
<td>RS (69,53)256</td>
<td>Convolutional, rate 5/6</td>
<td>64%</td>
</tr>
</tbody>
</table>

RS: Reed-Solomon (block code)

For the HIPERACCESS uplink direction the choice goes to three PHY modes as shown in Table 15. These three modes are identical to the three more robust ones used in the downlink direction. They only use the 4 and 16-QAM schemes. The RS (69,53) code is envisaged for outer coding as current decisions foresee just one MAC-PDU per codeword.

Regarding the DLC type of connection, it is already defined that HIPERACCESS DLC layer is connection oriented. This means that to send packets that belong to an application it is necessary to open a DLC connection to establish a path to those packets. This also guarantees that packets are received in the same order as they were sent.

As mentioned earlier the MAC-PDU length shall be around 53 bytes, which makes it suitable for carrying ATM cells. The exact length of the data payload part is already set as equal to 48 bytes. The exact length of the header is still to be defined.

The DLC layer has a MAC frame based structure where combined TDM and TDMA techniques can be used. The frame duration is fixed with a value of 1 ms.

The TDMA multiple access scheme is used for the HA uplink frame. In the downlink the frame is comprised of a TDM portion followed by an optional TDMA portion. The optional existence of a TDMA portion in the downlink direction is particularly suitable for half-duplex terminals because that enables them to transmit before they receive.

The HIPERACCESS specifications will allow a flexible and competitive alternative to wired access networks. In order to promote a mass market and thereby low cost products, it will be an interoperable standard. With this purpose in mind, BRAN project is co-operating closely with the IEEE 802.16 Working Group to harmonize the standards interoperability.
The first batch of HIPEERACCESS specifications [40] [41] [42] was published exactly when this writing was concluded.

2.7. Summary

In this chapter, several types of wireless networking solutions were presented in function of the following ranges:

- Cellular/wide area,
- Personal and home areas,
- Local area, and,
- Fixed/metropolitan area.

All those wireless data solutions will bring big benefits to mobile users, corporations and service providers. Those benefits will converge, specially, in the following aspects:

- Mobile users: access to information and services “wherever you are” whether in a meeting, on the road, or at home.
- Corporations: general productivity increase and competitive edge gain.
- Service providers: differentiation through the offer of wired and wireless IP services, resulting in a high growth market.

In Figure 5 a comparison of mobility and bit rate of some typical wireless data technologies is shown. For comparison purposes a wired LAN is also included in the figure.

Concerning Personal Area Networks, IrDA and Bluetooth technologies provide complementary implementations for data exchange and voice applications. For some devices it will be quite enough to comply with just one of the technologies, for others a flexible and efficient short-range wireless connectivity will need both. Nevertheless, infrared technology is not in a position as good as Bluetooth because of its ultra close point-to-point communications and the big disadvantage of needing line of sight. For now, the story on short-range wireless communication technology seems to lean to Bluetooth as indicated by its adoption by the main WPAN IEEE 802.15 standard.
Figure 5. Mobility vs. bit rate for some wireless data technologies.

As far as the major forces driving the WLAN area are concerned, the HIPERLAN/2 and IEEE 802.11a systems already approach the bit rate of a wired LAN with the advantage of getting indoor and outdoor mobility (and walk velocity as well). These two systems are in fact the two most important standards concerning upcoming WLANs technologies. Both use unlicensed or license-exempt 5 GHz bands with differentiate power levels. As shown in Figure 6 the imposed regulatory limits enable both low power indoor systems and medium power outdoor systems to peacefully coexist.

Of all the types of wireless networking technologies presented before, the wireless LAN type is the one that shows the best compromise between performance and mobility. Actually, although it is not its exclusive, the wireless LAN solution is particularly suitable to:

- Extend the local area network,
- Enable a free access to the corporate network, offering high-speed rates and features comparable to those of wired networks,
- Provide reliable real-time communications in network access areas, such as meeting rooms, airports, hotels, remote offices and home offices.
Figure 6. Regulatory limits for 5 GHz bands.

Wireless LAN technologies represent indeed the best option when mobility and high-speed network access or data transferring are required. The WLAN choice enables fast and secure exchange of important information, such as corporate data, e-mail and Internet uploading and downloading.

Moreover, the more performant WLANs at 5 GHz may even be used for quality demanding audio/video real-time applications. Nevertheless, they require an extended set of suitable QoS mechanisms not foreseen in current standards.
Chapter 3

The IEEE 802.11 wireless LAN standard

3.1. General considerations

The increasing need for "anywhere, anytime" communications and the convergence of voice, video and data communications is generating a great demand for broadband wireless networks. In response to this, several Working Groups have been created within the main networking/telecommunications standardization bodies with the mission of getting a harmonious deployment of wireless techniques and practices.

Some years ago, in the United States the IEEE 802 LAN/MAN Standards Committee formed the 802.11 wireless LAN Working Group to analyze the various wireless local area networking aspects. More recently the same Committee has created the 802.15 wireless Personal Area Network (PAN) and the 802.16 wireless Metropolitan Area Network (MAN) Working Groups to address corresponding issues.

In Europe ETSI has formed the BRAN project to build up standards and specifications for broadband radio access networks covering a wide range of applications and intended for different frequency bands. These systems deal mainly with wireless LANs and fixed broadband accesses.
Only specifications related with the local area networking issue are already available. The other projects are more delayed, in part because it was the success of wireless LANs that has stimulated their starts. These projects also intend, if applicable, to re-use WLAN technology.

All these facts lead us to the two more important outputs concerning wireless networking standards issued by IEEE and ETSI standardization bodies. They are, respectively, the IEEE 802.11 WLAN and ETSI/BRAN HIPERLAN 2 family of standards.

IEEE 802.11 WLAN standard is presented in the following sections of this chapter. BRAN project and its HIPERLAN type 2 wireless LAN standard is described in the next chapter.

3.2. 802.11 Overview

The 802.11 wireless LAN standard is part of a family of standards for local and metropolitan area networks that include some other popular 802.x standards.

This family of standards deals with the Physical and Data Link layers of the OSI Basic Reference Model. It is comprised of common procedural standards and specific access standards.

The main common procedural standards (and some specific access standards besides 802.11) of the IEEE 802 family are as follows:

- IEEE 802 Standard: Overview and Architecture [43]. It provides an overview of the family of IEEE 802 Standards. This document forms part of the 802.1 scope of work.


Figure 7 illustrates the relationship of IEEE 802.11 standard with all these 802.x standards and with the OSI Basic Reference Model. Looking at the figure, it becomes clear that IEEE 802.x standards are related with the lowest two layers and consist primarily of the Logical Link Control (LLC) and the various MAC and PHY layers for each LAN or MAN standard.

![Diagram of IEEE 802.11 relationship with the IEEE 802 family of standards and the OSI Basic Reference Model.]

Figure 7. IEEE 802.11 relationship with the IEEE 802 family of standards and the OSI Basic Reference Model.

The 802.x access standards, i.e., the ones with a PHY and a MAC specification, define several types of medium access technologies and associated physical media, each appropriate
for particular applications or system objectives. These standards, when described well, result in the interoperability of multiple vendors' equipment. Besides the 802.11 access standard other types were defined already in the past and others are now under investigation.

Consider now the Figure 8, where the IEEE 802.11 standard structure is shown. It is possible to distinguish the major intervention items object of standardization by the 802.11 Working Group. Some of these items (basic standard and some extensions) were already analyzed and standardized and some others are still in study.

![Diagram of the IEEE 802.11 standard structure.]

**Figure 8. IEEE 802.11 standard structure.**

The basic standard was approved in 1997 and includes the specification for MAC and PHY layers at 1 and 2 Mbit/s rates. The latter layer involves the use of Frequency Hopping Spread Spectrum (FHSS), Direct Sequence Spread Spectrum (DSSS) and diffuse Infrared systems.

Two years later, in 1999, the 11 Mbit/s DSSS PHY extension at 2.4 GHz and the 6-54 Mbit/s OFDM PHY extension at 5 GHz were also approved.
Nowadays, the main standardization issues in discussion are related to:

- QoS and efficiency enhancements to the current MAC specification (802.11 Task Group E),
- Roaming and interoperability between Access Points (Task Group F),
- An even higher rate extension to the 802.11b (Task Group G),
- Channel selection and transmit power enhancements for the operation in the 5 GHz band (Task Group H).

3.3. 802.11 MAC layer specification

One of the main functions of IEEE 802.11 MAC layer is to provide transport services to packets coming from upper layers. With that purpose in mind the MAC Asynchronous Data Service has been defined and, depending on the time-bounded nature of the data, two radio medium access methods have been specified as well. The functional implementation of these two methods is done through two entities named:

- The (main) Distributed Coordination Function (DCF), and,
- The (optional) Point Coordination Function (PCF).

The first acts as a general purpose medium access method the second being specifically included to accommodate time bounded connection-oriented services such as cordless telephony.

The MAC Asynchronous Data Service provides upper LLC sublayer entities with the ability to exchange MAC Service Data Units (SDUs). To guarantee this service the MAC layer uses the underlying 802.11 physical layer capabilities as well as intrinsic own level MAC functionalities such as the DCF access method. The Asynchronous Data Service and the Distributed Coordination Function are mandatory in all 802.11 devices, for both ad hoc and infrastructure network configurations.

The transport between peer LLC entities of asynchronous MAC-SDUs is done on a best-effort connectionless basis, hence the immediate delivery of submitted MAC-SDUs is not
completely guaranteed. For an enhanced support of delay-bounded data transfers the optional Point Coordination Function must be used.

PCF is always based on the mandatory DCF rules. As to be explained latter on, if PCF is currently implemented, this implies the introduction of the "polling lists" scheme of PCF into the general "contention" scheme of DCF. Contrary to DCF, PCF is defined to be usable only in infrastructure network configurations.

Regarding the message frames exchanged in MAC layer, these ones can be grouped into three different types:

- Control frames such as Request to Send (RTS), Clear To Send (CTS) and Acknowledgment (ACK) frames,
- Management frames (authentication, association, etc.),
- Data frames.

All these frames use a general framing structure originating MAC PDU formats consisting of the following basic components, or fields:

- A MAC PDU header comprising frame control, duration, address and sequence control information,
- A variable length frame body containing information specific to the frame type,
- A Frame Check Sequence (FCS) containing an IEEE 32-bit Cyclic Redundancy Code (CRC).

The general MAC PDU format with its set of fields is shown in Figure 9.

<table>
<thead>
<tr>
<th>Frame Control</th>
<th>Duration / ID</th>
<th>Address 1</th>
<th>Address 2</th>
<th>Address 3</th>
<th>Sequence Control</th>
<th>Address 4</th>
<th>Frame Body</th>
<th>FCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octets</td>
<td>2</td>
<td>2</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>6</td>
<td>0-2312</td>
<td>4</td>
</tr>
</tbody>
</table>

ID (station) Identity
FCS Frame Check Sequence

Figure 9. IEEE 802.11: General MAC PDU format.
As mentioned above, the mandatory and basic Media Access Control method in 802.11 is the DCF. This function uses a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique very similar with the CSMA/CD (Collision Detection) technique used in wired networks like Ethernet.

Nevertheless, the CSMA/CD technique is impractical in most WLANs because their transceivers are half-duplex and cannot receive while transmitting. Even if full duplex transceivers were used, the received radio transmission power levels emanated from the Mobile Terminal (MT) itself and from other MTs would be so different that other transmissions would not be detected. Therefore, a collision cannot be detected by a radio transceiver while transmission is in progress, hence the use of the Collision Avoidance technique.

When using the CSMA/CA technique Mobile Terminals have to sense the radio medium to determine if it is idle. If so, the MTs may transmit. However, if it is busy each MT has to wait until other transmissions stop and then it enters into a random backoff procedure. This random backoff prevents multiple MTs from seizing the medium immediately after completion of the preceding transmission.

Together with random backoff procedure there are also some important medium access timings named Interframe Space (IFS) timings and they will be briefly explained in the following paragraphs. Timing relationships for IFSs and random backoff are shown in Figure 10.

*Fast acknowledgment* is one of the salient features of the 802.11 standard. Contrary to others CSMA/CA implementations, generating ordinary acknowledgment delays, in 802.11 the time interval between completion of packet transmission and start of the ACK frame is a very short one. This period is called Short Interframe Space (SIFS) and, in DCF mode of operation, is used for an ACK frame, a CTS frame and a Data frame of a fragmented MAC-SDU. The SIFS is part of other 802.11 Interframe Space (IFS) timings.

For instance, another IFS timing is the one related to the start of new DCF data or management frames (i.e., frames other than ACK, CTS, etc.). Those frames must wait at least for an time interval equal to the DCF Interframe Space (DIFS) before transmitting data. If a transmitter senses a busy medium, it determines the random backoff period by setting an internal timer. When the medium becomes idle MTs wishing to transmit wait for a DIFS plus an integer number of slot times depending on the timer setting (0 to 7 slot times on first
attempt). Upon expiration of a DIFS the timer begins to decrement. If the timer reaches zero, the MT may begin the transmission. However, if another MT seizes the channel before the timer reaches zero, the timer setting is retained at the decremented value for subsequent transmission.

![Diagram of DIFS, SIFS, PIFS, and other source interactions.](image)

| SIFS       | Short Interframe Space |
| DIFS       | DCF Interframe Space   |
| PIFS       | PCF Interframe Space   |

**Figure 10. IEEE 802.11: CSMA/CA backoff algorithm and main Interframe Space (IFS) relationships.**

If a transmission is not acknowledged this may be due to a failure in the reception of the packet, or in the reception of corresponding ACK. Either case is indistinguishable to the sending MT, which has to undertake a retransmission procedure. On a second attempt, the random backoff window is increased to 15 slot times. The window is doubled on each successive attempt up to a maximum value of 256 slot times.

Another IFS timing is related to the PCF mode of operation. That timing is called PCF Interframe Space (PIFS) and is used only by PCF to gain priority access to the radio medium (that is why PIFS is smaller than DIFS). The PCF entity allows the transmission of contention free traffic after it detects the medium free during a period of time equal to the PIFS.
The PCF optional capability works in conjunction with DCF as shown in Figure 11. In fact, when a Point Coordinator is in operation the two access methods alternate, with a contention-free period followed by a contention period.

![Contention Free Period Repetition Interval Diagram]

- **B**: Beacon frame (start of Contention Free Period)
- **Dx**: Frames sent by Point Coordinator
- **Ux**: Frames sent by polled terminals
- **CF end**: Contention Free Period end frame

**Figure 11. IEEE 802.11: PCF/DCF period’s alternation and PCF transfers.**

The Point Coordinator gains priority access to the medium using a PIFS smaller than the DIFS used by the DCF. Once granted, the PCF contention free transfer provision, based on a dynamic polling list, enables a fast medium access for polled terminals, a SIFS being the only separation between consecutive transmissions.

If using these PCF rules and timings even MTs not understanding PCF procedures do not interfere with the contention free period. Their transmit opportunity will be set in the contention period using the general DCF mode of operation.

Going more deeply into DCF, this method relies on the ability of each MT to sense signals from all other MTs within the operation area. This approach is referred to as Physical Carrier Sense. The underlying assumption that every node can hear all other nodes is not always valid. Referring to Figure 12, the node 2 is within range of the node 1, but node 3 is out of range. Node 3 would not be able to detect transmissions from node 1, and the probability of collision is greatly increased. This is known as the “Hidden Node problem”.
Figure 12. IEEE 802.11: Solution for the "Hidden Node problem" by using a RTS/CTS procedure.

In order to combat this problem, a second carrier sense mechanism, the Virtual Carrier Sense, is described in the 802.11 standard. Virtual Carrier Sense is implemented by reserving the medium during a specified period of time for an impending transmission. This is efficiently achieved by the use of "Request to Send" and "Clear to Send" frames.

The RTS frame contains a duration/ID field that specifies a period of time during which the medium is reserved for a subsequent transmission. For nodes detecting the RTS frame, that reservation information is stored in a so-called Network Allocation Vector (NAV), which is present in every terminal. The NAV maintains a prediction of future traffic based on the duration information announced in RTS/CTS frames prior to the actual data exchange.

Referring again to Figure 12, node 1 sends a RTS frame to node 2 that will not be received by node 3. Upon receipt of RTS, node 2 responds with a CTS frame, which also contains the duration/ID field specifying the period of time during which the medium is
reserved. While node 3 did not detect the original RTS message, it will detect the CTS and update its NAV accordingly. Thus, collision is avoided even though some nodes are hidden from other nodes.

The RTS/CTS procedure is invoked according to a user specified parameter. It can be used always, never, or for packets that exceed an arbitrarily defined length.

3.4. 802.11 Physical layer specification

The IEEE 802.11 basic standard provides three variations of the physical (PHY) layer. They are the Direct Sequence Spread Spectrum, the Frequency Hopping Spread Spectrum and the diffuse Infrared options. All 802.11-defined PHY layers support 1 Mbit/s and 2 Mbit/s rates. In practice, only the first two, DSSS and FHSS, have any significant presence in the market, with an increasing predominance of DSSS systems.

The DSSS and FHSS PHY options were designed specifically to conform to FCC 15.247 regulation for operation in the 2.4 GHz ISM band. The FCC has established the operating rules specifically to facilitate shared use of the band for the transmission of data and voice by multiple users in an unlicensed environment. It has therefore stipulated the use of either DSSS or FHSS modulation when radiating in excess of roughly 0 dBm (1 mW).

In order to allow for the 802.11 MAC to operate with the least dependence on the chosen PHY layer method the standard divides the PHY layer into two sublayers, namely the Physical Layer Convergence Procedure (PLCP) and the Physical Medium Dependent (PMD) sublayers. Each sublayer implements one protocol function, as follows:

- A PLCP function that adapts the capabilities of the PMD system to the PHY layer service provided to the MAC. This is done by defining a method of mapping data units into a framing format suitable for sending and receiving information between two or more nodes using the associated PMD system,

- A PMD system whose function defines the characteristics and method of transmitting and receiving data through a wireless medium between two or more nodes.

The main features of FHSS and DSSS, as defined in 802.11, are described subsequently. To start with, aspects related to the FHSS PMD sublayer will be addressed.
3.4.1. 802.11 FHSS specification

In FHSS the carrier frequency hops from channel to channel in a prearranged pseudorandom manner. The receivers are programmed to hop in synchronism with the transmitter. If one channel is jammed, the data is simply retransmitted when the system hops to a clear channel.

Within each channel the data information is modulated using either Binary Frequency Shift Keying (2FSK) at 1 Mbit/s, or Quaternary FSK (4FSK) at 2 Mbit/s. As indicated by FCC, the occupied channel bandwidth of a basic 802.11 FHSS radio is then restricted to 1 MHz.

IEEE 802.11 specifies 79 channels in North America and most of Europe (just 23, 27 and 35 channels respectively in Japan, Spain and France) over which the FHSS radio transceivers hop in a predetermined manner. Besides hops over all available channels there are also different pseudorandom hopping patterns, so several WLANs can be located in close proximity to each other with a fairly low probability of collision on any given channel. Those pseudorandom hopping patterns are divided into three sets resulting in a total number of 78 (3×26), 12 (3×4), 27 (3×9) and 33 (3×11) hopping patterns respectively in North America and (most of) Europe, Japan, Spain and France.

802.11 does not specify a hop rate. That parameter is left up to local regulations. In the United States, FCC regulations stipulate the use of at least 75 hopping frequencies, with an average time of occupancy on any frequency not greater than 0.4 s within a 30 second period. This equates to a minimum hop rate of 2.5 hops/s.

Differently, the time to hop from one channel to another is already specified by 802.11. It states that the operating channel center frequency must settle to within ±60 kHz of the nominal center frequency in a maximum of 224 µs.

The FHSS system must reacquire the 802.11 signal once a hop is completed and the carrier has settled to its nominal frequency. Consequently, to assist the receiver with acquiring the FH signal the radio transmitter will send packets with a specific preamble allowing the receiver to sync up with the transmitter.

An 802.11 FH packet defined by the FHSS PLCP sublayer comprises the preamble, the header and the data fields, as shown in Figure 13. The preamble and the header are always
transmitted at 1 Mbit/s. The data payload part can be transmitted at 1 Mbit/s or 2 Mbit/s, that fact being indicated in the 4-bit header Signal Field.

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Header</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sync Word</td>
<td>Data Length</td>
<td>(whitened) Data</td>
</tr>
<tr>
<td>80 bits</td>
<td>Word</td>
<td>1-4095 bytes</td>
</tr>
<tr>
<td>Start Frame</td>
<td>Signal Field</td>
<td></td>
</tr>
<tr>
<td>Delimiter</td>
<td>12 bits</td>
<td></td>
</tr>
<tr>
<td>16 bits</td>
<td>4 bits</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Header Error</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Check</td>
<td></td>
</tr>
<tr>
<td></td>
<td>16 bits</td>
<td></td>
</tr>
</tbody>
</table>

96 bits   32 bits   variable

**Figure 13. IEEE 802.11: Packet composition for Frequency Hopping Spread Spectrum (FHSS) systems.**

In FHSS the recommended value for maximum data length is 400 octets at 1 Mbit/s and 800 octets at 2 Mbit/s. This corresponds to a frame duration around 3.3 ms, which is a good value to achieve a high performance in a variety of RF channel conditions. These include indoor multipath, channel stability for moving terminals and interference in the 2.4 GHz band.

### 3.4.2. 802.11 DSSS specification

DSSS relies on a completely different approach. In this method the spreading of the information is done directly over the digital stream, instead of executing hops in the carrier frequency. DSSS is the same kind of technology used in CDMA cellular phones, though IEEE 802.11 does not employ Code Division Multiple Access.

To perform that spreading function the information data bits are combined with a high-speed Pseudo-Noise (PN) code sequence using an exclusive OR function. The PN sequence specified in 802.11 is an 11-chip Barker code, that is, the sequence “10110111000”. The term “chip” is used instead of “bit” to denote the fact that the Barker code does not carry any binary information by itself.
In the case of a 1 Mbit/s information rate, the spreading result is an 11 Mchip/s digital stream, which then modulates a carrier frequency using Differential Binary Phase Shift Keying (DBPSK). In the case of a 2 Mbit/s information rate a Differential Quadrature Phase Shift Keying (DQPSK) is used; thus, two 11 Mchip/s digital streams are generated in order to feed the modulator quadrature inputs. Both modulations achieve a 11 Mbaud "symbol rate".

The effect of the Barker sequence is to spread the transmitted bandwidth of the resulting signal by a ratio of 11:1. At the same time, the peak power of the signal is reduced by an identical ratio, but keeping the total power unchanged. Upon reception, the signal is demodulated and the 11 Mchip/s binary stream(s) recovered. Bit decisions are made correlating the binary stream(s) with the same 11-chip Barker code. During this process the original bandwidth and peak power are restored. The correlation process has a significant benefit since it reduces the level of narrow band interference that falls in band by the same 11:1 ratio. This effect is known as processing gain.

The channel bandwidth of 802.11 DSSS radios is about 22 MHz for both DBPSK at 1 Mbit/s and DQPSK at 2 Mbit/s. Although there are 11 channels identified for DSSS systems operating in the 2.4 GHz ISM bands of North America and Europe, there may be a lot of overlap, since these channels are only 5 MHz apart. Whenever possible, it is recommended to use frequency separations of at least 25MHz. Even using this frequency separation the ISM band can accommodate three non-overlapping channels.

The formats of PLCP packets used by 802.11 DSSS and FHSS systems are very similar; however, there are some differences in some fields. The composition of a DSSS packet, with its preamble, header and data fields, is shown in Figure 14.

<table>
<thead>
<tr>
<th>Preamble</th>
<th>Header</th>
<th>Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sync Word 128 bits</td>
<td>Start FrameDelimiter 16 bits</td>
<td>Signal Field 8 bits</td>
</tr>
</tbody>
</table>

144 bits 48 bits variable

Figure 14. IEEE 802.11: Packet composition for Direct Sequence Spread Spectrum (DSSS) systems.
The preamble and the header are always transmitted at 1 Mbit/s, just like FHSS. As for the data payload part, the basic 802.11 specification defines transmissions at 1 Mbit/s or 2 Mbit/s. The actual data rate of the payload part is indicated in the header Signal Field.

As it will be shown in the next section, DSSS systems compliant with IEEE 802.11 “b” version are already capable of data bit rates of 5.5 Mbit/s and 11 Mbit/s. These enhanced bit rates are to be used only in the data payload part.

3.5. 802.11b Physical layer enhancement for the 2.4 GHz band

After the approval of the 802.11 basic standard new studies and evaluations were made targeting a general bit rate increase using the same 2.4 GHz frequency band. The result of that work was the adoption of the Complementary Code Keying (CCK) modulation scheme as the basis for the high rate extension of 802.11 DSSS PHY layer. Also known as IEEE 802.11 “b” version, the new supported data rates are 5.5 Mbit/s and 11 Mbit/s [50].

This higher rate extension was adopted because it easily provides a path for interoperability with the existing 1 and 2 Mbit/s networks by maintaining the same bandwidth and incorporating the same preamble and header (as referred to in the previous sub-section, the DSSS packet header has a “Signal Field” that enables the bit rate shift of the payload part). In fact, the 802.11b extension provides a DSSS-compatible multirate operation at 1, 2, 5.5 and 11 Mbit/s. In Figure 15 a DSSS packet is shown, along with the bit rates allowed for its preamble, header and data parts.

```
<table>
<thead>
<tr>
<th>1 Mbit/s DBPSK (Barker)</th>
<th>1 Mbit/s DBPSK (Barker)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 Mbit/s DQPSK (Barker)</td>
<td>2 Mbit/s DQPSK (Barker)</td>
</tr>
<tr>
<td>5.5 / 11 Mbit/s DQPSK (CCK)</td>
<td>5.5 / 11 Mbit/s DQPSK (CCK)</td>
</tr>
</tbody>
</table>
```

CCK          Complementary Code Keying

Figure 15. IEEE 802.11b: DSSS payload multirate operation.
Differently from the basic standard specification, in the 5.5 and 11 Mbit/s modes the spreading of the information data stream is not accomplished with a constant 11-chip Barker code sequence. Instead, in CCK modulation the spreading code is taken from a small set of nearly orthogonal complex codewords that depend on the information data. Each spreading code symbol is now composed by 8 chips. To obtain the same 11 Mbaud at the air interface the information stream sampling rate was raised to 1.375 Msample/s instead of the previous 1 Msample/s.

In the 11 Mbit/s case the serial to parallel information stream sampling at 1.375 MHz results in 8 bits of information for each sample. These 8 bits are used in the following way:

- Six bits are used to choose one 8-chip symbol from a set of 64 complex (I/Q) vectors, thereby modulating 6-bits on each 8-chip spreading code symbol,
- Two bits are used to perform the QPSK quadrature modulation over the whole code symbol.

The combination of the above two actions results in the modulation of 8 data bits into each 8-chip symbol. The final chipping rate is then 1.375 Msymbol/s × 8 chip/symbol, that is, 11 Mchip/s.

In the 5.5 Mbit/s case the operation is very similar to the 11 Mbit/s one. In this situation the serial to parallel information stream sampling at 1.375 MHz results in 4 bits of information for each sample. These 4 bits are used in the following way:

- Two bits are used to choose one 8-chip symbol from a set of 4 complex (I/Q) vectors, thereby modulating 2-bits on each 8-chip spreading code symbol,
- Two bits are used to perform the QPSK quadrature modulation over the whole code symbol.

The combination of the above two actions results in the modulation of 4 data bits into each 8-chip symbol. The final chipping rate is also 11 Mchip/s (1.375 Msymb/s times 8 chip/symb). The four complex CCK subcodes, used at 5.5 Mbit/s mode, are contained in the larger 64-subcode set that is used at 11 Mbit/s.

Despite the higher bit rates achieved by 802.11b, there is some trade off in terms of range. Figure 16 shows the actual range and rate capability of 802.11 systems at 2.4 GHz.
Figure 16. Range and rate capability of IEEE 802.11 systems at 2.4 GHz.

One output from the arrival of the DSSS 11 Mbit/s mode is that there is now a clearer distinction between the FHSS and DSSS competing technologies and corresponding market segments. Even with the clear advantage in speed going to DSSS, FHSS radios still continue to find applications where cost is more important than performance.

3.6. 802.11a Physical layer enhancement for the 5 GHz bands

Pushed by the spectrum availability at U-NII 5 GHz bands another IEEE 802.11 physical layer enhancement has been developed towards a much higher capacity than the ones at 2.4 GHz. This physical layer enhancement, known as the 802.11 “a” version, provides data payload communication capabilities of 6, 9, 12, 18, 24, 36, 48 and 54 Mbit/s.

The main characteristic of 802.11a systems is the use of an Orthogonal Frequency Division Multiplexing (OFDM) multicarrier modulation technique associated with different sub-modulations and coding rate schemes.
The basic principle of OFDM technique is the division of a total RF channel bandwidth into N frequency subchannels. In this way, a high-rate input data stream can be serial-to-parallel converted into N lower-rate streams, which in their turn simultaneously modulate the N narrowband carriers. Generally, these subcarriers are modulated in phase (PSK), in amplitude (ASK) or both (QAM).

In the 802.11a standard supplement an OFDM system is specified that uses 52 subcarriers, split in 48 subcarriers to be used by data and 4 to be used as pilot signals. The 48 data subcarriers can be modulated using Binary or Quadrature Phase Shift Keying, 16 Quadrature Amplitude Modulation (16QAM) or 64 Quadrature Amplitude Modulation (64QAM).

In addition to the modulation options there is also the Forward Error Correction function in the form of convolutional coding. The possible code rates are 1/2, 2/3 and 3/4. It is the combination of modulation and code rate schemes that determine the actual data bit rate in use.

The IEEE 802.11a physical layer data rate dependent parameters are shown in Table 16. Eight different data rates are available, of which the 6, 12 and 24 Mbit/s are mandatory.

<table>
<thead>
<tr>
<th>Data rate</th>
<th>Modulation</th>
<th>Code rate</th>
<th>Coded bits per subcarrier</th>
<th>Coded bits per OFDM symbol</th>
<th>Data bits per OFDM symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 Mbit/s</td>
<td>BPSK</td>
<td>1/2</td>
<td>1</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>9 Mbit/s</td>
<td>BPSK</td>
<td>3/4</td>
<td>1</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>12 Mbit/s</td>
<td>QPSK</td>
<td>1/2</td>
<td>2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>18 Mbit/s</td>
<td>QPSK</td>
<td>3/4</td>
<td>2</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>24 Mbit/s</td>
<td>16QAM</td>
<td>1/2</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>36 Mbit/s</td>
<td>16QAM</td>
<td>3/4</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>48 Mbit/s</td>
<td>64QAM</td>
<td>2/3</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>54 Mbit/s</td>
<td>64QAM</td>
<td>3/4</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>

In the 802.11a system a constant OFDM symbol rate equal to 250 ksymbol/s is used. This results in a nominal symbol duration of 4 µs. Nevertheless, to avoid intersymbol
interference a temporal Guard Interval is used in the initial part of the symbols. Intersymbol interference is mainly due to multipath propagation effects.

The Guard Interval acts like a buffer for multipath absorption and must be as long as the delay spread of the channel. In 802.11a a 0.8 µs Guard Interval is used thus leaving 3.2 µs for the useful part of the 4 µs symbol. Table 17 shows the main timing related parameters used by 802.11a OFDM systems.

Table 17. IEEE 802.11a: Physical layer timing related parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{sd}$: Number of data subcarriers</td>
<td>48</td>
</tr>
<tr>
<td>$N_{sp}$: Number of pilot subcarriers</td>
<td>4</td>
</tr>
<tr>
<td>$N_{st}$: Number of subcarriers, total</td>
<td>$52 (N_{sd} + N_{sp})$</td>
</tr>
<tr>
<td>$\Delta f$: Subcarrier frequency spacing</td>
<td>0.3125 MHz (=20 MHz/64)</td>
</tr>
<tr>
<td>$T_{FFT}$: IFFT/FFT period</td>
<td>3.2 µs (1/\Delta f)</td>
</tr>
<tr>
<td>$T_{preamble}$: PLCP preamble duration</td>
<td>16 µs ($T_{short} + T_{long}$)</td>
</tr>
<tr>
<td>$T_{signal}$: Signal field duration</td>
<td>4 µs ($T_{gi} + T_{FFT}$)</td>
</tr>
<tr>
<td>$T_{gi}$: Guard Interval duration</td>
<td>0.8 µs ($T_{FFT}/4$)</td>
</tr>
<tr>
<td>$T_{gi}$: Training symbols Guard Interval duration</td>
<td>1.6 µs ($T_{FFT}/2$)</td>
</tr>
<tr>
<td>$T_{sim}$: Symbol duration</td>
<td>4 µs ($T_{gi} + T_{FFT}$)</td>
</tr>
<tr>
<td>$T_{short}$: short training sequence duration</td>
<td>8 µs ($10*T_{FFT}/4$)</td>
</tr>
<tr>
<td>$T_{long}$: long training sequence duration</td>
<td>8 µs ($T_{gi} + 2*T_{FFT}$)</td>
</tr>
</tbody>
</table>

802.11a OFDM systems use 52 subcarriers and occupy a bandwidth around 16.6 MHz. As it will be seen ahead, to accommodate different co-located OFDM systems a proper 20 MHz channel spacing is also defined.

In what the 802.11a Physical Layer Convergence Procedure (PLCP) sublayer is concerned, its main function is to provide a convergence procedure in which Physical Service Data Units (PSDUs) are converted to and from Physical Protocol Data Units (PPDUs).

During transmission the PSDU is provided with a PLCP preamble and header, therefore creating the PPDU. At the receiver, the PLCP preamble and header are processed to help in
demodulation and recovery of the PSDU. In case of successful reception the PSDU is delivered to the MAC layer.

Figure 17 shows the format of the PPDU including the PLCP preamble, the PLCP header, the PSDU, the tail bits and the pad bits.

<table>
<thead>
<tr>
<th>PLCP Header</th>
<th>PSDU</th>
<th>Tail 6 bits</th>
<th>Pad bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>RATE 4 bits</td>
<td>Reserved 1 bit</td>
<td>LENGTH 12 bits</td>
<td>Parity 1 bit</td>
</tr>
<tr>
<td>Coded/OFDM (BPSK, ( r=1/2 ))</td>
<td>Coded/OFDM (RATE is indicated in SIGNAL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PLCP preamble 12 symbols</td>
<td>SIGNAL One OFDM symbol</td>
<td>DATA variable number of OFDM symbols</td>
<td></td>
</tr>
</tbody>
</table>

PLCP

Physical Layer Convergence Procedure

PSDU

Physical Service Data Unit

Figure 17. IEEE 802.11a: Physical PDU (PPDU) frame format.

In general, the PPDU is not all equally coded/modulated by the same physical mode. This results in segments with different bit rates.

For instance, consider the PLCP header containing its fields RATE, LENGTH and SERVICE plus a reserved bit, an even parity bit and six tail bits. In terms of modulation, the fields RATE, LENGTH, reserved bit and parity bit (with 6 "zero" tail bits appended) constitute a separate single OFDM symbol, denoted as SIGNAL, which is transmitted with the more robust combination of BPSK modulation and 1/2 code rate. The tail bits in the SIGNAL symbol enable decoding of the RATE and the LENGTH fields immediately after the reception of the tail bits.

In its turn, the SERVICE field of the PLCP header and the PSDU (with 6 "zero" tail bits and pad bits appended), denoted as DATA, are transmitted at the data rate described in the RATE field (6, 9, 12... 54 Mbit/s) and may constitute multiple OFDM symbols. The RATE and the LENGTH fields are absolutely required for decoding the DATA part of the packet.
Coming back to the general PPDU format, it begins with a PLCP preamble field, which is used for OFDM synchronization. It consists of 10 short symbols and 2 long symbols resulting in a total of 12 symbols. The beginning of a PPDU is shown in Figure 18. It includes the preamble structure and subsequent OFDM symbols with their Guard Intervals. Information relative to several timings and functionalities is also shown.

![Diagram of PLCP preamble structure and OFDM symbols]

**Figure 18. IEEE 802.11a: PLCP preamble structure and OFDM symbols.**

The PLCP preamble acts, in fact, as an OFDM training structure. Referring to same Figure 18 again, t1 to t10 denote short training symbols and T1 and T2 denote long training symbols. Contrary to long OFDM training symbols, short training symbols utilize only 12 out of 52 subcarriers. The total training length is 16 μs.

The PLCP preamble is followed by one OFDM symbol relative to the SIGNAL field and by a LENGTH-dependent number of OFDM symbols relative to the DATA field. The former symbol uses the more robust physical mode of Table 16 (6 Mbit/s BPSK) while the latter ones just use the physical mode indicated by the RATE field of the PLCP header.

As mentioned earlier, the SIGNAL field contains the RATE and LENGTH fields of the important PLCP header. The RATE field has four bits where information is conveyed about the type of modulation and the code rate used in the rest of the packet (see Table 16).
The LENGTH field is an unsigned 12-bit integer that indicates the number of octets (1-4095) in the PSDU that the MAC is currently requesting the PHY layer to transmit. After a transmission start request, that value is used by the PHY layer to determine the number of octet transfers that will occur between the MAC and the PHY.

The RATE and LENGTH fields, together with reserved, parity and tail bits, form the 24-bits SIGNAL field. Its processing is performed with the BPSK modulation of the subcarriers and with rate 1/2 convolutional coding. This results in a single OFDM symbol for the entire SIGNAL field.

The last PLCP header field is the SERVICE field. It has 16 bits denoted as bit 0 to bit 15. The first seven bits (bits 0 to 6), which are transmitted first, are set to zeros and are used to synchronize the descrambler in the receiver. The remaining 9 bits (bits 7 to 15) are reserved for future use.

Note that contrary to the SIGNAL field all bits in the DATA field are scrambled. The scrambler's generator polynomial is \( S(X) = X^7 + X^4 + 1 \).

An overview of the PLCP transmission procedure is depicted in Figure 19. Exchanged primitives with MAC layer and PHY-PMD sublayer, as well as the composition of several packet fields, are indicated there. In order to transmit data, the PHY-TXSTART.request primitive must be enabled so that the PHY entity is in the transmit state. Other transmit parameters such as data rate and PSDU length are also set by that primitive.

The corresponding overview of PLCP reception procedure is shown in Figure 20. In order to receive data, PHY-TXSTART.request must be disabled so that the PHY entity is in the receive state. Receive parameters such as data rate and length indications are passed to the MAC layer using the PHY-RXSTART.indicate primitive.

The OFDM subcarrier modulation mapping depends on the physical mode (bit rate) requested. In fact, the OFDM subcarriers are modulated using BPSK, QPSK, 16QAM or 64QAM modulation, depending on the RATE indication. Accordingly, the encoded binary serial input data is divided into groups of 1, 2, 4 or 6 bits respectively, and converted into complex numbers representing BPSK, QPSK, 16QAM or 64QAM constellation points. The bit group-to-complex number conversion is performed according to the constellation mappings depicted in Figure 21.
Figure 19. IEEE 802.11a: PLCP transmission procedure.

The 802.11a OFDM PHY layer is set to operate in the 5 GHz bands as allocated by the FCC regulatory body. To maximize the use of wireless systems in these bands, channel center frequencies are defined at every integral multiple of 5 MHz above 5 GHz. The relationship between center frequency and channel number ($n_{ch} = 0, 1, \ldots 200$) is given by:

$$\text{Channel center frequency} = 5000 + 5 \times n_{ch} \text{ (MHz)} \quad (1)$$
Figure 20. IEEE 802.11a: PLCP reception procedure.

This assignment provides a unique numbering system to all channels with 5 MHz spacing from 5 GHz to 6 GHz.

In 802.11a OFDM systems the channel spacing is defined as 20 MHz. Hence, a set of valid operating channel numbers to be used with the FCC U-NII bands allocation has been defined. That set is shown in Table 18.
Figure 21. IEEE 802.11a: BPSK, QPSK, 16QAM and 64QAM constellation bit mapping.
Table 18. IEEE 802.11a: Channelization scheme for the 5 GHz U-NII bands.

<table>
<thead>
<tr>
<th>Band</th>
<th>Operating channel numbers</th>
<th>Channel center frequencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-NII lower band</td>
<td>36</td>
<td>5180 MHz</td>
</tr>
<tr>
<td>5.15-5.25 GHz</td>
<td>40</td>
<td>5200 MHz</td>
</tr>
<tr>
<td></td>
<td>44</td>
<td>5220 MHz</td>
</tr>
<tr>
<td></td>
<td>48</td>
<td>5240 MHz</td>
</tr>
<tr>
<td>U-NII middle band</td>
<td>52</td>
<td>5260 MHz</td>
</tr>
<tr>
<td>5.25-5.35 GHz</td>
<td>56</td>
<td>5280 MHz</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>5300 MHz</td>
</tr>
<tr>
<td></td>
<td>64</td>
<td>5320 MHz</td>
</tr>
<tr>
<td>U-NII upper band</td>
<td>149</td>
<td>5745 MHz</td>
</tr>
<tr>
<td>5.725-5.825 GHz</td>
<td>153</td>
<td>5765 MHz</td>
</tr>
<tr>
<td></td>
<td>157</td>
<td>5785 MHz</td>
</tr>
<tr>
<td></td>
<td>161</td>
<td>5805 MHz</td>
</tr>
</tbody>
</table>

3.7. Summary

In this chapter the major aspects of the IEEE 802.11 wireless LAN standard have been presented. The description started with its relationship with the IEEE 802 family of standards and the OSI Basic Reference Model. The IEEE Standard 802.11 structure was also described.

Going into more detail, in the MAC layer specification the MAC PDU format and its two modes of operation, the DCF (Distributed Coordination Function) and the PCF (Point Coordination Function), have been shown. The first and main mode of operation uses a contention based CSMA/CA mechanism with an access backoff algorithm. The second uses a contention free scheme based on dynamic polling lists. The respective Interframe Space (IFS) timings are also mentioned. The 802.11 MAC layer description ends with the Virtual Carrier Sense mechanism and the RTS/CTS procedure.

Regarding the basic 802.11 physical layers, the main features relative to the 1-2 Mbit/s FH and DS spread spectrum systems have been described. The same procedure was taken
concerning the DS 802.11 “b” version, which uses a CCK modulation scheme enabling a maximum rate of 11 Mbit/s. Regarding the 802.11 “a” version, to be used in the 5 GHz bands, the physical PDU frame format has been presented, as well as the main OFDM modulation characteristics.

Table 19 summarizes the main characteristics of the wireless IEEE Standards 802.11, 802.11b and 802.11a.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>802.11</th>
<th>802.11b</th>
<th>802.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>2.4 GHz</td>
<td>2.4 GHz</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Physical data rate</td>
<td>1-2 Mbit/s</td>
<td>1-11 Mbit/s</td>
<td>6-54 Mbit/s</td>
</tr>
<tr>
<td>Layer 3 data rate (maximum)</td>
<td>1.2 Mbit/s</td>
<td>5 Mbit/s</td>
<td>32 Mbit/s</td>
</tr>
<tr>
<td>Medium access control/Media sharing</td>
<td>CSMA/CA</td>
<td>CSMA/CA</td>
<td>CSMA/CA</td>
</tr>
<tr>
<td>Physical layer system</td>
<td>FHSS, DSSS or Infrared</td>
<td>DSSS (CCK)</td>
<td>OFDM</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>22 MHz</td>
<td>22 MHz</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Connectivity</td>
<td>Connection-less</td>
<td>Connection-less</td>
<td>Connection-less</td>
</tr>
<tr>
<td>QoS support</td>
<td>PCF</td>
<td>PCF</td>
<td>PCF</td>
</tr>
<tr>
<td>Fixed network support</td>
<td>Ethernet</td>
<td>Ethernet</td>
<td>Ethernet</td>
</tr>
<tr>
<td>Radio link quality control</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
Chapter 4

The HIPERLAN type 2 wireless LAN standard

4.1. ETSI/BRAN framework

Pursuing the "any service, anywhere, anytime" communications paradigm ETSI created the BRAN project in order to specify broadband radio access network systems. These systems are intended to cover a large variety of applications using licensed and license exempt spectrum.

The categories of systems developed by the BRAN project are as follows:

- High PErformance Radio Local Area Network type 1 (HIPERLAN/1) systems provide high-speed (20 Mbit/s typical data rate) radio LAN communications that are compatible with wired LANs based on Ethernet [47] and Token Ring [49] standards; restricted user mobility is supported within the local service area only.

- HIPERLAN type 2 is a standard for a high-speed radio communication system (data rates from 6 to 54 Mbit/s) enabling the connection of portable devices either with each other or with broadband networks based on IP, ATM or other technologies. It supports multimedia applications by providing mechanisms to handle QoS. Besides the local service area, wide area mobility may be supported by standards outside the scope of the BRAN project (e.g., roaming).
- A HIPERACCESS system will offer outdoor, high-speed (25 Mbit/s typical data rate) fixed radio access to customer premises allowing an operator to provide connections to residential households and small businesses; it will operate in either licensed or license exempted spectrum (its use in a frequency band embracing the 40.5-43.5 GHz is now under study by CEPT/ERC).

- A HIPERLINK system will grant very high-speed (up to 155 Mbit/s data rate) radio links for static interconnections of wireless sub-networks and/or access points enabling the formation of fully wireless networks; the intended frequency for its operation is in the range 17.1-17.3 GHz as allowed in CEPT/ERC Recommendation 70-03 [51].

The first edition of the HIPERLAN/1 standard occurred in 1996 under the responsibility of ETSI Sub-Technical Committee RES10. Concerning HIPERLAN/2 systems, already within the scope of BRAN project, their main specifications were published during the year 2000. HIPERACCESS systems definitions are now ongoing, with the first set of specifications published very recently [40] [41] [42]. The work related to HIPERLINK systems has not started yet.

Notwithstanding the good specification made for HIPERLAN/1 systems, equipment vendors have not invested in the deployment of this product since the predictably superior HIPERLAN/2 specification made them wait for this last one.

4.2. HIPERLAN/2 Overview

HIPERLAN type 2, or HL/2, is one of the new wireless LAN standards developed to support both asynchronous data and time critical services through the use of a dynamic resource reservation strategy.

Aiming at very acceptable Quality of Service levels, and supporting a set of bit rates up to 54 Mbit/s, HIPERLAN/2 provides a flexible platform for a variety of business and home multimedia applications:
- In a typical business application scenario, a mobile terminal gets services over a fixed corporate/public network infrastructure;
- In a typical home application scenario, a low-cost and flexible network is supported to interconnect wireless consumer devices.

The HL/2 radio access network can be used with a variety of core networks due to the flexible architecture approach taken by all ETSI/BRAN systems. The approach consists of standardizing only the radio access network and some of the convergence layer functions relative to the different core networks. The core network's specific functions remain the object of the corresponding fora (e.g., IETF, ATM Forum, IEEE and other ETSI projects).

The architectural reference model used to clearly identify BRAN systems standardization boundaries and involved entities is shown in Figure 22.

![Diagram](image)

**Figure 22.** BRAN systems architectural reference model.

The scope of ETSI HL/2 technical specifications is limited to the air interface, the service functions of the radio access network, the convergence layer functions and some other supporting capabilities required to accomplish the services.
From a protocol layering point of view, the HL/2 functional specifications encompass the Physical layer, the Data Link Control layer and the Convergence Layer (CL). The latter layer performs service specific functions between the DLC layer and corresponding Network layers. In other words, there are convergence sublayers used on top of the HL/2 PHY and DLC that, together with bottom part of CL, provide specific access to networks such as IP, ATM, UMTS or IEEE 1394. In Figure 23 the corresponding layering protocol architecture is shown in a more detailed way.

![Diagram of HIPERLAN/2 protocol layering architecture.](image)

Figure 23. HIPERLAN/2 protocol layering architecture.

This radio access methodology turns HIPERLAN/2 into a true multi-network air interface. Nevertheless, it should be noted that to specify a complete HL/2-based system further specifications, such as network and other higher layers, are required. These specifications are assumed to be available or to be developed by other standardization bodies.

The HIPERLAN/2 radio network topology can be set based on an infrastructure manner or on an ad hoc manner. The infrastructure topology denotes that there exists a radio device
equipment which controls the access to the radio medium and simultaneously bridges HL/2 to the rest of the existing network. That radio/networking device equipment is called an Access Point, or AP.

In ad hoc topologies Access Points do not exist but the access to the radio medium is still centrally controlled. This functionality is done by one of the Mobile Terminals (MTs) in operation in the respective area. That mobile terminal is called the Central Controller (CC).

Normally, infrastructure and ad hoc topologies are associated, respectively, with business and home environments.

A HL/2 network for a business environment consists typically of a number of APs, each of which covers a certain geographic area. Together they form a radio access network with full or partial coverage of an area of almost any size. The coverage areas may or may not overlap each other, thus simplifying roaming of terminals inside the radio access network. Each AP serves a number of MTs which have to be associated to it. In the case where the quality of the radio link degrades to an unacceptable level, the terminal may move to another AP by performing a handover.

In home environments a HIPERLAN/2 network is operated as an ad hoc LAN that can be put in operation in a plug-and-play manner.

The HL/2 home system shares the same basic features with the HL/2 business system by defining the following equivalence between both systems:

- A subnet in the ad hoc LAN configuration is equivalent to a cell in the infrastructure network configuration,

- A Central Controller in the ad hoc LAN configuration is equivalent to the Access Point in the infrastructure network configuration; however, the Central Controller is dynamically selected from HL/2 portable devices, and can be handed over to another portable device if the old one leaves the network,

- Multiple subnets in a home are made possible by having multiple CCs operating at different frequencies.

Independently of the used topology (infrastructure or ad hoc) the HL/2 supports two basic modes of operation, the first being mandatory for all HL/2 devices:
- Centralised mode (CM): in this mode, all traffic pass through the AP/CC, even if the data exchange is between mobile terminals belonging to the same radio cell; the assumption is that a major share of the traffic is exchanged with outside terminals elsewhere in the network.

- Direct mode (DM): the medium access is still managed in a centralized manner but, for terminals within the same radio cell, the user data traffic is directly exchanged between terminals without going through the AP/CC.

With the above kind of architectural definition it is possible to have a common HIPERLAN/2 protocol stack, both for user and control planes, independently of topology and mode of operation actually in use.

Going a little bit further within this subject, Figure 24 shows the protocol stack on the Access Point/Central Controller side and its associated functions. Starting from the bottom level, the physical layer delivers a basic data transport function by providing a baseband modem and a RF part. The baseband modem also contains a forward error correction function.

The DLC layer consists of the Error Control (EC) function, the MAC function and the Radio Link Control (RLC) function. Apart the MAC, which performs tasks related with the time frame structure and respective access, the DLC is divided in the data transport functions, located mainly on the right hand side of the figure, and the control functions on the left hand side.

The user data transport function on the right hand side is fed with user data packets arriving from higher layers via the User Service Access Point (U-SAP). This part contains the EC function, which may perform an ARQ (Automatic Repeat Request) protocol. As the DLC protocol operates in a connection-oriented fashion it usually implies multiple connection end points in the U-SAP. This means that one EC instance has to be created for each DLC connection, its identification being done by a Connection Identifier (CONN_ID).

DLC connections can be created and released dynamically if the higher layer is connection-oriented. In case the higher layer is connectionless at least one DLC connection must be set up in order to handle all user data.

The left part of Figure 24 contains the RLC sublayer, which delivers a transport service to the DLC Connection Control (DCC), the Radio Resource Control (RRC) and the Association Control Function (ACF). For each mobile terminal associated with this AP/CC
(where this protocol stack stands) a corresponding RLC instance is needed. A MAC_Identifer (MAC_ID), unique for each mobile terminal, identifies each of these RLC instances.

The RLC sublayer is specified in a separate HL/2 DLC standard document [52].

![Diagram of HIPERLAN/2 protocol stack and functions](image)

**Figure 24. HIPERLAN/2 protocol stack and functions (user and control planes).**

Within the HL/2 specification domain the Convergence Layer occupies the top of the protocol stack. The CL is also separated in a Data Transport and a Control part. The Data Transport part provides the adaptation of the user data format to the message format of the DLC layer. In fact, apart other convergence adaptations, if the user data format is bigger than the payload capacity of a single HL/2 DLC packet (i.e., the higher layers correspond to core network technologies other than ATM) it uses also a segmentation and reassembly function. The Control part of CL may use the control functions in the DLC, for example, when negotiating CL parameters before actual communications establishment.
This separation of basic DLC and CL services and functions has allowed a simple and modular approach to the global specification of HIPERLAN/2 systems, including the air interface and the radio access service interfaces.

Another important functionalities of HL/2 systems are the Dynamic Frequency Selection (DFS) and the Transmit Power Control (TPC).

Dynamic Frequency Selection is very important since HL/2 systems will have to be able to share the same spectrum with some radar systems, some of which are mobile (e.g., airborne and maritime radars). This type of sharing may originate local interference conditions hence requiring a dynamic adaptation to overcome it. This is achieved by DFS, which is also a needed method to facilitate the uncoordinated sharing among HIPERLAN systems present in the same geographical area. Further on, HL/2 systems are required to spread their emissions over the available frequency channels thus reducing the chance that a concentration of HIPERLAN emissions at a specific frequency channel results in a larger than allowed interference.

Finally, HL/2 systems are required to implement Transmit Power Control in uplink, downlink and direct link so as to minimize their potential interference. The objective of the TPC mechanism is to reduce the average RF output by at least 3 dB relative to the RF output of systems not implementing TPC. The means to implement TPC include the following:

- Adjustment of the uplink RF power to a level low enough to achieve reliable communication between two HIPERLAN devices, that is, between Mobile Terminals and the AP in uplink communications or between two MTs in a direct link communication,

- Adjustment of the downlink RF power to a level low enough to achieve reliable communication between the HIPERLAN Access Point and the most distant terminal device.

The implementation of Dynamic Frequency Selection and Transmit Power Control requires the support of both DLC and PHY layer functions.
4.3. HIPERLAN/2 Physical layer

The physical layer of HIPERLAN/2 is based on the OFDM modulation scheme [53]. In order to improve the radio link capability due to different interference situations and different distances from Mobile Terminals to the Access Point, a multi-rate PHY layer is applied. A suitable rate is selected by a link adaptation scheme, as explained next.

The data rate, which ranges from 6 Mbit/s to 54 Mbit/s, can be varied by using various signal alphabets for modulating the OFDM sub-carriers and by applying different puncturing patterns to a mother convolutional code. BPSK, QPSK and 16QAM are used as mandatory modulation formats, whereas 64QAM is applied as an optional one for both Access Points and Mobile Terminals.

The physical mode dependent parameters for the HL/2 PHY layer are very similar to the ones used in IEEE Std. 802.11a. Table 20 shows the physical dependent parameters for HL/2 as well for IEEE 802.11a. Unless stated all listed modes are specified by both 5 GHz wireless standards.

**Table 20. HIPERLAN/2: Physical mode dependent parameters.**

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding rate</th>
<th>Nominal bit rate (Mbit/s)</th>
<th>Coded bits per sub-carrier</th>
<th>Coded bits per OFDM symbol</th>
<th>Data bits per OFDM symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>6</td>
<td>1</td>
<td>48</td>
<td>24</td>
</tr>
<tr>
<td>BPSK</td>
<td>3/4</td>
<td>9</td>
<td>1</td>
<td>48</td>
<td>36</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>12</td>
<td>2</td>
<td>96</td>
<td>48</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>18</td>
<td>2</td>
<td>96</td>
<td>72</td>
</tr>
<tr>
<td>16QAM (IEEE only)</td>
<td>1/2</td>
<td>24</td>
<td>4</td>
<td>192</td>
<td>96</td>
</tr>
<tr>
<td>16QAM (HL/2 only)</td>
<td>9/16</td>
<td>27</td>
<td>4</td>
<td>192</td>
<td>108</td>
</tr>
<tr>
<td>16QAM</td>
<td>3/4</td>
<td>36</td>
<td>4</td>
<td>192</td>
<td>144</td>
</tr>
<tr>
<td>64QAM (IEEE only)</td>
<td>2/3</td>
<td>48</td>
<td>6</td>
<td>288</td>
<td>192</td>
</tr>
<tr>
<td>64QAM</td>
<td>3/4</td>
<td>54</td>
<td>6</td>
<td>288</td>
<td>216</td>
</tr>
</tbody>
</table>
The main function of the HL/2 PHY layer is the provision of information transfer services to the next upper HL/2 layer, that is, the DLC. For this purpose, it uses several functionalities to adapt the different DLC PDU trains into framing formats called PHY bursts.

There are five different types of PHY bursts:

- Broadcast bursts;
- Downlink bursts;
- Uplink bursts with short preamble;
- Uplink bursts with long preamble;
- Direct link bursts (for Direct Mode operation).

These PHY burst types are strongly related to the DLC PDU train types arriving from the DLC layer. In fact, DLC specifies six different PDU train types:

- Broadcast PDU train;
- FCH (Frame Channel) and ACH (Access Feedback Channel) PDU train;
- Downlink PDU train;
- Uplink PDU train with short preamble;
- Uplink PDU train with long preamble;
- Direct link PDU train (for Direct Mode operation).

The mapping of PDU trains onto PHY bursts depends on the Access Point use of single or multiple sectors, as depicted in Figure 25.

If the number of sectors per AP is one the Broadcast and FCH-ACH PDU trains are concatenated into a unique PDU train, which is then mapped onto a Broadcast PHY burst. If that number exceeds one the Broadcast and FCH-ACH PDU trains are mapped onto Broadcast and Downlink PHY bursts, respectively.

The creation of appropriate PHY bursts are, therefore, necessary for transmitting and receiving management and user information between radio devices. To accomplish this task, several functional entities are implemented in the HL/2 Physical layer, as shown by the block diagram in Figure 26.
Figure 25. HIPERLAN/2: Mapping of DLC PDU trains onto PHY bursts.

Figure 26. HIPERLAN/2: Physical layer block diagram (transmitter side).

The numbers 1 to 7 shown in Figure 26 identify the output results from each different stage of the PHY layer reference configuration, as follows:

1) information bits (PDU train),
2) scrambled bits,
3) encoded bits,
4) interleaved bits,
5) sub-carrier-symbols,
6) complex baseband OFDM symbols,
7) PHY bursts.
Some PHY blocks actions, such as FEC coding and sub-carrier mapping, are directly dependent on the chosen PHY mode. For instance, the possible values of the FEC code rate, 1/2, 9/16 and 3/4, depend on the PHY mode used.

As for the sub-carrier mapping block, the knowledge of which PHY mode is actually selected for data transmission is essential to map the previous block bit stream into OFDM sub-carrier symbols. Therefore, the interleaved binary serial input data (numbered 4 in Figure 26) is first divided into groups of 1, 2, 4 or 6 bits ($b_1, \ldots, b_n$) and then converted into complex numbers representing BPSK, QPSK, 16QAM or 64QAM constellation points. The conversion is performed according to the constellation mappings shown in Figure 27 (for the HL/2 64QAM constellation refer to Figure 21).

![Fig 27](image)

Figure 27. HIPERLAN/2: BPSK, QPSK and 16QAM constellation bit mappings.

The HIPERLAN/2 constellation bit mapping is perfectly identical to the one used by IEEE 802.11a. Table 21 shows the direct relationship between input bit groups and I and Q values for all possible modulations. Obviously, these values are also valid for the 802.11a PHY layer sub-carrier modulations.
Table 21. HIPERLAN/2: Bit-mapping tables for BPSK, QPSK, 16QAM and 64QAM OFDM sub-carriers.

<table>
<thead>
<tr>
<th>BPSK (1-bit group)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input bit $b_1$</td>
<td>I-out</td>
<td>Q-out</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>-1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>QPSK (2-bit group)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input bit $b_1$</td>
<td>I-out</td>
<td>Input bit $b_2$</td>
<td>Q-out</td>
</tr>
<tr>
<td>0</td>
<td>-1</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>16QAM (4-bit group)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input bits $b_1b_2$</td>
<td>I-out</td>
<td>Input bits $b_3b_4$</td>
<td>Q-out</td>
</tr>
<tr>
<td>00</td>
<td>-3</td>
<td>00</td>
<td>-3</td>
</tr>
<tr>
<td>01</td>
<td>-1</td>
<td>01</td>
<td>-1</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>11</td>
<td>1</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>64QAM (6-bit group)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input bits $b_1b_2b_3$</td>
<td>I-out</td>
<td>Input bits $b_4b_5b_6$</td>
<td>Q-out</td>
</tr>
<tr>
<td>000</td>
<td>-7</td>
<td>000</td>
<td>-7</td>
</tr>
<tr>
<td>001</td>
<td>-5</td>
<td>001</td>
<td>-5</td>
</tr>
<tr>
<td>011</td>
<td>-3</td>
<td>011</td>
<td>-3</td>
</tr>
<tr>
<td>010</td>
<td>-1</td>
<td>010</td>
<td>-1</td>
</tr>
<tr>
<td>110</td>
<td>1</td>
<td>110</td>
<td>1</td>
</tr>
<tr>
<td>111</td>
<td>3</td>
<td>111</td>
<td>3</td>
</tr>
<tr>
<td>101</td>
<td>5</td>
<td>101</td>
<td>5</td>
</tr>
<tr>
<td>100</td>
<td>7</td>
<td>100</td>
<td>7</td>
</tr>
</tbody>
</table>
At the output of the sub-carrier mapping block, the stream of complex valued symbols is divided into groups of 48 complex numbers, representing 48 constellation points. As OFDM symbols contain 48 carriers for data transmission, this means one constellation point per sub-carrier. Thus, the information relative to each group of 48 points is transmitted in a single OFDM symbol.

Besides data carriers, OFDM symbols contain also reference synchronization information in pilot carriers. In each symbol there are 4 pilot carriers together with the 48 data carriers. Hence, each OFDM symbol is made of a set of 52 carriers.

The time duration of the OFDM symbol equals the 4 μs value, divided between 0.8 μs for the Guard Interval and 3.2 μs for the useful part. The Guard Interval has two possible durations, one mandatory with a value of 0.8 μs and an optional with a value of 0.4 μs. Other numerical values for the OFDM Physical layer parameters are shown in Table 22.

**Table 22. HIPERLAN/2: OFDM Physical layer parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling rate ($f_s = 1/T$)</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Useful symbol part duration ($T_U$)</td>
<td>3.2 μs (64 × T)</td>
</tr>
<tr>
<td>Guard Interval / Cyclic Prefix duration ($T_{CP}$)</td>
<td>Mandatory: 0.8 μs (16 × T)</td>
</tr>
<tr>
<td>Symbol interval ($T_S = T_U + T_{CP}$)</td>
<td>4.0 μs (80 × T)</td>
</tr>
<tr>
<td>Number of data sub-carriers ($N_{SD}$)</td>
<td>48</td>
</tr>
<tr>
<td>Number of pilot sub-carriers ($N_{SP}$)</td>
<td>4</td>
</tr>
<tr>
<td>Total number of sub-carriers ($N_{ST}$)</td>
<td>52 ($N_{SD} + N_{SP}$)</td>
</tr>
<tr>
<td>Sub-carrier spacing ($Δ_f$)</td>
<td>0.3125 MHz (1/$T_U$)</td>
</tr>
<tr>
<td>Spacing between the two outmost sub-carriers</td>
<td>16.25 MHz ($N_{ST} × Δ_f$)</td>
</tr>
</tbody>
</table>

The complex baseband format of a HL/2 OFDM symbol, containing its 52 ($N_{ST}$) sub-carriers, can be written as:
\[ r_n(t) = \sum_{l=-N_{\text{SY}}/2 \atop l \neq 0}^{N_{\text{SY}}/2} C_{l,n} \cdot \Psi_{l,n}(t) \]

with
\[ \Psi_{l,n}(t) = \begin{cases} e^{j2\pi l \Delta_f (t-T_{CP} - nT_S)}, & nT_S \leq t \leq (n+1)T_S \\
0, & \text{else} \end{cases} \]

where
- \( n \) denotes the OFDM symbol number;
- \( l \) denotes the sub-carrier number (-26 \leq l \leq -1, 1 \leq l \leq 26);
- \( C_{l,n} \) is the (data or pilot) complex symbol for the carrier \( l \) of the \( n \)-th OFDM symbol.

The 52 sub-carriers used are equally spaced and are numbered from -26 to 26, with the sub-carrier falling at DC \((l = 0)\) not being used. Besides the 48 carriers used for data transmission, the four pilot carriers for the transmission of reference signals are defined as occupying the carriers numbered \( -21, -7, 7, 21 \).

The mapping from all data \((D_i)\) and pilot \((P_j)\) complex symbols into sub-carrier frequencies is depicted in Figure 28.

![Diagram of sub-carrier frequency allocation](image)

**Figure 28. HIPERLAN/2: Sub-carrier frequency allocation.**

As explained up to now, data belonging to a DLC PDU train (numbered 1 in Figure 26) results, consequently, in OFDM symbols. These symbols are then concatenated in order to outcome a subsequent data train but in a physical baseband format. This format, also called \textit{PHY payload}, consists of a variable number \((N_S)\) of OFDM symbols, depending on the DLC.
PDU train size and the PHY modes used. The structure of this PHY payload section is presented in Figure 29, corresponding to position number 6 in the block diagram of Figure 26.

![Figure 29. HIPERLAN/2: PHY payload format.](image)

GI - Guard Interval  \( N_s \) - Number of OFDM symbols  \( T_s \) - Symbol interval

Only the inclusion of preamble parts (ahead of PHY payloads) is missing, to arrive at the final PHY stage before the radio transmission block. The inclusion of preambles creates, therefore, the PHY bursts (position number 7 in Figure 26).

Independently of the PHY burst type used (see Figure 25) all bursts are composed of a preamble and an associated PHY payload. In spite of the existence of this common structure, the preamble duration and content is different depending on the PHY burst type. Moreover, the preamble can be composed of short and/or regular OFDM symbols. Figure 30 shows the basic format of a PHY burst with its preamble and payload fields. Table 23 indicates the duration of each preamble section.

![Figure 30. HIPERLAN/2: PHY burst format.](image)
Table 23. HIPERLAN/2: Preamble lengths of PHY burst types.

<table>
<thead>
<tr>
<th>PHY burst type</th>
<th>PREAMBLE lengths</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total (t_preamble)</td>
<td>Short section (t_short)</td>
<td>Regular section (t_regular)</td>
</tr>
<tr>
<td>Broadcast</td>
<td>16 µs</td>
<td>8 µs</td>
<td>8 µs</td>
</tr>
<tr>
<td>Downlink</td>
<td>8 µs</td>
<td>-</td>
<td>8 µs</td>
</tr>
<tr>
<td>Uplink with short preamble</td>
<td>12 µs</td>
<td>4 µs</td>
<td>8 µs</td>
</tr>
<tr>
<td>Uplink with long preamble</td>
<td>16 µs</td>
<td>8 µs</td>
<td>8 µs</td>
</tr>
<tr>
<td>Direct link</td>
<td>16 µs</td>
<td>8 µs</td>
<td>8 µs</td>
</tr>
</tbody>
</table>

As previously referred to, the nominal carrier frequencies for operation of HL/2 devices have to be allocated to two frequency bands at 5 GHz [23]. The lower frequency band occupies the 5150-5350 MHz frequency range, with a power limit of 200 mW EIRP, while the upper one occupies the 5470-5725 MHz frequency range, with a power limit of 1 W EIRP.

Within each of those bands there is an association between a carrier number (n_carrier) and a nominal carrier frequency (f_c):

\[
n_{\text{carrier}} = \frac{f_c - 5000}{5} \quad (f_c \text{ in MHz}) \quad (3)
\]

This equation is perfectly equivalent with the one presented in the IEEE 802.11a section, resulting in the same 5 GHz channel numbering.

The nominal carrier frequencies in HL/2 devices have to be spaced 20 MHz apart. To coordinate the spectrum use, in the European case the allowable nominal carrier frequencies (or respective carrier numbers) are only the ones shown in Table 24.

In HL/2 devices operating in the 5 GHz lower band the carrier numbers / frequencies match completely the 802.11a channelization scheme for the lower and middle U-NII bands (see Table 18).
Table 24. HIPERLAN/2 devices operation: nominal carrier frequencies in European’s 5 GHz bands.

<table>
<thead>
<tr>
<th>n_{carrier}</th>
<th>Band</th>
<th>f_c (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>36</td>
<td>lower</td>
<td>5 180</td>
</tr>
<tr>
<td>40</td>
<td>lower</td>
<td>5 200</td>
</tr>
<tr>
<td>44</td>
<td>lower</td>
<td>5 220</td>
</tr>
<tr>
<td>48</td>
<td>lower</td>
<td>5 240</td>
</tr>
<tr>
<td>52</td>
<td>lower</td>
<td>5 260</td>
</tr>
<tr>
<td>56</td>
<td>lower</td>
<td>5 280</td>
</tr>
<tr>
<td>60</td>
<td>lower</td>
<td>5 300</td>
</tr>
<tr>
<td>64</td>
<td>lower</td>
<td>5 320</td>
</tr>
<tr>
<td>100</td>
<td>upper</td>
<td>5 500</td>
</tr>
<tr>
<td>104</td>
<td>upper</td>
<td>5 520</td>
</tr>
<tr>
<td>108</td>
<td>upper</td>
<td>5 540</td>
</tr>
<tr>
<td>112</td>
<td>upper</td>
<td>5 560</td>
</tr>
<tr>
<td>116</td>
<td>upper</td>
<td>5 580</td>
</tr>
<tr>
<td>120</td>
<td>upper</td>
<td>5 600</td>
</tr>
<tr>
<td>124</td>
<td>upper</td>
<td>5 620</td>
</tr>
<tr>
<td>128</td>
<td>upper</td>
<td>5 640</td>
</tr>
<tr>
<td>132</td>
<td>upper</td>
<td>5 660</td>
</tr>
<tr>
<td>136</td>
<td>upper</td>
<td>5 680</td>
</tr>
<tr>
<td>140</td>
<td>upper</td>
<td>5 700</td>
</tr>
</tbody>
</table>

4.4. Basic functions of the HIPERLAN/2 DLC layer

As previously referred to, two main specifications address the DLC layer. The first one [8] includes the basic data transport functions consisting of Error Control (EC) and Medium Access Control (MAC) protocols. The second specification [52] defines the Radio Link Control (RLC) sublayer that is used for exchanging data in the control plane between an Access Point and a Mobile Terminal.
In this section the basic DLC functions for the purpose of transporting data and control information between HIPERLAN/2 devices are described, with an emphasis in MAC-related functions (EC functions are described in next section). Figure 31 shows the position of DLC Basic Data Transport function within the HIPERLAN/2 protocol stack.

![Diagram: DLC Basic Data Transport function in HIPERLAN/2 protocol stack.]

Figure 31. DLC Basic Data Transport function in HIPERLAN/2 protocol stack.

The MAC protocol is based on a dynamic Time Division Multiple Access / Time Division Duplex (TDMA/TDD) scheme with centralized control. This centralized control is implemented either in an Access Point (AP) or in a Central Controller (CC). These entities are thus responsible for the creation of periodic MAC frames, at the air interface. Frames period is 2 ms.

Due to its DLC connection-oriented strategy, the HL/2 MAC frame is almost all occupied by connections that have previously requested resources. These requests are directed to the AP or CC (AP/CC), which control the allocation of resources.
To perform the resources allocation task the AP/CC need to know the state of their own buffers and of the buffers in the different MTs. Therefore, the MTs report their buffer states in Resource Request (RR) messages to the AP/CC. The AP/CC allocates the resources according to the buffer states on a fair basis and, if required, taking quality of service parameters into account. The allocation of resources is conveyed by Resource Grant (RG) messages.

RR and RG messages are just two examples of the DLC messages extensive set. All those messages have to be transported in an appropriate manner. To accomplish this task, all data and control information are mapped, firstly, onto the so-called logical channels, which in turn are mapped onto the transport channels.

Both logical and transport channels are defined in order to improve transparency and to define exact terms for the structures that are used to make up MAC frames. Therefore, a certain number of logical and transport channels, including their message contents, meaning, numbers of bits and generation rules, are defined in the HL/2 specification.

Logical channels are used to deal with message contents and respective meaning. On its own side, transport channels reflect message lengths, rules to assemble a MAC frame and the respective access methods.

In HIPERLAN/2 a set of logical channel types is defined for different kinds of data transfer services:

- Broadcast Control CHannel (BCCH),
- Frame Control CHannel (FCCH),
- Random access Feedback CHannel (RFCH),
- RLC Broadcast CHannel (RBCH),
- Dedicated Control CHannel (DCCH),
- User Broadcast CHannel (UBCH),
- User Multicast CHannel (UMCH),
- User Data CHannel (UDCH),
- Link Control CHannel (LCCH), and,
- A$S$ociation Control CHannel (ASCH).

Logical channels are always referred to with four letters abbreviation.
Each logical channel type is mainly defined by the type of information it carries. Therefore, the interpretation of message values is done accordingly.

Table 25 shows some of the DLC HL/2 logical channels characteristics.

<table>
<thead>
<tr>
<th>Logical channel</th>
<th>Direction</th>
<th>Support</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCCH</td>
<td>Downlink</td>
<td>Mandatory for APs/CCs (MTs have to interpret the BCCH)</td>
<td>Broadcast control channel information concerning the whole radio cell.</td>
</tr>
<tr>
<td>FCCH</td>
<td>Downlink</td>
<td>Mandatory for APs/CCs (MTs have to interpret the FCCH)</td>
<td>Information describing the structure of the MAC frame at the air interface.</td>
</tr>
<tr>
<td>RFCH</td>
<td>Downlink</td>
<td>Mandatory for APs/CCs (MTs have to interpret the RFCH)</td>
<td>Information about the results of terminals random access attempts.</td>
</tr>
<tr>
<td>RBCH</td>
<td>Downlink and Direct Link (*)</td>
<td>Mandatory for APs/CCs and MTs</td>
<td>Broadcast RLC control information concerning the whole radio cell.</td>
</tr>
<tr>
<td>DCCH</td>
<td>Downlink, Uplink and Direct Link (*)</td>
<td>Mandatory for APs/CCs and MTs</td>
<td>Conveying of RLC messages (implicitly established during terminal association).</td>
</tr>
<tr>
<td>UBCCH</td>
<td>Downlink and Direct Link (*)</td>
<td>Mandatory for APs/CCs and MTs</td>
<td>Transmission of user broadcast data.</td>
</tr>
<tr>
<td>UMCH</td>
<td>Downlink and Direct Link (*)</td>
<td>Mandatory for APs/CCs (MTs have to interpret the UMCH)</td>
<td>Transmission of user multicast data.</td>
</tr>
<tr>
<td>UDCH</td>
<td>Downlink, Uplink and Direct Link (*)</td>
<td>Mandatory for APs/CCs and MTs</td>
<td>Transmission of user data.</td>
</tr>
<tr>
<td>LCCH</td>
<td>Downlink, Uplink and Direct Link (*)</td>
<td>Mandatory for APs/CCs and MTs</td>
<td>Transmission of ARQ Feedback, Discarding and RRs (uplink) messages.</td>
</tr>
<tr>
<td>ASCH</td>
<td>Uplink</td>
<td>Mandatory for APs/CCs and MTs</td>
<td>Conveying of new association request and handover request messages.</td>
</tr>
</tbody>
</table>

(*) Channel enabled in Direct Link direction only if Direct Mode features are supported.
The transport channels are the basic elements to make up the PDU trains. These trains are then delivered to and received from the HL/2 PHY layer. In fact, the transport channels describe the basic message formats to be used in HL/2 devices.

The defined HL/2 transport channels, designated with three letters abbreviation, are the following:

- Broadcast CHannel (BCH),
- Frame CHannel (FCH),
- Access feedback CHannel (ACH),
- Long transport CHannel (LCH),
- Short transport CHannel (SCH), and,
- Random CHannel (RCH).

Transport channels carry a fixed amount of data, except the FCH that can carry a variable amount. The length, direction and used PHY modes are the main characteristics of transport channels, but message contents and their interpretation, however, are dependent on the used logical channels. Table 26 shows an overview of DLC HL/2 transport channels characteristics.

<table>
<thead>
<tr>
<th>Transport channel</th>
<th>Direction</th>
<th>PHY mode</th>
<th>Length (octets)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCH</td>
<td>Downlink</td>
<td>Binary PSK and code rate 1/2</td>
<td>15</td>
<td>Sent in every MAC frame for each sector.</td>
</tr>
<tr>
<td>FCH</td>
<td>Downlink</td>
<td>Binary PSK and code rate 1/2</td>
<td>Multiple of 27</td>
<td>Sent in every MAC frame for each sector that contains scheduled data.</td>
</tr>
<tr>
<td>SCH</td>
<td>DL/UL/DiL</td>
<td>Set in FCCH</td>
<td>9</td>
<td>PHY mode is set and adapted per connection.</td>
</tr>
<tr>
<td>LCH</td>
<td>DL/UL/DiL</td>
<td>Set in FCCH</td>
<td>54</td>
<td>PHY mode is set and adapted per connection.</td>
</tr>
<tr>
<td>ACH</td>
<td>Downlink</td>
<td>Binary PSK and code rate 1/2</td>
<td>9</td>
<td>Sent in every MAC frame for each sector.</td>
</tr>
<tr>
<td>RCH</td>
<td>Uplink</td>
<td>Binary PSK and code rate 1/2</td>
<td>9</td>
<td>Contention based access.</td>
</tr>
</tbody>
</table>

DL - Downlink  UL - Uplink  DiL - Direct Link
SCH and LCH transport channels can use different PHY modes, hence, spending a variable number of OFDM symbols. Table 27 shows the number of OFDM symbols per transport channel and the allowed PHY modes.

Table 27. HIPERLAN/2: Number of OFDM symbols per transport channel (excluding physical layer preambles).

<table>
<thead>
<tr>
<th>PHY mode</th>
<th>BCH (15 oct.)</th>
<th>FCH (*) (n x 27 oct.)</th>
<th>ACH (9 oct.)</th>
<th>SCH (9 oct.)</th>
<th>LCH (54 oct.)</th>
<th>RCH (9 oct.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK, code rate=1/2</td>
<td>5</td>
<td>n x 9</td>
<td>3</td>
<td>3</td>
<td>18</td>
<td>3</td>
</tr>
<tr>
<td>BPSK, code rate=3/4</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>12</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QPSK, code rate=1/2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>QPSK, code rate=3/4</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16QAM, code rate=9/16</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>16QAM, code rate=3/4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>64QAM, code rate=3/4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

(*) n - number of information blocks in the FCH.

The mapping of logical channels to transport channels allows only some combinations depending on the involved transmission direction as illustrated in Figure 32, Figure 33 and Figure 34, for the downlink, uplink and direct link directions, respectively.

**Logical channel**

```
BC CH | FC CH | RF CH | LC CH | RB CH | DC CH | UD CH | UB CH | UM CH
```

**Transport channel**

```
BC H | FCH  | ACH  | SCH  | LCH  |
```

*Figure 32. HL/2 DLC mapping between logical channels and transport channels in the downlink direction.*
In the downlink direction the BCCH, FCCH and RFCH logical channels have the particularity of being directly and exclusively mapped to corresponding BCH, FCH and ACH transport channels.

After the presentation of logical and transport channels it is essential to know the adopted HL/2 basic MAC frame structure. This one is depicted in Figure 35.

Each MAC frame consists of BCH, FCH, ACH and RCHs transport channels. If user data is to be transmitted, a DL phase and/or an UL phase carrying SCH and LCH transport channels is defined. If direct mode is supported and there is data to be transmitted in this
mode, the MAC frame also contains a DiL phase, between the DL and UL phase, carrying also SCH and LCH transport channels.

![MAC frame diagram]

**Figure 35. HIPERLAN/2: MAC frame structure (Direct link phase optional).**

The order of the transport channels, from a MT's point of view, is as follows:


The DiL phase can only exist if both AP/CC and MTs support it.

All possible combinations of the DLC MAC frame are shown in Figure 36.

![Possible combinations diagram]

**Figure 36. HIPERLAN/2: Possible combinations of the DLC MAC frame.**
From a user data transport perspective the most important transport channels are the LCH and the SCH. The first one (LCH, 54 octets) may be used to convey the UDCH, UBCH and UMCH logical channels, which in their turn carry the respective user data. The second one (SCH, 9 octets) may be used to convey the LCCH logical channel, which carries sensitive ARQ Feedback and Discarding messages related to the ongoing user data transfer.

The LCH transport channel consists of 432 bits (54 octets) divided among a LCH PDU type field (2 bits), a payload field (406 bits) and a 24-bit Cyclic Redundancy Check (CRC) field. Its transfer syntax is depicted in Figure 37.

```
<table>
<thead>
<tr>
<th>Octet 1</th>
<th>LCH PDU type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Octet 2</td>
<td></td>
</tr>
<tr>
<td>Octet 3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Payload (406 bits)</td>
</tr>
<tr>
<td>Octet 51</td>
<td></td>
</tr>
<tr>
<td>Octet 52</td>
<td></td>
</tr>
<tr>
<td>Octet 53</td>
<td>CRC-24</td>
</tr>
<tr>
<td>Octet 54</td>
<td></td>
</tr>
</tbody>
</table>
```

**Figure 37. HIPERLAN/2: Transfer syntax for the LCH transport channel.**

The possible LCH contents are the UDCH, UBCH, UMCH, DCCH and RBCH logical channels. An empty LCH transport channel is also possible (it is called dummy LCH). The actual LCH use is indicated by the LCH PDU type field, coded as shown in Table 28. The definition of which logical channel is to be transferred to is set by Resource Grant messages carried on the FCCH logical channel.

As for the SCH transport channel, this consists of 72 bits (9 octets) with a SCH PDU type field (4 bits), an information field (52 bits) and a 16-bit CRC field. Its transfer syntax is illustrated in Figure 38.
Table 28. HIPERLAN/2: LCH PDU type field coding.

<table>
<thead>
<tr>
<th>LCH PDU type</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>To carry UDCH, UBCH, UMCH, DCCH or RBCH logical channels</td>
</tr>
<tr>
<td>01</td>
<td>Dummy LCH</td>
</tr>
<tr>
<td>10</td>
<td>Future use</td>
</tr>
<tr>
<td>11</td>
<td>Future use</td>
</tr>
</tbody>
</table>

![Figure 38. HIPERLAN/2: Transfer syntax for the SCH transport channel.](image)

The SCH transport channel carries the LCCH, DCCH and RBCH logical channels, which themselves contain messages for various functions. The SCH PDU type field distinguishes these message types. Table 29 shows the message identifiers allocation used in this field.

As mentioned earlier, the most relevant logical channels for the user data transfer function are the UDCH and the LCCH. Some of their characteristics are presented hereafter.

The UDCH logical channel is employed to transmit user data between the AP/CC and a MT in centralized mode, or between two terminals in direct mode. In Figure 39 the UDCH transfer syntax is depicted. It consists of the same fields as the LCH transport channel plus a
10-bit Sequence Number (SN) field provided by the Error Control (EC) function. This way the available payload size for upper layer data is now 396 bits instead of 406 as before.

Table 29. HIPERLAN/2: SCH PDU type field coding.

<table>
<thead>
<tr>
<th>SCH PDU Type</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>0000</td>
<td>Reserved</td>
</tr>
<tr>
<td>0001</td>
<td>ARQ Feedback</td>
</tr>
<tr>
<td>0010</td>
<td>Discarding</td>
</tr>
<tr>
<td>0011</td>
<td>RR for uplink</td>
</tr>
<tr>
<td>0100</td>
<td>RLC to/from the AP/CC</td>
</tr>
<tr>
<td>0101</td>
<td>RR for direct link</td>
</tr>
<tr>
<td>0110</td>
<td>Not allowed (used for ACH)</td>
</tr>
<tr>
<td>0111</td>
<td>RLC in DM (RBCH, DCCH)</td>
</tr>
<tr>
<td>1000</td>
<td>Encryption Seed (only in downlink RBCH)</td>
</tr>
<tr>
<td>1001</td>
<td>Dummy SCH</td>
</tr>
<tr>
<td>1010-1111</td>
<td>Reserved</td>
</tr>
</tbody>
</table>

Figure 39. HIPERLAN/2: Transfer syntax for the UDCH logical channel.
As UDCHs are subject to EC mechanisms, a logical channel is needed to carry the EC messages. This requirement is fulfilled with the use of a LCCH channel.

In fact, for a particular UDCH in centralized mode, whichever in downlink or uplink phases, a LCCH is employed to transmit ARQ Feedback and Discarding messages between respective EC entities in the AP and MT. In direct mode, the same type of messages is exchanged during the DiL phase but just between the two EC entities of the respective MTs. The contents of some important EC messages using a LCCH logical channel are described in the next section.

Besides the ARQ Feedback and Discarding messages, the LCCH is also used in the uplink direction for the transmission of Resource Requests messages.

4.5. HIPERLAN/2 DLC error control modes

To enable some protection to the data carried in LCH transport channels, ETSI/BRAN Project has defined a basic set of error control modes to be implemented in the DLC layer of HL/2.

This basic set of error control modes, to be supported by the AP/CC and the MTs, is formed by the following three modes:

- Acknowledged mode,
- Repetition mode,
- Unacknowledged mode.

The major difference among them is concerned with the reliability offered by each other.

The Acknowledged mode provides reliable transfers using retransmissions to improve the global link quality. These retransmissions are based on acknowledgement messages sent by the receiver. The Repetition mode provides (almost) reliable transfers by repeating the message transmission for a predetermined number of times. The Unacknowledged mode provides low latency unreliable transfers, executing a single transmission per message.
The application of those modes is also strongly related to the connection type involved. Depending on the unicast, multicast or broadcast connection type, the feasibility of an acknowledge action may be possible or not.

In fact, in a broadcast connection it would be completely impossible to give an answer to all feedback acknowledgement messages. In a multicast connection, if not completely impossible, the processing of feedback acknowledgements would have an increasing complexity, depending on the multicast group size.

In HIPERLAN/2, all logical channels, mapped into a 54-octect LCH transport channel, use one of the error control modes above defined. Those logical channels are the following:

- UDCH (user data),
- UBCH (user broadcast),
- UMCH (user multicast),
- RBCH (RLC broadcast),
- DCCH (dedicated control).

UDCHs can be sent either in acknowledged or in unacknowledged mode. In the case of the acknowledged mode an implicit bi-directional LCCH is set up.

In relation to the UBCHs, these can be sent either in repetition or in unacknowledged mode. In the case of the repetition mode, an implicit unidirectional LCCH is set up.

For the UMCHs, DCCHs (on LCH) and RBCHs (on LCH) the unacknowledged mode is used.

Table 30. HIPERLAN/2: Logical channels (using the LCH transport channel) versus error control modes.

<table>
<thead>
<tr>
<th>Logical channel (using LCH)</th>
<th>Error Control Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acknowledged</td>
</tr>
<tr>
<td>UDCH</td>
<td>Yes</td>
</tr>
<tr>
<td>UBCH</td>
<td>-</td>
</tr>
<tr>
<td>UMCH</td>
<td>-</td>
</tr>
<tr>
<td>RBCH</td>
<td>-</td>
</tr>
<tr>
<td>DCCH</td>
<td>-</td>
</tr>
</tbody>
</table>
The possible combinations between logical channels and error control modes are shown in Table 30.

Each HL/2 error control setup between transmitter and receiver parts corresponds to different data and control flows, as shown in Figure 40, Figure 41 and Figure 42.

Figure 40 depicts the situation of the only logical channel using the acknowledged mode, the UDCH. In this case a corresponding LCCH is available to be used, from the receiver to the transmitter, for ARQ Feedback messages and, from the transmitter to the receiver, for eventual Discarding messages.

![Figure 40. HL/2 error control: Data and control flows in acknowledged mode.](image)

Figure 41 shows the situation of the only logical channel using the repetition mode, the UBCH. In this case an implicit unidirectional LCCH is available, from the transmitter to the receiver, in order to provide a path to eventual Discarding messages.

![Figure 41. HL/2 error control: Data and control flows in repetition mode.](image)
Figure 42 illustrates the situation for logical channels using the unacknowledged mode. In this case, the data flows from the transmitter to the receiver with no associated control data path, hence, not allowing ARQ Feedback or Discarding messages.

![Diagram showing unacknowledged mode](image)

**Figure 42. HL/2 error control: Data and (no) control flows in unacknowledged mode.**

For unicast user data connections (UDCHs) the acknowledged mode is the main EC mode and is based on ARQ mechanisms in order to provide more reliable transmissions.

To assist in the implementation of the corresponding EC functions it is necessary to reserve some fields of the user packet. As shown in the previous section, when UDCHs transfer syntax was described (see Figure 39), the user packet possesses the SN and the CRC fields. This packet can be interpreted as a DLC User Protocol Data Unit (U-PDU) and is recalled in Figure 43.

<table>
<thead>
<tr>
<th>P-type</th>
<th>SN</th>
<th>DLC-SDU</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>396</td>
<td>24</td>
</tr>
</tbody>
</table>

**Figure 43. HIPERLAN/2 DLC User-PDU format.**
The 10-bit SN field and the CRC-24 field are dedicated to error control functions. The SN field allows the identification and the alignment of correctly received U-PDUs and is going to be used later on in positive acknowledgment messages. The CRC-24 field is used for error detection covering the whole PDU.

Sequence numbers are incremented by 1 for each U-PDU and computed modulo $2^{10}$. This limited range of distinct SNs (1024) can originate a possible malfunction, due to SN interpretation ambiguities, if no limit is applied to new packet transmissions before older packets are correctly received (or discarded).

To avoid this problem, a SN window mechanism is applied both in the transmitter and in the receiver. The window size is negotiated at connection set up, as described in the Radio Link Control specification [52]. The possible window sizes are 32, 64, 128, 256 and 512 sequence numbers. The latest value is half the size of the sequence number space.

The receiver SN window is the interval of sequence numbers that are eligible for reception. The bottom of the receiver window is the lowest sequence number not yet received correctly by the receiver.

The transmitter SN window is the interval of sequence numbers that are eligible for transmission. The bottom of the transmitter window is the lowest sequence number that has not yet been positively acknowledged by the receiver.

In the receiver-transmitter direction, the information relative to sequence number’s acknowledgments is transmitted by way of ARQ Feedback messages. That information is condensed through a technique known as Bitmap Blocks. Accordingly, the ARQ Feedback messages convey, besides others, two important sets of information:

- The addresses of Bitmap Blocks through the use of Bitmap Block Numbers (BMNs);
- The acknowledgments themselves using the Bitmap Blocks (BMBs).

Bitmap Block Numbers locate the Bitmap Blocks within the sequence number space. As each BMB contains eight bits, the sequence number space (with a total of 1024 SNs) is partitioned into 128 blocks of 8 consecutive SNs. BMNs range, then, from block 0 to block 127.
In relation to sequence number's acknowledgments, a bit set to 1 in a Bitmap Block positively acknowledges the packet with respective SN. A bit set to 0 signals a corresponding negative acknowledgement.

The ARQ Feedback message contains three BMBs. For the addressing of the first (BMB1) a 7-bit long absolute address (BMN1) is used; for the other two blocks (BMB2 and BMB3) a 5-bit long relative addressing scheme (BMN2 and BMN3) is used.

Figure 44 illustrates an example of the BMNs and BMBs handling and their interpretation into SNs and respective acknowledgments.

Figure 44. HL/2 error control: Bitmap Blocks handling example.

Besides the above acknowledgement scheme, the receiver may positively acknowledge all PDUs with sequence numbers up to a certain value, by setting a certain bit in the ARQ Feedback message. This bit is called "Cumulative Acknowledgement Indicator" (CAI) and is shown in Table 31 along with the other content of the ARQ Feedback message for uplink, downlink and direct link phases.
Table 31. HIPERLAN/2: Contents of the ARQ Feedback message for uplink, downlink and direct link phases.

<table>
<thead>
<tr>
<th>Name</th>
<th>Bits</th>
<th>Contents</th>
</tr>
</thead>
<tbody>
<tr>
<td>SCH PDU Type</td>
<td>4</td>
<td>0001</td>
</tr>
<tr>
<td>LCH PHY mode</td>
<td>4</td>
<td>Proposed PHY mode for related DLCC downlink LCHs (Uplink only).</td>
</tr>
<tr>
<td>(Uplink only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SCH PHY mode</td>
<td>3</td>
<td>Proposed PHY mode for related DLCC downlink SCHs (Uplink only).</td>
</tr>
<tr>
<td>(Uplink only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC</td>
<td>1</td>
<td>When set to 1, it indicates that flow control is active.</td>
</tr>
<tr>
<td>ABIR</td>
<td>1</td>
<td>When set to 1, it indicates that more SCH bandwidth is needed for the signaling of ARQ Feedback (Uplink only).</td>
</tr>
<tr>
<td>(Uplink only)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAI</td>
<td>1</td>
<td>When set to 1, it indicates that BMB1 contains a Cumulative Ack.</td>
</tr>
<tr>
<td>Future use</td>
<td>1</td>
<td>Future use.</td>
</tr>
<tr>
<td>BMN1</td>
<td>7</td>
<td>Block Number of the Bit Map Block 1. Absolute block number.</td>
</tr>
<tr>
<td>BMB1</td>
<td>8</td>
<td>Bit Map Block 1.</td>
</tr>
<tr>
<td>BMN2</td>
<td>5</td>
<td>Block Number of the Bit Map Block 2. Relative to BMN1.</td>
</tr>
<tr>
<td>BMB2</td>
<td>8</td>
<td>Bit Map Block 2.</td>
</tr>
<tr>
<td>BMN3</td>
<td>5</td>
<td>Block Number of the Bit Map Block 3. Relative to BMN2.</td>
</tr>
<tr>
<td>BMB3</td>
<td>8</td>
<td>Bit Map Block 3.</td>
</tr>
<tr>
<td>CRC</td>
<td>16</td>
<td>CRC-16</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>72</strong></td>
<td></td>
</tr>
</tbody>
</table>

FC – Flow Control  
DLCC – DLC Connection  
ABIR – ARQ Bandwidth Increase Request  
CAI – Cumulative Acknowledgement Indicator

When using CAI bit it is possible for the transmitter to set its window bottom to the lowest negatively acknowledged PDU within BMB1. All PDUs below that value are regarded as positively acknowledged by the receiver.

At the receiver side, the sequence number indicated as being a “Cumulative Acknowledgement” is simultaneously the bottom of the receiver window.

In order to deal with time-expired packets, belonging to delay-constrained applications, another important function of the acknowledged mode is the provision of a packet discard mechanism [54, 55].
The discard procedure is initiated with the transmission of a Discarding message, by the transmitter, informing the receiver that it wants to discard some PDUs that it has in its transmission buffer. This way, the receiver can proceed with the delivery of pending SDUs to the upper layer (taking eventual error minimization actions), hence, ensuring a relatively low latency transmission.

4.6. Summary

In this chapter the major aspects of the ETSI/BRAN HIPERLAN type 2 wireless LAN standard were presented.

In the overview section, the BRAN systems reference model, the HL/2 protocol layering architecture and the user/control planes main functions were introduced. After that, the physical layer was described, including the several available PHY modes, the OFDM and sub-carriers modulation, the PHY burst formats and the respective preamble lengths.

As for the HIPERLAN/2 DLC layer, the basic data transport function was analyzed with its error control and MAC blocks. As for the data transfer service, the use of logical and transport channels was explained. The mapping between logical and transport channels and the description of some of them (UDCH, LCCH, LCH and SCH) were also exposed. The MAC frame structure with its distinct downlink, uplink and direct link phases was not forgotten as well.

With reference to the HL/2 DLC error control modes, the three defined modes were presented, namely the “acknowledged”, the “repetition” and the “unacknowledged” ones. The SN window mechanism and the ARQ Feedback Bitmap Blocks handling were also described.

Just to conclude the presentation of the two most important wireless LAN standards: it is perhaps interesting to compare now their characteristics. In Table 32 the main characteristics of HIPERLAN/2 and IEEE 802.11a wireless systems are compared indeed.

Despite few differences in some PHY modes (e.g., 24 Mbit/s in 802.11a, 27 Mbit/s in HL/2) and in the length signaling mechanism (SIGNAL field in 802.11a, conveyed by MAC in HL/2), the cooperative work between IEEE 802.11a and HIPERLAN/2 Working Groups results in a strong alignment between the respective PHY layers. They have succeeded in
specifying a unique radio platform at 5 GHz, thus sustaining a potential development of cost-efficient multi-mode terminals for wireless high-speed communications.

Table 32. Main characteristics of HIPERLAN/2 and IEEE 802.11a systems.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>HIPERLAN/2</th>
<th>IEEE 802.11a</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>5 GHz</td>
<td>5 GHz</td>
</tr>
<tr>
<td>Physical data rate (maximum)</td>
<td>6, 9, 12, 18, 27, 36, 54 Mbit/s</td>
<td>6, 9, 12, 18, 24, 36, 48, 54 Mbit/s</td>
</tr>
<tr>
<td>Medium Access Control / Media sharing</td>
<td>Central resource control TDMA/TDD</td>
<td>CSMA/CA</td>
</tr>
<tr>
<td>Physical layer system</td>
<td>OFDM</td>
<td>OFDM</td>
</tr>
<tr>
<td>Channel bandwidth</td>
<td>20 MHz</td>
<td>20 MHz</td>
</tr>
<tr>
<td>Connectivity</td>
<td>Connection-oriented</td>
<td>Connection-less</td>
</tr>
<tr>
<td>QoS support</td>
<td>Dynamic resource requests (ATM / 802.1p / RSVP)</td>
<td>PCF</td>
</tr>
<tr>
<td>Fixed network support</td>
<td>Ethernet, IP, ATM, UMTS, IEEE 1394</td>
<td>Ethernet</td>
</tr>
<tr>
<td>Radio link quality control</td>
<td>Link adaptation</td>
<td>No</td>
</tr>
</tbody>
</table>

An interesting discussion about the pros and cons of IEEE 802.11 and HIPERLAN/2 is presented in [56]. Nevertheless, when comparing the current standard versions, it is undeniable that the HL/2 centralized scheduling and fixed packet sizes strategy seems to give higher system throughput than the 802.11 CSMA/CA, DCF/PCF and variable sized packets. Moreover, HIPERLAN/2 has been conceived to transport real-time services. That is a great advantage!
Chapter 5

WLAN improvements using novel Hybrid ARQ mechanisms

5.1. A review of ARQ schemes

ARQ is a mechanism developed for error free data communications where the received packets with undetected (or presumably corrected) errors are “positive acknowledged” to the transmitter. If, instead, the receiver detects errored packets (with unrecovered errors) these packets are “negative acknowledged” to the transmitter, which then is responsible for the retransmission of the corrupted packets, no matter how long it takes.

The way the acknowledged messages and retransmitted packets interact with the normal packet flow has originated three methods known as Stop-and-Wait (SW), Go-Back-N (GBN) and Selective-Repeat (SR).

In spite of requiring a higher protocol execution complexity the Selective-Repeat strategy is by far the more efficient. Hereafter, it is assumed that all ARQ mechanisms use a SR strategy.

Besides these ARQ packet flow strategies, another important aspect to take into account is the coding strategy used in the transmitted packets and in the corresponding retransmissions. In fact, the “plain” error detection and “plain copy” packet retransmission can be improved by the so-called Hybrid ARQ (HARQ) schemes (i.e., a combination of FEC and
ARQ). Among these schemes the extra complexity can vary within a certain extent depending on the added functionalities and how they are implemented. The final goal is always an overall performance increase.

Table 33 summarizes the most common ARQ schemes.

<table>
<thead>
<tr>
<th>ARQ scheme</th>
<th>Functionality</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure detection</td>
<td>Detection and packet retransmission</td>
</tr>
<tr>
<td>Type I Hybrid</td>
<td>Detection/correction and packet retransmission</td>
</tr>
<tr>
<td>Type II Hybrid</td>
<td>Detection, redundancy retransmission and correction</td>
</tr>
<tr>
<td>Type III Hybrid</td>
<td>Detection/correction, redundancy retransmission and correction</td>
</tr>
</tbody>
</table>

Conventional pure detection ARQ uses a Cyclic Redundancy Check (CRC) code to achieve the largest detection capability; but since a single bit error is enough to force a retransmission, it may be advantageous to use a correcting code instead of an only detecting CRC. In this case the ARQ scheme is named Type I Hybrid ARQ.

It is also possible to concatenate two codes in order to improve the global ARQ throughput. From the transmitter point of view the first code applied to the information word is the outer code, the second being the inner code. From the receiver point of view the first decoding stage refers to the inner code and the second one to the outer code.

Type II and Type III Hybrid ARQs normally use serially concatenated coding with a half-rate outer code [57]. A half-rate code means that the number of parity check bits \((n-k)\) is equal to the number of information bits \(k\) in each \(n\)-bit codeword, resulting in a code rate \(k/n\) equal to \(1/2\). Codewords are computed on the data delivered from higher layers but, for each codeword, only one of the parts (information or parity) is inserted in the DLC User-PDU payload. Figure 45 shows an example of a transmitter-receiver setup for a Type II/III HARQ communication.

Type II uses a correction code and a CRC for the outer and inner coding respectively. Type III uses correction codes for both outer and inner coding. Besides CRC for error detection, the correction codes used are the Bose, Chaudhuri and Hocquenghem (BCH) and the Reed-Solomon (RS) codes.
Figure 45. Transmitter-receiver setup for Type II/III Hybrid ARQ schemes.

To distinguish between "information" and "parity" packets in Type II/III HARQs a type indication field is also necessary; henceforth this field is called *Info/Parity indication*.

The following sub-section describes the Pure detection ARQ PDU format currently used in the HIPERLAN/2 system. In section 5.3 the specially defined Hybrid ARQ PDU formats are presented.

### 5.1.1. The HL/2 Pure detection ARQ PDU format

Pure error detection ARQ schemes normally use a CRC to detect errors in the received packets. CRC is a very efficient technique and is widely used in both data transmission and storage systems. Using a length of $n-k$ bits, and a generator polynomial with an even number of coefficients, a good CRC has the following error detection capability:

- All single error bursts,
- All double error bursts,
- All bursts with an odd number of errors,
- All error bursts of length $n-k$ or less,
- A very large majority of error bursts with length larger than $n-k$. 
The HIPERLAN/2 system uses a pure detection and plain copy retransmission ARQ scheme, with a 24-bit CRC to detect errors in all fields of the received user packets. As previously depicted, the 432-bit HL/2 User-PDU format, with its CRC-24 field, takes the form shown in Figure 46.

<table>
<thead>
<tr>
<th>P-type</th>
<th>SN</th>
<th>DLC-SDU</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>396</td>
<td>24</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>DLC User-PDU</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-type</td>
<td>PDU type indication</td>
</tr>
<tr>
<td>SN</td>
<td>Sequence Number</td>
</tr>
<tr>
<td>DLC-SDU</td>
<td>DLC User-PDU payload</td>
</tr>
<tr>
<td>CRC-24</td>
<td>Cyclic Redundancy Check</td>
</tr>
</tbody>
</table>

**Figure 46. DLC User-PDU format with CRC coding.**

The HL/2 generator polynomial used to obtain the 24 parity check bits of CRC is the following:

\[
\text{HL/2 CRC-24,} \quad G(x) = x^{24} + x^{10} + x^9 + x^6 + x^4 + x^3 + x + 1
\]  

(4)

Unlike user packets using the HL/2 Long transport channel, which contain the above 24-bit CRC, control messages using the HL/2 Short transport channel contain a 16-bit CRC. In this case the generator polynomial is:

\[
\text{HL/2 CRC-16,} \quad G(x) = x^{16} + x^{12} + x^8 + x^7 + x^6 + x^3 + x + 1
\]  

(5)

Exception made to the HL/2 User-PDU format just presented, all PDU formats described henceforth are new and were conceived by the author in order to accommodate different Hybrid ARQ types.
5.2. Overview of novel Hybrid ARQ mechanisms

As pointed out in the previous section more complex and higher performance ARQ schemes are feasible other than just allowing error detection/correction and plain copy packet retransmission - that is, Type II/III Hybrid ARQs schemes. Unfortunately, they present some problematic issues.

One of the main problems of Type II/III HARQs is how to provide the receiver with correct control data when transmission conditions are bad. This is very important specially when the packet control information is concerned.

In fact, when errors are detected in a received packet the essential packet control information within it – the Sequence Number and the Info/Parity indication – cannot be considered reliable because the errors may have occurred exactly within that zone.

The current state of the art, in what concerns high-speed wireless LAN communications, reflects these difficulties and, consequently, neither IEEE nor ETSI/BRAN have tried to adopt such Type II/III HARQ schemes in their WLAN standards.

Besides, in the literature it is possible to state that, due to the specific WLAN communications characteristics, the emphasis of the current state of the art still goes to aspects related with the performance improvement of plain packet retransmission schemes (pure detection or Type I Hybrid ARQs). In general, those aspects are related with complementary issues such as:

- The estimation of the communication channel condition and a corresponding adaptation in the number of transmitted copies for each user packet [58],
- The definition of a minimal overhead slot based selective-repeat ARQ [59],
- The support of a link adaptation method enabling dynamic changes in the PHY layer bit rate speed [60], and,
- The minimization of the co-channel interference by limiting the burstiness of the transmissions and by an asymmetric placement of the silent periods [61].

Some of these methods are relatively complex and difficult to adapt to present standards. Others are developments of concepts already included in the HIPERLAN/2 standard.
Regarding their performance achievements, these methods minimize to a certain amount the effects of actual link error conditions hence obtaining some performance gains. Nevertheless, these gains are still somewhat limited due to the use of plain packet retransmission schemes.

In this thesis two new ways of improving the performance of Type II/III Hybrid ARQ schemes are presented. They are the core of the original contribution work presented subsequently [9].

One proposed and crucial improvement is the provision of a method that conveys the packet control information to the receiver in a safer way. This guarantees the fundamental condition for the operation of more powerful Type II/III HARQ schemes.

Using this new method it is possible to preserve the correct knowledge of the SN and the Info/Parity indication, even under a considerable number of errors in the main stream. The novel protection mechanism, used to safely convey the packet control information, is described in section 5.4.

The other proposed improvement is the implementation, at the receiver Error Control entity, of a “save & combine” mechanism applied to the (re) transmitted packet payloads. This mechanism enables the existence of multiple copies of the information and redundancy parts of each packet (i.e., with the same SN), guaranteeing that more codewords are tested for each copy arrival. The multiple copies combination mechanism is described in section 5.5.

The standard adaptation and implementation aspects of the two proposed improvements are other main issues of the developed work. Another very important contribution is the performance comparisons for all these ARQ models under several radio channel conditions. All these aspects constitute the central focus of analysis presented in this thesis.

Although specially targeted at wireless mobile environments, this analysis suggests that other error-prone environments, subject to errors and packet losses, can also benefit from the application of these original improvements, particularly when applied to real-time audio/video services (e.g., internet telephone links).
5.3. Type I/II/III Hybrid ARQ PDU formats

Before the presentation of the novel mechanisms (sections 5.4 and 5.5) this section deals with the necessary definition of the several DLC User-PDU formats which result from the Hybrid ARQ schemes chosen to be tested.

The first two sub-sections (5.3.1 and 5.3.2) describe inner coding schemes and related PDU formats which enable the implementation of Type I HARQs. Together with the pure detection scheme these ones are indispensable for later performance comparison purposes.

The succeeding sub-sections (5.3.3 to 5.3.6) deal with the implementation of Type II and Type III HARQs already considering the use of the proposed novel error control mechanisms. Accordingly, the description of the inner and outer coding schemes and the definition of new PDU headers and payload formats are consequently presented.

All format definitions take the HIPERLAN/2 DLC User-PDU format as a basis, thus meaning that, whenever applicable, the sizes of the fields are as close as possible to the corresponding fields of the HL/2 User-PDU.

5.3.1. Type I HARQ with BCH coding

As the HIPERLAN/2 DLC User-PDU contains 432 bits, 24 of them reserved for the CRC function, a search for BCH (n,k) codes containing approximately the same ratio between information (k) and redundancy (n–k) bits was performed, with the correcting capability (t bit errors) in mind as well.

For any positive integer m (m ≥ 3) there exists a binary BCH code with the following characteristics:

- Block length: \( n = 2^m - 1 \) bits
- Correction capability: \( t < 2^{m-1} \) bits
- Number of parity-check digits: \( n - k \leq mt \) bits
The analysis of primitive BCH codes with $n=511$ leads to the codes (511,484) and (511,493). Shortening these codes in 79 bits results in two shortened code options.

The first option was the BCH (432,405) code with 27 parity-check bits and a correction capability of $t=3$ bits; the second option was the BCH (432,414) code with 18 parity-check bits and a correction capability of $t=2$ bits.

Since the second code offers somewhat limited error correction/detection capability the first one was chosen. This is the main (inner) code used to detect and correct errors in User-PDUs arriving to the DLC layer.

Hence, having a BCH parity field with 27 bits, the packet was defined as shown in Figure 47.

<table>
<thead>
<tr>
<th>P-type</th>
<th>SN</th>
<th>DLC-SDU</th>
<th>C1 Par.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>393</td>
<td>27</td>
</tr>
</tbody>
</table>

$\xrightarrow{432}$

DLC User-PDU

P-type | PDU type indication | Length: 2 bits
SN | Sequence Number | Length: 10 bits
DLC-SDU | DLC User-PDU payload | Length: 393 bits
C1 Par. | Inner (BCH) code parity | Length: 27 bits

Figure 47. DLC User-PDU format with BCH coding.

In error correcting block codes, such as BCH, detected errors may be accepted as corrected if their number is equal to or less than a certain programmable corrective action threshold, hereafter identified as $\lambda$ ($\lambda \leq t$). Nevertheless, the higher is $\lambda$ the lower is the detection range ($l$) of the code.

In fact, there is a relationship between the corrective action threshold $\lambda$ and the detection range $l$, which enables a certain "tradeoff" between both. The relationship between these two figures and the correcting capability ($t$) is set by the following equation:

$$2t = \lambda + l \quad (\lambda \leq t \leq l) \quad (6)$$
The relationship with the minimum Hamming distance \( d \) of the code can be devised from the well-known formula \( d \geq 2t+1 \):

\[
d \geq \lambda + t + 1 \quad (\lambda \leq t \leq l)
\]

(7)

The \( \lambda \) corrective action threshold is applicable both to inner and outer codes*. In the inner code, if \( \lambda_1 \) is set to zero that means the code will be only used to detect errors, hence the ARQ is a Pure detection and retransmission type. If \( \lambda_1 \) is set such as \( 1 \leq \lambda_1 \leq t_1 \) then a Type I HARQ scheme is actually used.

With this inner (432,405) BCH coding, where \( t_1=3 \), \( \lambda_1 \) can take on the value 0 for a Pure detection scheme or take on one of the values \( \{1, 2, 3\} \) for a Type I HARQ scheme. In the first case \( (\lambda_1=0) \) it is better to just use the CRC coding presented in section 5.1.1.

5.3.2. Type I HARQ with RS coding

Just like with the BCH codes previously described, a similar search for RS codes is necessary in order to find an approximate number of information and redundancy bits for the User-PDU.

Unlike binary codes, where bits are taken from the Galois field GF(2), RS codes work with groups of bits taken from the Galois field GF\( (2^m) \). These groups are composed of \( m \) bits and are called symbols. All values, such as information length \( (k) \), redundancy length \( (n-k) \) and correction capability \( (t) \) are referred to in symbol units.

A \( t \)-error-correcting RS code with symbols from GF\( (2^m) \) has the following characteristics:

- Block length: \( n = 2^m - 1 \) symbols \((n \times m \text{ bits})\)
- Correction capability: \( t \) symbols
- Number of parity-check digits: \( n - k = 2t \) symbols \((2t \times m \text{ bits})\)
- Number of information digits: \( k = n - 2t \) symbols \((k \times m \text{ bits})\)

* Hereafter, the subscripts 1 and 2 will refer to DLC inner and outer codes, respectively.
To take the maximum advantage of a code the amount of shortening shall be minimum (ideally none). Thus, to reach the 432 bits of User-PDU the best value for m is 7 \( (n=2^7-1=127 \text{ symbols} = 889 \text{ bits}) \) since \( m=6 \) is not enough \( (n=2^6-1=63 \text{ symbols} = 378 \text{ bits}) \). Moreover, the use of a larger symbol size does not result in any performance advantage when the channel BER is high [62].

Using \( m=7 \) an approximate value for the number of parity-check digits is 4 symbols (28 bits), resulting in an error correction capability of \( t=2 \) symbols. Using these parameters the primitive RS code to be used will be a \((127,123)\) code over \( GF(128) \). To obtain the 432 bits of the User-PDU, a shortening of 457 bits has to be made.

Hence, having a RS parity field with 28 bits the shortening of the RS code results in a packet as shown in Figure 48.

For this inner RS coding, where \( t_1=2 \) symbols, \( \lambda_1 \) can take on the value 0 for a Pure detection scheme or take on one of the values \( \{1, 2\} \) for a Type I HARQ scheme. Just as with BCH coding, in the first case \( (\lambda_1=0) \) it is better to just use the previously presented CRC coding as well.

<table>
<thead>
<tr>
<th>P-type</th>
<th>SN</th>
<th>DLC-SDU</th>
<th>C1 Par.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>10</td>
<td>392</td>
<td>28</td>
</tr>
</tbody>
</table>

- **DLC User-PDU**
  - **P-type**
    - PDU type indication
    - Length: 2 bits
  - **SN**
    - Sequence Number
    - Length: 10 bits
  - **DLC-SDU**
    - DLC User-PDU payload
    - Length: 392 bits
  - **C1 Par.**
    - Inner (RS) code parity
    - Length: 28 bits

*Figure 48. DLC User-PDU format with RS coding.*

### 5.3.3. Type II HARQ with CRC-BCH coding

Besides an inner code, a DLC half rate outer code has also to be chosen in Type II/III HARQ schemes. In this outer code, for each codeword only one of the parts (information or redundancy) is inserted in the User-PDU payload.
As shown before, in HIPERLAN/2 the size of that payload is 396 bits. The search for primitive BCH codes with more than 396 bits in the information part and an approximate size in the redundancy part leads to the BCH (1023,628) code with 395 redundant bits and a correction capability of t=43 bits. Shortening this code in 233 bits changes it to the required half rate format, more precisely a (790,395) code.

This (790,395) BCH code is the chosen one whenever an outer BCH coding scheme is used. Even being not equal in the payload size (difference of 1 bit) this code is close enough to do the intended performance comparisons.

Hence, when using the (790,395) BCH as the outer code and the CRC-24 as the inner code, a difference of 432−(395+24)=13 bits remains to be used as packet control information, i.e., as the header of the User-PDU.

These header bits would be composed of PDU type, Info/Parity indication and SN fields when testing a normal, but vulnerable, implementation of Type II (or III) HARQ schemes. But, when evaluating the implementation of these same schemes with the novel proposed error control mechanisms, the SN field becomes redundant and is thus replaced by a useful header protection field.

For the considered CRC-BCH coding, Figure 49 shows the DLC User-PDU format adopted, with 13, 395 and 24 bits respectively used for header, payload and error control functions.

<table>
<thead>
<tr>
<th>P-type</th>
<th>Inf/Par</th>
<th>H-prot.</th>
<th>Payload</th>
<th>CRC</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>10</td>
<td>395</td>
<td>24</td>
</tr>
</tbody>
</table>

432

DLC User-PDU

<table>
<thead>
<tr>
<th>P-type</th>
<th>PDU type indication</th>
<th>Length: 2 bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inf/Par</td>
<td>Info/Parity indication</td>
<td>Length: 1 bit</td>
</tr>
<tr>
<td>H-prot.</td>
<td>Header protection</td>
<td>Length: 10 bits</td>
</tr>
<tr>
<td>Payload</td>
<td>DLC User-PDU payload</td>
<td>Length: 395 bits</td>
</tr>
<tr>
<td>CRC</td>
<td>Cyclic Redundancy Check</td>
<td>Length: 24 bits</td>
</tr>
</tbody>
</table>

*Figure 49. DLC User-PDU format with CRC-BCH coding (use of novel mechanisms).*

* For Type II/III HARQ schemes, the acronyms of the codes are used following the order “inner-outer code”.*
In this CRC-BCH coding the error correction capability is \( t_2 = 43 \) bits. So, in terms of the \( \lambda_2 \) corrective action threshold the most interesting values belong to the set \{40, 41, 42\}. The value of \( \lambda_1 \) is always zero since CRC is a detection-only code.

### 5.3.4. Type II HARQ with CRC-RS coding

Here the methodology is identical to the one presented just before. Nevertheless, when evaluating the RS half-rate outer code it is necessary to choose the value \( m \) in the first place. This value has to allow codeword lengths equal to or larger than the double of the PDU payload (approximately \( 2 \times 396 \) bits). As before, this value is set to \( m = 7 \) (\( n = 2^7 - 1 = 127 \) symbols = 889 bits).

The search for primitive RS codes over GF(128) with more than 396 bits in the information part and an approximate size in the redundancy part leads to the \((127,71)_{128}\) RS code. This code has 56 redundant symbols (392 bits) and a correction capability of \( t = 28 \) symbols. The parameters of this RS code when expressed in bits have values of \( n = 889 \) and \( k = 497 \) bits.

To obtain the intended half rate format a shortening of 15 symbols (105 bits) is necessary, consequently resulting in a \((112,56)_{128}\) RS code. This code is the chosen one whenever an outer RS coding scheme is used.

The difference to the HL/2 payload size is now larger than before (a difference of 4 bits) but a better approximation is not possible due to a certain mismatch between the payload field size (396 bits) and the allowable parameters sizes of the RS code.

Thus, when using the CRC-24 as the inner code and the \((112,56)_{128}\) RS as the outer code 16 bits remain for the packet control information.

These 16 bits would be composed of PDU type and SN fields when testing Pure detection and Type I HARQ schemes. When evaluating a Type II HARQ scheme with a CRC-RS coding the same 16 bits are fulfilled with corresponding PDU type, Info/Parity indication and header protection fields. Figure 50 shows the DLC User-PDU format adopted in this case.

In this CRC-RS coding the value of \( t_2 \) is 28 symbols. So, the most interesting values of the corrective action threshold \( \lambda_2 \) are the values 26 and 27. As said before, the value of \( \lambda_1 \) is zero due to CRC correction inability.
5.3.5. Type III HARQ with BCH-BCH and BCH-RS coding

In Type III HARQ schemes both inner and outer codes are BCH and/or RS error correction codes. Besides the powerful correcting outer code, this strategy enables a fast "low level" corrective action carried out by the inner code. This means that, depending on the occurred error pattern, some retransmissions can be avoided when compared with inner CRC coding.

The length search methodology for inner and outer codes is the same as before. When using BCH-BCH concatenation the two following codes will be applied:

- **Inner code:** \( \text{BCH (432,405), n-k = 27, t = 3 bits;} \)
- **Outer code:** \( \text{BCH (790,395), n-k = 395, t = 43 bits.} \)
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The application of these two codes results in a DLC User-PDU format as shown in Figure 51. This is the format adopted in the simulator when using a Type III ARQ scheme with a BCH-BCH coding.

When using BCH as the inner code and RS as the outer code the parameters will be:

- Inner code: BCH (432,405), n–k = 27, t = 3 bits;
- Outer code: RS (112,56)_{128}, n–k = 56, t = 28 symbols.

The application of these two codes results in a DLC User-PDU format as shown in Figure 52. This is the format adopted in the simulator when using a Type III ARQ scheme with a BCH-RS coding.

<table>
<thead>
<tr>
<th>P-type</th>
<th>Inf/Par</th>
<th>H-prot.</th>
<th>Payload</th>
<th>C1 Par.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>10</td>
<td>392</td>
<td>27</td>
</tr>
</tbody>
</table>

DLC User-PDU

- P-type: PDU type indication (Length: 2 bits)
- Inf/Par: Info/Parity indication (Length: 1 bit)
- H-prot.: Header protection (Length: 10 bits)
- Payload: DLC User-PDU payload (Length: 392 bits)
- C1 Par.: Inner (BCH) code parity (Length: 27 bits)

Figure 52. DLC User-PDU format with BCH-RS coding (use of novel mechanisms)

5.3.6. Type III HARQ with RS-RS and RS-BCH coding

In this case a RS code will be used as the inner code. For a RS-RS coding method the two codes will be:

- Inner code: RS (127,123)_{128} shortened in 457 bits, n–k = 4, t = 2 symbols;
- Outer code: RS (112,56)_{128}, n–k = 56, t = 28 symbols.
The resulting User-PDU format for this RS-RS coding is depicted in Figure 53.

<table>
<thead>
<tr>
<th>P-type</th>
<th>Inf/Par</th>
<th>H-prot.</th>
<th>Payload</th>
<th>C1 Par.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>9</td>
<td>392</td>
<td>28</td>
</tr>
</tbody>
</table>

DLC User-PDU

- **P-type**: PDU type indication
- **Inf/Par**: Info/Parity indication
- **H-prot.**: Header protection
- **Payload**: DLC User-PDU payload
- **C1 Par.**: Inner (RS) code parity

Length: 2 bits
Length: 1 bit
Length: 9 bits
Length: 392 bits
Length: 28 bits

**Figure 53.** DLC User-PDU format with RS-RS coding (use of novel mechanisms)

In a Type III ARQ scheme using a RS-BCH coding method the two codes will be:

- **Inner code**: RS \((127,123)_{128}\) shortened in 457 bits, \(n-k = 4\), \(t = 2\) symbols;
- **Outer code**: BCH \((790,395)\), \(n-k = 395\), \(t = 43\) bits.

The resulting User-PDU format for this RS-BCH coding is illustrated in Figure 54.

<table>
<thead>
<tr>
<th>P-type</th>
<th>Inf/Par</th>
<th>H-prot.</th>
<th>Payload</th>
<th>C1 Par.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>6</td>
<td>395</td>
<td>28</td>
</tr>
</tbody>
</table>

DLC User-PDU

- **P-type**: PDU type indication
- **Inf/Par**: Info/Parity indication
- **H-prot.**: Header protection
- **Payload**: DLC User-PDU payload
- **C1 Par.**: Inner (RS) code parity

Length: 2 bits
Length: 1 bit
Length: 6 bits
Length: 395 bits
Length: 28 bits

**Figure 54.** DLC User-PDU format with RS-BCH coding (use of novel mechanisms)
5.4. A new protection mechanism of packet control information

As previously referred to, when composing the HIPERLAN/2 MAC frame the 54-octets User-PDUs (Figure 43) of a DLC connection are mapped into the same size Long transport Channel (LCH). The shorter ARQ acknowledgements and some other link control messages are mapped into the 9 octets Short transport Channel (SCH).

Figure 55 shows the HIPERLAN/2 MAC frame structure and corresponding ordering of the different transport channel formats. In this context the acronym BCH means Broadcast Channel (not to be confused with the BCH correcting code).

![MAC frame diagram]

2 DLC connections allocated to MT₁

Allocations to other MTs

BCH - Broadcast Channel
FCH - Frame Channel
ACH - Access feedback Channel
DL - Downlink
DiL - Direct Link

UL - Uplink
RCHs - Random Channels
Pre - Physical Layer Preamble
SCH - Short transport Channel (9 octets)
LCH - Long transport Channel (54 octets)

Figure 55. HIPERLAN/2 MAC frame structure.

LCH and SCH transport formats may use more than one physical mode. These modes and their relationship with the transport channels, as defined in HIPERLAN/2 specifications [8] [53], are recalled in Table 34.
Table 34. HIPERLAN/2 physical modes and transport channels.

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Coding rate</th>
<th>Nominal bit rate (Mbit/s)</th>
<th>Transport channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK</td>
<td>1/2</td>
<td>6</td>
<td>BCH, FCH, ACH, SCH, LCH, RCH</td>
</tr>
<tr>
<td>BPSK</td>
<td>3/4</td>
<td>9</td>
<td>SCH, LCH</td>
</tr>
<tr>
<td>QPSK</td>
<td>1/2</td>
<td>12</td>
<td>LCH</td>
</tr>
<tr>
<td>QPSK</td>
<td>3/4</td>
<td>18</td>
<td>SCH, LCH</td>
</tr>
<tr>
<td>16QAM</td>
<td>9/16</td>
<td>27</td>
<td>LCH</td>
</tr>
<tr>
<td>16QAM</td>
<td>3/4</td>
<td>36</td>
<td>LCH</td>
</tr>
<tr>
<td>64QAM</td>
<td>3/4</td>
<td>54</td>
<td>LCH</td>
</tr>
</tbody>
</table>

In order to efficiently use the available bandwidth, DLC User-PDUs normally employ the LCH transport channel at high bit rate physical modes. The tradeoff is a higher vulnerability to errors. Short feedback messages, such as an ARQ positive acknowledgement containing a sequence numbers list, carry highly sensitive information. Corresponding transport in SCHs are conveyed through slower but more reliable physical modes.

With the adoption of the packet structure shown in Figure 43, a straightforward implementation of Type II/III HARQ schemes would imply that the SN field and the Info/Parity indication would be transported within User-PDUs, jeopardizing its normal operation.

In this work it is proposed that, for each DLC connection (DLCC), the information about the SNs is condensed into a forward direction packet list and transported in one or more SCHs aside with corresponding LCHs containing the User-PDUs. Figure 56 shows these forward direction lists, within a MAC frame structure, using SCHs allocated to the respective DLCCs. This way, the packet control information gets a significant increase in its protection, hence guaranteeing the normal operation of Type II/III HARQ schemes.

The DLCC SN lists may use the same method as the one specified for HIPERLAN/2 ARQ acknowledgement messages, which also uses SCHs. Those messages, containing Bitmap Blocks, can carry positive or negative acknowledgement status for 24 packets, divided into 3 blocks of 8 contiguous SNs, and a cumulative acknowledgement indicator that positively acknowledges all packets whose SNs are up to the indicated number. Adopting this method up to 24 semi-contiguous packet SNs can be listed, not excluding a mixed situation where a list with a “SN-start” and a “SN-end” can be used for contiguous SNs.
Figure 56. Transport of “forward direction” SN lists for each DLCC.

For each DLCC, and considering the respective SCH and LCH sizes (9 and 54 bytes, respectively), the overhead consequently created depends on the ratio between the number of SCHs used to transport the packet list ($N_{R_{SCH}}$), and the number of LCHs used to transport the packets ($N_{R_{LCH}}$). Nominal bit rates of the different SCH/LCH physical modes ($BitRate_{SCH/LCH}$) have also to be considered on this computation. The overhead ($OH_{SNlist}$) formula is then set by:

$$OH_{SNlist} = \frac{9}{54} \cdot N_{R_{SCH}} \cdot \frac{BitRate_{LCH}}{BitRate_{SCH}}$$

(8)

As an example, consider a frame where a certain DLC connection has 8 plus 16 contiguous User-PDUs to be transmitted and corresponding LCHs are using the 54 Mbit/s physical mode. Suppose then that one SCH is enough to contain the entire SN list and is using the 18 Mbit/s physical mode. In this case the overhead would be $(9/54) \times (1/24) \times (54/18) = 0.02083$.

Overhead values augment when there is a decrease in the SCH/LCH bit rates ratio and/or the needed number of SCHs ($N_{R_{SCH}}$) increases. That happens because SN lists do not map so well into Bitmap Blocks. This latter situation is more likely to occur when packet retransmissions start to increase in consequence of a degradation of transmission conditions. But, as the performance of Type II/III HARQs is exactly more significant in those conditions,
when compared with Pure detection and Type I HARQ, even overheads of up to 10% are still small when balanced with the efficiency gains so obtained.

For good transmission conditions, where performance differences among ARQ schemes are relatively small, the forward direction SN list may be suspended, to appear only when the radio channel gets bad. Hence, it is still possible to save this bandwidth resource to be used in another way.

5.5. Hybrid ARQs with multiple copies combination

The great advantage of Type II/III HARQ schemes, when safely operated (probably using the novel solution exposed in previous section), is the use of an outer code with a powerful error correction capability.

Due to the “double size” outer code characteristic, when compared with packet payload size, when an error occurs it is still necessary to save the errored packet contents. This one will be combined later on with the next corresponding retransmission in order to get an outer code codeword.

This means that, for each packet, a typical Type II/III HARQ uses two memories (M=2) to save, respectively, the information and the parity parts. In this typical case, only the two most recent copies are kept, which is somewhat restrictive when compared with the possibility of having more copies available.

Following the above idea an extended receiver implementation of Type II/III Hybrid ARQs is proposed. This new implementation is characterized by the existence of M (even) memories for each packet (i.e., for packets having the same SN). M/2 memories are used to save “information packets”; the other M/2 memories are used to save “parity check packets”. Figure 57 shows a possible receiver implementation setup for multiple copies combination, namely using six memories per packet (M=6).

The rationale behind this mechanism is that every received copy of a packet (even with unrecovered errors) contains almost every bit intact. Hence, when the inner decoder states an unrecovered error, it passes the received packet payload to this second level of decoding. Having several copies memorized, it is possible to combine more information and parity parts.
This way, for each packet retransmission arrival, more codewords are fed to the outer decoder, improving its success rate.

**Figure 57. Receiver implementation of a Type II/III HARQ scheme with multiple copies combination (M=6).**

The multiple copies combination mechanism presents another advantage when used in delay-constrained services, such as audio/video services. When the radio channel has significantly long bad periods, it may happen that none of the information-parity combinations
reach the established corrective action threshold ($\lambda_2$) before the packet expires*. This implies that, in a normal situation, the packet is considered lost and all respective data subsequently discharged.

Still, for audio/video services it may be interesting to forward the "presumably corrected" version of the packet, even if the error levels found are above $\lambda_2$ (but equal or below $t_2$). This is justified by the fact that some audio/video decoders may conceal the eventual error presence.

In this case, when approaching the packet due-time, it is possible to choose the information-parity combination that exhibits the minimum error level. If this error level (obviously above $\lambda_2$) is below the outer code error correction capability ($t_2$) there is a big chance that the respective codeword decoding will result in an error free packet.

5.6. Summary

This chapter started with a review of ARQ schemes, pointing out the functionalities associated with each one. With that purpose in mind, the coding strategies used for packets and for eventual retransmissions were described.

It was seen that an ARQ scheme can range from a conventional pure detection and plain copy packet retransmission to a detection/correction and redundancy packet retransmission. The most powerful schemes are the Type II/III Hybrid ARQs, both using concatenated inner and outer codes.

Normally, in Type II/III HARQs the outer code adopts a half-rate format but, within each packet payload, only one of the parts (information or parity) is transported. To distinguish between information and parity packets it is necessary to use an "Info/Parity indication" field.

To exploit the better performance of Type II/III HARQs it is absolutely fundamental to have error-free packet control information, but this is exactly one of the main difficulties associated with these HARQ types.

---

* In the outer decoding of Type II/III HARQs a packet is considered "good" if the error level is found below or equal to the $\lambda_2$ corrective action threshold.
A consequence of these difficulties is the almost complete absence of publications concerning WLAN communications using Type II/III Hybrid ARQs. Indeed, the current state of the art is still positioned in the development of methods that try to improve the plain packet retransmission schemes.

To overcome this problem and simultaneously achieve significant improvements in wireless LAN data connections, an original contribution work took place resulting in the development of two novel error control mechanisms, presented and characterized in this chapter.

The first one is a completely new protection method of the critical packet control information (SN and Info/Parity indication) required by Type II/III HARQs. The author proposes the creation of “forward direction packet lists” to be carried on by channels using the most reliable PHY modes. Those lists contain the Sequence Numbers of corresponding User-PDUs scheduled to be transmitted in each DLC connection.

Concurrentely, what was a “normal” SN field is now occupied by an Info/Parity indication and by a header protection field. This way it is possible to have a perfect knowledge of SNs and Info/Parity indications, thus enabling the operation of Type II/III HARQs under adverse conditions, but still exploiting their superior performance.

The second proposal consists of an extended receiver implementation for the same type of HARQs, allowing a combination of multiple copies in the outer code decoding. This implementation enhancement is characterized by the existence of M memories (4, 6...) for each packet, instead of two memories only. This will allow a faster packet decoding and validation and the occurrence of more reliable (even if not validated) packet copies. This aspect is particularly important for applications with stringent packet due-times.

For the DLC User-PDU formats the HIPERLAN/2 (conventional ARQ) CRC-based 432-bit packet has been used as a basis. Other ARQ schemes involve the use of CRCs and/or error correcting codes and some adaptations are necessary in the DLC PDU formats to maintain the total size of 432 bits. In this chapter the PDU format adaptations for Hybrid ARQ schemes using CRC, BCH and RS codes have been shown. The relations among correction capability (t), corrective action threshold (λ) and detection range (I) of error correcting block codes (BCH and RS) have also been presented.
Chapter 6

System modeling, simulation and results

6.1. System model elements

In order to compare the various classic ARQ solutions with the proposed alternative solutions a flexible system model was developed with the aid of some computational and graphical simulation tools, such as the MATLAB/Simulink family of software products.

The system model includes the main connections and components of a typical wireless communication system. Figure 58 shows the relevant system model elements used in the developed simulation program and the proposed DLC main data units.

The upper half part of the figure shows the block diagram of the communication chain. From left to right, the DLC Error Control, DLC MAC and PHY layer blocks are shown on the transmitter side, till the dashed line representing the Radio Interface. From this line on, the counterpart elements are shown on the receiver side. Both forward (above) and backward (below) direction links are represented.

The lower half part of the figure shows the DLC data units that interact with the Error Control block:

(a) The DLC Service Data Unit (DLC-SDU),

(b) The DLC-SDU plus the outer coding parity (Type II/III HARQs only),

(c) The DLC User Protocol Data Unit (DLC U-PDU).
(a) DLC Service Data Unit (DLC-SDU):

(b) Outer Coding (Type II/III HARQs only):

(c) DLC User Protocol Data Unit (DLC U-PDU):

Pure detection and Type I HARQ:

Type II and III Hybrid ARQs: Normal tx. and even-numbered retransmissions (2nd, 4th...) Odd-numbered retransmissions (1st, 3rd, 5th...
6.2. Radio channel models

Two radio channels were considered: the Additive White Gaussian Noise (AWGN) memoryless channel and the Gilbert-Elliot (GE) memory channel, described in the next sections.

6.2.1. Additive White Gaussian Noise memoryless channel

The first radio channel model taken into consideration was the AWGN memoryless channel with a bilateral power spectral density $N_0/2$.

The combination *modulator–air channel–demodulator* can be seen as a discrete channel since level quantization is done at the modulator input and demodulator output. Hence, when the channel is affected by AWGN and hard decision is used, that combination can be seen as a Binary Symmetric Channel (BSC).

In a BSC the bit error probability is independent of the transmitted bits. As shown in Figure 59, this results in a memoryless BSC characterized by an equal error probability when transmitting "zeros" or "ones" called the Bit Error Rate of the channel (BERc).

![Diagram](image)

Figure 59. Memoryless Binary Symmetric Channel.
In terms of simulation the BSC is implemented using a Matlab/Simulink block. To generate the random errors this block uses a Poisson distribution with parameter BER_e. The resulting errors are then added to encoded bits.

Relatively to the original Simulink Library block, the author modified this one in order to accept dynamical variations of the BER_e.

6.2.2. Gilbert-Elliot memory channel

The second radio channel model taken into consideration was the GE memory channel [63] [64]. Besides random error patterns, the GE channel model is appropriate to simulate burst error patterns [65]. As shown next, this means that the parameterization choices are much wider in the GE model than in the AWGN model.

As depicted in Figure 60, the GE model uses a two-state Markov chain (Markov processes are often used to model channels with memory [66]). The two states are normally called the “good” and the “bad” states. Each state is characterized by a different channel bit error rate, BER_good and BER_bad, and by an occupancy mean time, mt_good and mt_bad.

From the mean time values it is possible to derive the probability of the radio channel being in one of the states, called hereafter the P_good and the P_bad state probabilities. The respective expressions are presented in Equations 9 and 10.

\[
P_{\text{good}} = \frac{mt_{\text{good}}}{mt_{\text{good}} + mt_{\text{bad}}} \\
\]

\[
P_{\text{bad}} = \frac{mt_{\text{bad}}}{mt_{\text{good}} + mt_{\text{bad}}} \\
\]

Normally BER_{good} is significantly lower than BER_{bad}. Additionally, in the GE model the bit error probability (BER_e) is the weighted average channel BER calculated over BER_{bad} and BER_{good}, that is:

\[
BER_e = BER_{\text{bad}} \times P_{\text{bad}} + BER_{\text{good}} \times P_{\text{good}} \\
\]
(P, Q, p, q: State transition probabilities)

\[ P+Q = 1, \quad P = \frac{\text{bit unit time}}{mt_{\text{good}}}, \quad P << Q \]

\[ p+q = 1, \quad p = \frac{\text{bit unit time}}{mt_{\text{bad}}}, \quad p << q \]

<table>
<thead>
<tr>
<th>Parameters</th>
<th>State “Good”</th>
<th>State “Bad”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean time in the state</td>
<td>( \frac{mt_{\text{good}}}{mt_{\text{good}} + mt_{\text{bad}}} )</td>
<td>( \frac{mt_{\text{bad}}}{mt_{\text{good}} + mt_{\text{bad}}} )</td>
</tr>
<tr>
<td>State probability</td>
<td>( P_{\text{good}} )</td>
<td>( P_{\text{bad}} )</td>
</tr>
<tr>
<td>Error probability</td>
<td>BER_{\text{good}}</td>
<td>BER_{\text{bad}}</td>
</tr>
<tr>
<td>No error probability</td>
<td>1 – BER_{\text{good}}</td>
<td>1 – BER_{\text{bad}}</td>
</tr>
</tbody>
</table>

\[ BER_{\text{good}} << BER_{\text{bad}} \]

\[ BER_{\text{bad}} < 0.5 \]

Figure 60. The Gilbert-Elliot memory channel model.

In terms of simulation the GE channel model is implemented with the help of a block specially developed by the author (shown in section 6.3.1). To generate the random occupancy times of “good” and “bad” states this block uses exponential distributions with parameters \( mt_{\text{good}} \) and \( mt_{\text{bad}} \), respectively.

The error generation process is identical to the AWGN channel model as long as, for each state of GE model, the bit error probability is clearly defined (BER_{\text{good}} or BER_{\text{bad}}).
6.3. Simulation outline

There are four steps related with the assessment of the proposed error control mechanisms:

- The development of the simulation models,
- The development of the simulation analysis tools,
- The simulation runs,
- The analysis of results.

The first three aspects are described, respectively, in sections 6.3.1, 6.3.2 and 6.3.3.

The analysis of simulation results is done in sections 6.4 and 6.5, respectively, for the AWGN and GE radio channel models.

6.3.1. Simulation models

To perform the simulation of certain system conditions it is first necessary to develop a relatively complex simulation model matching those conditions. This implies that, over the basic simulator developed by the author and for each new added function, ARQ scheme or block coding scheme, a considerable time-consuming model adjustment/upgrading had to be completed.

This approach to the simulator development (models and tools), with its continuous adaptation to the work underway in the international standardization bodies, prevented an initial full-line accomplishments strategy. Instead, the simulations were carried out in order to get step-by-step comparative results on the conventional and the proposed schemes.

In this line of action, the simulation models and their runs were first executed using only one code (BCH) and the AWGN channel model. Later on, it evolved to the use of the other coding schemes considered (CRC and RS) and the GE channel model.

In Figure 61 an example of the main level of a developed simulation model is shown. Three parts compose the main level. One is related with the communication system blocks
(upper part of the figure). Another one has to do with the simulation initialization blocks (middle part of the figure). The third part is concerned with the blocks that collect and process information related to performance data (lower part of the figure).

**Figure 61. The main level of the simulation models.**

The main level acts as one of the core parts of the simulation activity for each implemented simulator. Accordingly, to maintain identical conditions in the simulation of the different schemes, and apart from the radio channel model used, the main level was kept unaltered.

When testing the same error control mechanisms and ARQ scheme, simulation models for the two radio channels used (AWGN and GE) only differ in the respective error implementation blocks.

In Figure 62 the block developed by the author to implement the GE channel model is shown (topmost hierarchical level). In this block the duration of “good” and “bad” states
"Slot Good" and "Slot Bad" outputs) are successively generated using exponential distributions with parameters $m_{\text{good}}$ and $m_{\text{bad}}$, respectively. Depending on the current state the "BERc vector" output is modified accordingly.

![Gilbert-Elliot bit model](image)

**Figure 62.** Gilbert-Elliot simulator block (high hierarchical level).

![Receiver simulator block](image)

**Figure 63.** Receiver simulator block (high hierarchical level).
The major differences in the simulation models are due to the implementation of the various conventional and proposed error control mechanisms, combined with the distinct coding options.

This model's multiplicity is fundamentally incorporated in the transmitter and receiver blocks present in the simulator's main level. In Figure 63 an example of a receiver block developed by the author is shown (topmost hierarchical level).

The inner and the outer decoders, a temporary memory for received packets, an overall block control and an output buffer for packets already validated are incorporated in this receiver block.

### 6.3.2. Simulation analysis

The simulation analysis is based on the information that is constantly gathered along each simulation. With this data collection, and using the author's developed Simulink blocks and Matlab routines, it is possible to obtain diverse performance metrics and other information relative to the simulated DLC connections.

Regarding the computed performance metrics these are as follows:

- Average number of packet retransmissions,
- Standard deviation of the number of packet retransmissions,
- Global throughput efficiency of the DLC connection,
- Residual bit error rate.

These performance metrics are defined as:

\[
\bar{r} = \frac{1}{m} \sum_{i=1}^{m} r_i = \frac{1}{m} \sum_{r=0}^\infty r \cdot m_r
\]  
(12)

Average number of retransmissions:

\[
\sigma_r = \sqrt{\frac{1}{m} \sum_{i=1}^{m} (r_i - \bar{r})^2}
\]  
(13)

Standard deviation of number of retransmissions:
Throughput efficiency:

\[ \eta = \frac{m}{m + \sum_{i=1}^{m} r_i} \cdot \frac{k_1}{n_1} = \frac{1}{1 + \bar{r}} \cdot \frac{k_1}{n_1} \]  

(14)

Residual BER:

\[ BER_{res} = \frac{1}{m \cdot bpp} \sum_{i=1}^{m} e_i \]  

(15)

where

- \( m \) denotes the total number of information packets (DLC SDUs) conveyed by the DLC connection; counted at the transmitter DLC User SAP;
- \( r \) is the number of retransmissions per packet \( (r=0,1,2,\ldots,\infty) \);
- \( r_i \) denotes the number of retransmissions relative to the \( i \)-th DLC SDU \( (i=1,2,\ldots,m) \);
- \( m_r \) is the number of information packets that have required \( r \) retransmissions \( (m_r=0,1,2,\ldots,m) \);
- \( k_i/n_i \) is the inner code rate;
- \( e_i \) denotes the number of bit errors in the \( i \)-th DLC SDU \( (i=1,2,\ldots,m) \); counted at the receiver DLC User SAP;
- \( bpp \) denotes the number of bits per packet (DLC SDU size).

Besides these performance metrics it is also interesting to see, for each scheme, how the number of retransmissions depends on the channel BER. With that purpose in mind, a software tool to collect information and process histograms of retransmissions was additionally developed.

In Figure 64 examples of histograms of the number of retransmissions per packet are shown. Vertical axes represent the \( m_r/m \) ratio while horizontal axes represent the number of retransmissions per packet \( (r) \). In this chapter the information on all histograms has this same structure.

The validation of the simulations was done by simulating wireless systems similar to those in [59], [60] and [67] and by comparing the simulation results obtained to corresponding published ones. The same procedure was taken as well in relation to other general communication systems using Type II/III Hybrid ARQs [57] [68].
The basic performance curves confirmed by the references will also be used for the comparison of performance between the conventional and the proposed error control mechanisms, in order to verify the actual improvement achievements. These curves will be indicated in the section 6.4.

![Histograms of retransmissions per packet](image)

Sign "+": means a number of retransmissions equal or larger than the number preceding it

**Figure 64. Examples of histograms of the number of retransmissions per packet.**

### 6.3.3. Simulation runs

As for the methodology for each simulation run, it has been decided that the transmitter had to transfer a predetermined number of packets to the receiver, using a DLC connection with constant capacity (expressed in number of time slots per MAC frame). This latter
assumption is in accordance with systems with a centralized control, like HIPERLAN/2, both in infrastructure and ad hoc modes.

Therefore, when using a certain physical mode, the available bandwidth in terms of bit rate is set by the product frame usage percentage $\times$ PHY mode bit rate. Hence, when intending to use two different PHY modes, but maintaining the same available bandwidth, it is necessary to adjust the frame usage percentage.

In this study, the simulations have been executed for two different percentages of utilization of the MAC frame and a constant available bandwidth.

In the first sets of simulated DLC connections, the following characteristics have been assumed:

- Utilization of 90% of the MAC frame (1.8 ms),
- Use of a 12 Mbit/s physical mode.

In the second sets of simulated DLC connections, the assumptions have been the following:

- Utilization of 20% of the MAC frame (0.4 ms),
- Use of a 54 Mbit/s physical mode.

For both situations, the above characteristics assumptions result in DLC connections with a 10.8 Mbit/s maximum gross rate ($0.9 \times 12 = 0.2 \times 54 = 10.8$ Mbit/s) without coding.

In relation to the performance curves they were obtained varying the channel BER when using the AWGN model, or the corresponding average when using the GE model.

6.4. Simulation results for the AWGN memoryless channel

The first sets of simulation runs have used the AWGN memoryless channel for the modeling of the radio medium. Besides its simpler implementation when compared with the

* In HL/2 it is possible to get a fixed capacity agreement between an Access Point/Central Controller and a Mobile Terminal; this negotiation is made during a “connection setup” or a “connection modify” process.
GE model, it provides an important initial behavior characterization of each ARQ scheme under discussion.

In the following sub-sections several comparison results are shown for conventional and proposed ARQ schemes. In 6.4.1 the results relative to simulations using BCH codes and a 90% MAC frame usage are shown. Results for identical conditions but using also CRC and RS codes are shown in 6.4.2. Finally, in 6.4.3, the simulations results for a 20% MAC frame usage and using all the three codes are shown as well.

According with the figures typically used in the characterization of wireless channels random errors [69], in these simulations the AWGN channel BER was specified in the range from $10^{-4}$ to $10^{-1}$.

### 6.4.1. BCH coding with a 90% MAC frame usage

The BCH code was used for the first stage assessment of the ARQ schemes (i.e., conventional or Type I Hybrid ARQs versus Type II/III HARQs with the proposed improvement mechanisms). Accordingly, the 432-bit DLC User-PDU formats shown in Figure 47 and Figure 51 were therefore utilized.

Additionally to the PDU formats cited above, some simulations were also run with smaller packets. Nevertheless, the choice of inner and outer BCH codes followed the same guidelines used for the 432-bit packets. The resulting codes are shown in Table 35.

<table>
<thead>
<tr>
<th>Packet length</th>
<th>BCH inner code $(n_1, k_1, t_1)$</th>
<th>BCH outer code $(n_2, k_2, t_2)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>94</td>
<td>(94, 73, 3)</td>
<td>(126, 63, 10)</td>
</tr>
<tr>
<td>158</td>
<td>(158, 134, 3)</td>
<td>(248, 124, 18)</td>
</tr>
<tr>
<td>289</td>
<td>(289, 262, 3)</td>
<td>(504, 252, 30)</td>
</tr>
<tr>
<td>432</td>
<td>(432, 405, 3)</td>
<td>(790, 395, 43)</td>
</tr>
</tbody>
</table>
The half rate outer codes, corresponding to smaller packets, are derived from primitive BCH codes, namely the (127,64), (255,131) and (511,259) codes, by applying the minimum shortening (respectively, 1, 7 and 7 bits). Ten bits, corresponding to the packet header, are then added to k₂ bits resulting in a k₁-bit word. Subsequent BCH inner codes, with total lengths n₁=94, 158 and 289, are chosen to have the same correcting capability t₁=3 bits.

In the next pages it is possible to observe the simulation results involving the comparisons between the following schemes:

- Pure ARQ versus Type I HARQ,
- Pure ARQ versus Type II HARQ,
- Type I versus Type III HARQs,
- Type II/III HARQs with and without multiple copies combination.

Figure 65 shows the performance curves of Pure detection (λ₁=0) and Type I (1 ≤ λ₁ < t₁) Hybrid ARQs, for 94 and 432-bit packet sizes, when in presence of an AWGN memoryless channel. For the larger packet size the conventional Pure detection ARQ has a reference curve (λ₁=0, n₁=432) which matches the curve published in [67] (and also very similar to those in published in [60]).

Analyzing the performance curves of the throughput efficiency and the residual BER, it is possible to conclude that, when using detection/correction codes such as BCH, Type I HARQ performs always better than Pure detection.

As expected, the curves in Figure 65 corresponding to λ₁=2, λ₁=1 and λ₁=0 show a decreasing efficiency for any BERₜ. But for the residual BER, the likely trade-off between efficiency and residual BER swaps between λ₁=1 and λ₁=0 curves.

Indeed, the curve corresponding to λ₁=1 not only presents lower residual BER values than the λ₁=2 curve but also lower than the λ₁=0 curve.

This is explained by the fact that when BERₜ is high a large portion of the packets contains errors. If λ₁=0 (hence not performing any correction) the only chance for packets to get through is when a “clean” copy arrives or when an undetected error occurs.

As there is a significant increase in the number of retransmissions, the chances for the code to fall in an undetected error situation also increase.
As shown in Figure 65, this leads to a higher residual BER curve in $\lambda_1=0$ than in $\lambda_1=1$.

In this case, and analyzing both efficiency and residual BER, a $\lambda_1=1$ value is the best choice. It will be seen in the following examples, using also inner codes with $t_1=3$, that a $\lambda_1=1$ value represents always a very good option.
Figure 66. Throughput efficiency and average number of retransmissions on AWGN channels: Pure detection ($\lambda_1=0$) versus Type II ($\lambda_1=0$, $\lambda_2<\lambda_2$) Hybrid ARQ schemes.

Figure 66 shows a comparison between Pure detection and Type II ($\lambda_1=0$, $\lambda_2<\lambda_2$) Hybrid ARQs for 432-bit and 94-bit packet sizes. Besides the reference curves of Pure detection ARQs, the curves corresponding to Type II HARQs match the curves published in [57].

As expected, Type II HARQ clearly outperforms the Pure detection scheme, showing the characteristic of only requiring about one retransmission for a large extension of high BER values (more noticeable in the larger packet size), until it breaks down.
Figure 67. Throughput efficiency and average number of retransmissions on AWGN channels: Type I versus Type III Hybrid ARQ schemes (432-bit packets).

Figure 67 (432-bit packets) and Figure 68 (94-bit packets) show the same kind of comparisons but for Type I and Type III \((1 \leq \lambda_1 < t_1, \lambda_2 < t_2)\) HARQs. As in the previous case, Type I is clearly outperformed by Type III scheme.

In this latter scheme (with performance curves similar to those published in [68]) it is found that a good compromise, in terms of efficiency and residual BER, is achieved with \(\lambda_1 = 1\) and \(\lambda_2 = t_2 - 2\).
Figure 68. Throughput efficiency and residual BER on AWGN channels: Type I versus Type III Hybrid ARQ schemes (94-bit packets).

Figure 69 shows a comparison made with a Type III HARQ for 2, 4 and 6-memory multiple copies combination and using two consecutive $\lambda_2$, that is, $\lambda_2=28$ and 29 ($t_2=30$).

In each $\lambda_2$ situation, the difference in the number of retransmissions between the 2 and 4-memory cases is of some significance when the channel BER is high, increasing a little bit more when the 2 and 6-memory cases are compared.
Figure 69. Average number of retransmissions and residual BER on AWGN channels: Type III HARQ with 2, 4 and 6-memory multiple copies combination (289-bit packets).

In the example given, the retransmission curve corresponding to the 2-memory and $\lambda_2=29$ is practically equal to the 6-memory and $\lambda_2=28$ curve. This indicates that it is possible to achieve a much lower residual BER, as pointed out in the corresponding curves (from $0.8.10^{-3}$ to $0.15.10^{-3}$ for a BER$_c=0.07$), maintaining the same average number of retransmissions. If a memory saving is necessary, the 4-memory solution still presents a considerable improvement when compared with the 2-memory solution (less 2 retransmissions for $\lambda_2=28$ and BER$_c=0.07$).
6.4.2. Other coding methods with a 90% MAC frame usage

After the experiments with BCH coding just described, there is the need of getting comparisons involving the other coding methods considered, that is, the CRC and the RS codes. Accordingly, the simulation system was upgraded to incorporate those coding methods as well.

Regarding the DLC connections, the same characteristics of the previous sub-section are assumed, that is, a 12 Mbit/s physical mode and a 90% utilization of the MAC frame (1.8 ms).

A first characterization is done comparing CRC, RS and BCH codes when using Pure detection and Type I Hybrid ARQ schemes, recalling that $\lambda_1 \in \{0,1,2\}$ for the used RS code and $\lambda_1 \in \{0,1,2,3\}$ for the used BCH code (hereafter DLC-PDUs have always a $n_1=432$ bits).

The resulting curves are shown in Figure 70. These graphics show that, independently of the code used, the curves are effectively delineated by the corrective action threshold $\lambda_1$ (i.e., better efficiency is achieved with larger $\lambda_1$ values).

In addition to throughput efficiency and average number of retransmissions curves several histograms relative to the number of retransmissions per packet were also obtained. In Figure 71 histograms for the CRC, RS and BCH codes are shown for several channel BERs, when using Pure detection and Type I Hybrid ARQ schemes. These histograms confirm the influence of the corrective action threshold in the number of retransmissions, when one goes from $\lambda_1=0$ to $\lambda_1=2$. This is more evident with high values of channel BER such as BER$_e=0.005$ and BER$_e=0.007$.

Including now a Type II Hybrid ARQ together with the previous schemes it is possible to see, in Figure 72, the difference in the efficiency and number of retransmissions curves. In this case, ARQ schemes with CRC, BCH ($\lambda_1=1$) and CRC-BCH ($\lambda_2=41$) codes are compared. Figure 73 shows the corresponding histograms of the number of retransmissions.

Now histograms show a big difference in the Type II HARQ (CRC-BCH) behavior when compared with Pure detection (CRC) or Type I HARQ (BCH). Contrary to the latter schemes, which suffer a progressive increase in the number of retransmissions, $r$, in function of channel BER, in Type II HARQ $r \leq 1$ even for the highest channel BER value simulated. For low bit error rates, the Type II HARQ does not perform so well as Type I due to its inner code correction inability ($\lambda_1=0$).
Figure 70. Throughput efficiency and average number of retransmissions: Pure detection versus Type I Hybrid ARQ schemes (CRC: $\lambda_i=0$; RS: $\lambda_i=0,1$; BCH: $\lambda_i=0,1,2$).

As for the inner code effect, it is interesting to note the presence of identical values in column 0 (no retransmissions) with CRC and CRC-BCH schemes, for any BER. In fact, despite the intrinsic differences between these schemes, when a packet’s first transmission arrives with no (or undetected) errors the two schemes achieve the same performance since they use the same inner code.
Figure 71. Histograms of the number of retransmissions per packet for different values of $\lambda_1$ (CRC: $\lambda_1=0$; RS: $\lambda_1=1$; BCH: $\lambda_1=2$).

Adding now the Type III Hybrid ARQs simulation results to the previous Type II schemes it is possible to analyze the influence of the inner and outer codes in the global performance. The corresponding curve results and histograms are shown, respectively, in Figure 74 and Figure 75.
Figure 72. Throughput efficiency and average number of retransmissions: CRC-BCH ($\lambda_1=0$, $\lambda_2=41$) Type II HARQ versus CRC ($\lambda_1=0$) and BCH ($\lambda_1=1$).

Figure 74 clearly shows the influence of $\lambda_1$ and $\lambda_2$ in the curves obtained in the simulation. It is possible to observe that significantly better performance curves are achieved with the highest corrective action thresholds, in both $\lambda_1$ and $\lambda_2$. Their effects predominate, respectively, in the lower (up to $10^{-2}$) and higher (over than $2.10^{-2}$) values of channel BER.
Figure 73. Histograms of the number of retransmissions per packet for a CRC-BCH $(\lambda_1=0, \lambda_2=41)$ Type II HARQ versus CRC $(\lambda_1=0)$ and BCH $(\lambda_1=1)$.

In Figure 75 some histograms of the number of retransmissions with Type II and Type III Hybrid ARQs are shown.
Figure 74. Throughput efficiency and average number of retransmissions: Type II versus Type III Hybrid ARQ schemes with several codes.

It is important to observe that these histograms now correspond to BERc values that are substantially higher than in the previous depicted histograms (the lower right subplot now corresponds to $BER_c=0.06$). For instance, with a $BER_c=0.007$ the Pure detection and Type I Hybrid ARQ schemes already present a rather unsatisfactory performance, requiring several retransmissions per packet (see Figure 71). In the same circumstances Figure 75 shows that Type II and III HARQs only need one retransmission at most.
Figure 75. Histograms of the number of retransmissions per packet for Type II and Type III Hybrid ARQs.
6.4.3. CRC, RS and BCH coding with a 20% MAC frame usage

The execution of this set of simulations is intended to find out if relevant variations exist when using a different frame usage percentage. The radio channel model used is the same AWGN memoryless channel as before.

As said before, the following characteristics have been assumed:

- Utilization of 20% of the MAC frame (0.4 ms),
- Use of a 54 Mbit/s physical mode,
- Maximum gross rate of 10.8 Mbit/s (without any coding).

The first comparison involves several ARQ schemes from Pure detection ($\lambda_1=0$, CRC) to Type III ($\lambda_1=1$, $\lambda_2<\lambda_2$) Hybrid ARQs. The results are shown in Figure 76.

In this figure it is possible to observe that the efficiency curves are identical to the several ones shown for the 90% frame usage situation. This is due to the AWGN channel characteristic, which causes equal effects independently of the timing values involved.

As for the residual BER, it is possible to see that a scheme set with appropriate corrective action threshold values, such as BCH-BCH with $\lambda_1=1$ and $\lambda_2=41$, can have a fairly good performance up to significant BERc values.

Figure 77 shows performance curves for all the same schemes considered but this time comparing the mean and the standard deviation of the number of retransmissions.

As for the Pure detection and Type I schemes, it is possible to notice that the average number of retransmissions suffers a continuing value increase from rather low values of channel BER. As for Type II and III the average number of retransmissions rises just to value 1, until $\text{BER}_c=0.03$, and then it breaks out starting a corresponding increase.

Interesting to observe is the behavior of the standard deviation curves for Type II and III HARQ schemes. After an increase up to value 0.5 (meaning, in this particular case, that approximately half of the total number of information packets go through in the first transmission and the other half requires one retransmission) a decrease occurs just to value zero. This indicates that all packets experience a number of retransmissions identical to the average. In this case, this means that the probability of occurring exactly one retransmission, for each information packet transmitted, is equal to 1 (i.e., $P(r=1) = 1$).
Figure 76. Throughput efficiency and residual BER: several ARQ schemes when operating with 20% of the MAC frame (AWGN channel).

The histograms for this situation of a 20% MAC frame usage are shown in Figure 78 and Figure 79, respectively for Pure detection/Type I and Type II/III schemes.

In what Type II and III HARQs are concerned, the considerations relative to the retransmissions standard deviation curves (Figure 77) can be confirmed by the respective histograms shown in Figure 79.
Figure 77. Average number of retransmissions and respective standard deviation: several ARQ schemes when operating with 20% of the frame (AWGN channel).

For instance, for a BER$_c$=0.02 almost all packets require exactly one retransmission to pass through, confirming that P($r=1$)≈ 1 because $\sigma_r$≈ 0. This represents a great improvement when compared with the histograms of Pure detection or Type I schemes shown in Figure 78.

No significant differences were found between the 90% and the 20% MAC frame usage. This is justified by the time-constant error characteristics derived from the use of an AWGN channel model.
Figure 78. Histograms of the number of retransmissions per packet for Pure detection and Type I Hybrid ARQs when operating with 20% of the frame (AWGN channel).
Figure 79. Histograms of the number of retransmissions per packet for Type II and Type III HARQs when operating with 20% of the frame (AWGN channel).
6.5. Simulation results for the GE memory channel

As previously referred to, the parameters of the Gilbert-Elliot memory channel model include the state BERs (BER_{bad} and BER_{good}), the occupancy mean times (m_{good} and m_{bad}) and the state probabilities (P_{good} and P_{bad}). With all these parameters it was possible to carry out a fairly extensive set of simulations.

In relation to state BERs, a simulation strategy was adopted with two different ratios between the BER corresponding to the "bad" state (BER_{bad}) and the BER corresponding to the "good" state (BER_{good}). With this purpose in mind, the values

\[
\frac{BER_{bad}}{BER_{good}} = 10 \text{ and } 100
\]

have been chosen to simulate, respectively, a fairly small and a fairly large channel variation in terms of BER.

As for the occupancy mean times, three values were chosen for m_{bad}: 100 \mu s, 10 \mu s and 1 \mu s. Depending on the physical mode used, 12 Mbit/s or 54 Mbit/s, the value of m_{bad} will correspond to different burst errors lengths, as shown in Table 36. The severity of these burst errors depends, obviously, on the BER specified to the "bad" state (BER_{bad}).

<table>
<thead>
<tr>
<th>Mean time in the &quot;bad&quot; state (m_{bad})</th>
<th>Average burst error length</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12 Mbit/s PHY mode</td>
<td>54 Mbit/s PHY mode</td>
</tr>
<tr>
<td>100 \mu s</td>
<td>1200 bits</td>
<td>5400 bits</td>
</tr>
<tr>
<td>10 \mu s</td>
<td>120 bits</td>
<td>540 bits</td>
</tr>
<tr>
<td>1 \mu s</td>
<td>12 bits</td>
<td>54 bits</td>
</tr>
</tbody>
</table>

Regarding the state probabilities, three values were also chosen for P_{bad}: 20\%, 40\% and 60\%. The confluence of m_{bad} and P_{bad}, by using equations 9 and 10, results in the corresponding m_{good} and P_{good} values.

As previously referred to, in simulations taking place with the GE memory channel model BER_c means the weighted average BER calculated over BER_{bad} and BER_{good} (see
equation 11). Just like the AWGN channel, the simulations with the GE channel have used a BER_c specified in the range from $10^{-4}$ to $10^{-1}$.

6.5.1. 90% MAC frame usage and small variation GE channel

This section shows the results of a selected group of simulations performed with DLC connections using the 12 Mbit/s PHY mode and occupying 90% (1.8 ms) of the MAC frame capacity. The respective GE channel model is characterized by a relatively small BER_bad/BER_good ratio. In this case, this ratio is set to 10 ($BER_{bad} = 10 \times BER_{good}$).

This group of simulations, with the respective histograms and curve results, include the following conditions:

1. “Bad” state mean time: $mt_{bad} = 100\mu s$, “Bad” state probability: $P_{bad} = 60\%$
   (Retransmission histograms: Figure 80; Curve results: Figure 81).

2. “Bad” state mean time: $mt_{bad} = 10\mu s$, “Bad” state probability: $P_{bad} = 40\%$
   (Retransmission histograms: Figure 82; Curve results: Figure 83).

3. “Bad” state mean time: $mt_{bad} = 1\mu s$, “Bad” state probability: $P_{bad} = 20\%$
   (Retransmission histograms: Figure 84; Curve results: Figure 85).

Observing the curve results in Figures 81, 83 and 85 it is obvious that Type III HARQ (BCH-BCH coding) scheme performs always better in the three conditions considered. The Type II HARQ (CRC-RS coding) performance is also very good being particularly close to Type III for high values of $BER_c$ when $mt_{bad}=10\mu s$ or $1\mu s$.

As shown by the curve results and by the histograms in Figures 80, 82 and 84, when in presence of high values of $BER_c$ the smaller values of $mt_{bad}$ (1μs and 10μs) are specially adverse for the Pure detection and Type I HARQ schemes.

For the same conditions, when using Type II and III HARQ schemes the large majority of the packet transfers only requires one retransmission. Concurrently with this conclusion, for the condition $mt_{bad}=100\mu s$ it is even possible to have a small percentage of packets passing at first tentative.
Figure 80. Histograms of the number of retransmissions per packet in a GE channel with $BER_{bad}=10 \times BER_{good}$, $mt_{bad}=100\mu s$ and $P_{bad}=60\%$ (90\% frame usage).
Figure 81. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $\text{BER}_{\text{bad}}=10 \times \text{BER}_{\text{good}}$, $m_{\text{bad}}=100\mu s$ and $P_{\text{bad}}=60\%$ (90% frame usage).
Figure 82. Histograms of the number of retransmissions per packet in a GE channel with $\text{BER}_{\text{bad}} = 10 \times \text{BER}_{\text{good}}$, $\text{mt}_{\text{bad}} = 10\mu s$ and $P_{\text{bad}} = 40\%$ (90\% frame usage).
Figure 83. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $\text{BER}_{\text{bad}}=10\times\text{BER}_{\text{good}}$, $m_{\text{bad}}=10\mu s$ and $P_{\text{bad}}=40\%$ (90% frame usage).
Figure 84. Histograms of the number of retransmissions per packet in a GE channel with BER_{bad}=10\times BER_{good}, mt_{bad}=1\mu s and P_{bad}=20\% (90\% frame usage).
Figure 85. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $BER_{bad}=10\times BER_{good}$, $mt_{bad}=1\mu s$ and $P_{bad}=20\%$ (90\% frame usage).
6.5.2. 90% MAC frame usage and large variation GE channel

This section shows the results of another selected group of simulations. Now DLC connections still use the 12 Mbit/s physical mode, occupying 90% of the MAC frame capacity, but the GE channel model is characterized by a relatively large BER_{bad}/BER_{good} ratio. In this case, this ratio is set to 100 (BER_{bad} = 100 \times BER_{good}).

This group of simulations, with respective histograms and curve results, include the following conditions:

1. "Bad" state mean time: \( m_{t_{bad}} = 100 \mu s \), "Bad" state probability: \( P_{bad} = 60\% \),
   (Retransmission histograms: Figure 86; Curve results: Figure 87).

2. "Bad" state mean time: \( m_{t_{bad}} = 10 \mu s \), "Bad" state probability: \( P_{bad} = 40\% \),
   (Retransmission histograms: Figure 88; Curve results: Figure 89).

3. "Bad" state mean time: \( m_{t_{bad}} = 1 \mu s \), "Bad" state probability: \( P_{bad} = 20\% \),
   (Retransmission histograms: Figure 90; Curve results: Figure 91).

Referring to the curve results of this group of simulations, shown in Figures 87, 89 and 91, once again it is possible to observe the best performance of Type III HARQ (BCH-BCH coding) in all these conditions.

Confirming the tendency of a slight performance degradation for decreasing values of \( m_{t_{bad}} \), the results achieved with the BER_{bad}/BER_{good} = 100 ratio are better than the ones achieved with the ratio 10. As an example a comparison between the histograms in Figures 80 and 86 is described next.

Observing the bottom right subplots (BER_{c} \approx 0.05) of these histograms, one notices that:

1. When the communication channel presents a BER_{bad}/BER_{good} ratio of 10, the CRC and the BCH coding present the largest incidence of retransmissions in column 6+ while the CRC-RS and the BCH-BCH present it in column 1 (Figure 80).

2. When the communication channel presents a BER_{bad}/BER_{good} ratio of 100, all schemes show a substantial incidence increase in column 0 (Figure 86). This is due
to the number of packets passing without requiring any retransmission when the GE radio channel is in the "good" state.

Figure 86. Histograms of the number of retransmissions per packet in a GE channel with $BER_{bad} = 100 \times BER_{good}$, $mt_{bad} = 100\mu s$ and $P_{bad} = 60\%$ (90\% frame usage).
Figure 87. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with BER_{bad}=100\times BER_{good}, m_{bad}=100\mu s and P_{bad}=60\% (90\% frame usage).
Figure 88. Histograms of the number of retransmissions per packet in a GE channel with BER_{bad}=100\times BER_{good}, m_{bad}=10\mu s and P_{bad}=40\% (90\% frame usage).
Figure 89. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $\text{BER}_{\text{bad}}=100 \times \text{BER}_{\text{good}}$, $m_{\text{bad}}=10\mu$s and $P_{\text{bad}}=40\%$ (90% frame usage).
Figure 90. Histograms of the number of retransmissions per packet in a GE channel with $\text{BER}_{\text{bad}}=100\times\text{BER}_{\text{good}}$, $t_{\text{bad}}=1\mu s$ and $P_{\text{bad}}=20\%$ (90% frame usage).
Figure 91. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $BER_{bad}=100 \times BER_{good}$, $mt_{bad}=1 \mu s$ and $P_{bad}=20\%$ (90% frame usage).
6.5.3. 20% MAC frame usage and small variation GE channel

This section shows the results of a selected group of simulations where the DLC connection utilizes now a 54 Mbit/s physical mode, occupying 20% (0.4 ms) of the MAC frame capacity. The respective GE channel model is again characterized by a relatively small BER\textsubscript{bad}/BER\textsubscript{good} ratio of 10 (BER\textsubscript{bad} = 10 × BER\textsubscript{good}).

This group of simulations, with respective histograms and curve results, include the same previously used conditions, which are:

1. "Bad" state mean time: \( m_{t_{\text{bad}}} = 100 \mu s \), "Bad" state probability: \( P_{\text{bad}} = 60\% \),
   (Retransmission histograms: Figure 92; Curve results: Figure 93).

2. "Bad" state mean time: \( m_{t_{\text{bad}}} = 10 \mu s \), "Bad" state probability: \( P_{\text{bad}} = 40\% \),
   (Retransmission histograms: Figure 94; Curve results: Figure 95).

3. "Bad" state mean time: \( m_{t_{\text{bad}}} = 1 \mu s \), "Bad" state probability: \( P_{\text{bad}} = 20\% \),
   (Retransmission histograms: Figure 96; Curve results: Figure 97).

The analysis of these results shows again that the best performance is achieved with Type III HARQ (BCH-BCH coding) followed by Type II HARQ (CRC-RS coding). Pure detection scheme (CRC coding) is by far the worst of all.

When comparing the curve results with the 20% MAC frame usage (Figures 93, 95 and 97) with the corresponding ones for the 90% situation (Figures 81, 83 and 85) the differences are relatively imperceptible but the 20% situation still has a slight advantage.

The major exception comes into view when comparing the standard deviation of the number of retransmissions (\( \sigma_r \)) for the condition \( m_{t_{\text{bad}}} = 100 \mu s \) (bottom graphs of Figures 81 and 93). In this case, for high values of BER\textsubscript{c} the 20% situation presents larger \( \sigma_r \) values than the 90% MAC frame usage case.

The same difference is also visible in the histograms shown in Figures 80 and 92, specially in their bottom right subplots (BER\textsubscript{c}≈0.05). Indeed, considering only Type II/III HARQ schemes, for the 90% MAC frame usage (Figure 80) it is possible to observe some (even small) spreading in the number of retransmissions.
For the 20% MAC frame usage (Figure 92) a large incidence concentration is seen in column 1 and, at a less extent, in column 0. This is due to the fact that when the 54 Mbit/s physical mode is used a packet takes less time to be transmitted. Hence, its probability to come across an entirely "good" radio channel period is higher than when using the 12 Mbit/s physical mode.

Figure 92. Histograms of the number of retransmissions per packet in a GE channel with $\text{BER}_{\text{bad}} = 10 \times \text{BER}_{\text{good}}$, $\text{mt}_{\text{bad}} = 100\mu s$ and $\text{P}_{\text{bad}} = 60\%$ (20% frame usage).
Figure 93. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with BER_{bad}=10\times BER_{good}, mt_{bad}=100\mu s and P_{bad}=60\% (20\% frame usage).
Figure 94. Histograms of the number of retransmissions per packet in a GE channel with $\text{BER}_{\text{bad}}=10\times\text{BER}_{\text{good}}$, $m_{\text{bad}}=10\mu$s and $P_{\text{bad}}=40\%$ (20\% frame usage).
Figure 95. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $\text{BER}_{\text{bad}} = 10 \times \text{BER}_{\text{good}}$, $m_{\text{bad}} = 10\mu s$ and $P_{\text{bad}} = 40\%$ (20\% frame usage).
Figure 96. Histograms of the number of retransmissions per packet in a GE channel with $\text{BER}_{\text{bad}}=10\times\text{BER}_{\text{good}}$, $m_{\text{bad}}=1\mu$s and $P_{\text{bad}}=20\%$ (20\% frame usage).
Figure 97. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $\text{BER}_{\text{bad}}=10 \times \text{BER}_{\text{good}}$, $\text{mt}_{\text{bad}}=1\mu s$ and $P_{\text{bad}}=20\%$ (20% frame usage).
6.5.4. 20% MAC frame usage and large variation GE channel

This section shows the results of the last selected group of simulations, with a DLC connection still using a 54 Mbit/s physical mode, and 20% of the MAC frame capacity, and a GE channel model with a BER_{bad}/BER_{good} ratio equal to 100 (BER_{bad} = 100\times BER_{good}).

This group of simulations, with respective curve results and histograms, include then the following conditions:

1. “Bad” state mean time: \( m_{t_{bad}} = 100\mu s \), “Bad” state probability: \( P_{bad} = 60\% \),
   (Retransmission histograms: Figure 98; Curve results: Figure 99).

2. “Bad” state mean time: \( m_{t_{bad}} = 10\mu s \), “Bad” state probability: \( P_{bad} = 40\% \),
   (Retransmission histograms: Figure 100; Curve results: Figure 101).

3. “Bad” state mean time: \( m_{t_{bad}} = 1\mu s \), “Bad” state probability: \( P_{bad} = 20\% \),
   (Retransmission histograms: Figure 102; Curve results: Figure 103).

Once more Type III and Type II HARQ schemes present very good performances for all simulated conditions. Nevertheless, the advantage is not so big as before since the degradation experienced by the Pure detection (CRC coding) scheme is not so intense in these conditions.

An example of this fact can be seen for the condition \( m_{t_{bad}} = 10\mu s \) if one compares the Figures 101, 89 and 95. For instance, when analyzing the throughput efficiency curves of BCH-BCH and CRC coding the differences between both are respectively 0.2, 0.27 and 0.4 at \( BER_c = 10^{-2} \).

The situation described above is confirmed with the collected retransmission histograms. Taking as example the condition \( m_{t_{bad}} = 1\mu s \), the histograms shown in Figures 102, 90 and 96 reveal a sustained advantage of Type II/III HARQ schemes in opposition to the decreasing performance of Pure detection scheme.
Figure 98. Histograms of the number of retransmissions per packet in a GE channel with $\text{BER}_{\text{bad}}=100 \times \text{BER}_{\text{good}}$, $\text{m}_{\text{bad}}=100\mu s$ and $P_{\text{bad}}=60\%$ (20% frame usage).
Figure 99. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $\text{BER}_{\text{bad}} = 100 \times \text{BER}_{\text{good}}$, $m_{\text{bad}} = 100\mu s$ and $P_{\text{bad}} = 60\%$ (20\% frame usage).
Figure 100. Histograms of the number of retransmissions per packet in a GE channel with $\text{BER}_{\text{bad}}=100 \times \text{BER}_{\text{good}}$, $m_{\text{bad}}=10\mu s$ and $P_{\text{bad}}=40\%$ (20% frame usage).
Figure 101. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $BER_{bad} = 100 \times BER_{good}$, $mt_{bad} = 10\mu s$ and $P_{bad} = 40\%$ (20% frame usage).
Figure 102. Histograms of the number of retransmissions per packet in a GE channel with \( \text{BER}_{\text{bad}} = 100 \times \text{BER}_{\text{good}} \), \( m_{\text{bad}} = 1 \mu s \) and \( P_{\text{bad}} = 20\% \) (20\% frame usage).
Figure 103. Throughput efficiency and mean and standard deviation of the number of retransmissions in a GE channel with $\text{BER}_\text{bad}=100\times\text{BER}_\text{good}$, $m_{\text{bad}}=1\mu$s and $P_{\text{bad}}=20\%$ (20% frame usage).
6.6. Summary

This chapter dealt with the important tasks of system modeling, simulation program development and analysis of simulation results.

It starts with a description of the elements to be included in the system model. With this purpose in mind the main components of a typical wireless communication system have been identified and modeled. The handling of existent and proposed DLC main data units have been object of a special attention and constitute one of the core parts of the simulation program developed by the author.

After the description of the model elements, in section 6.2, the radio channel models used in the simulations have been identified and characterized. They are the Additive White Gaussian Noise memoryless channel and the Gilbert-Elliott memory channel. This latter channel model allows more parameters to be changed when compared with the AWGN channel.

In section 6.3 the simulation outline is exposed starting with considerations about the simulation models. Further on, some actual examples of the author's developed simulators, taken from the MATLAB/Simulink simulation tool, are then shown. The depicted examples include the main level of the simulation models and some of its main blocks.

In the same section the methodology used for each simulation run is explained, pointing out its interaction with parameters such as the channel BER and the number of packets to transfer. The characterization of performance metrics and of histograms of the number of retransmissions per packet is also done in this section, which ends with the subject matter of simulation analysis. The literature references, containing results against which the performance curves obtained have been compared, validating the developed simulation models, are identified here.

Two large groups of simulation results have been presented, one for the AWGN channel and the other for the GE channel, respectively, in sections 6.4 and 6.5. The illustration of the AWGN results begins with the BCH codes, and then includes the CRC and the RS codes. As for the GE channel an extensive set of results for various conditions of the radio channel have been obtained using identical coding schemes. A selection of results, including small and large channel variations in terms of BER, are then depicted.
Essentially, the comparison of the results highlights the performance differences between conventional ARQs and Hybrid ARQ schemes using the novel mechanisms proposed. For both AWGN and GE models, the results show a great advantage of Type II/III HARQs using those new techniques, making their use possible even in the presence of radio channels characterized by high BERs.

For high-speed real-time services where some moderate error occurrence is yet tolerable, such as medium quality video, the Type III Hybrid ARQ scheme is an excellent solution since it provides extra throughput efficiency within a large BER range. Moreover, even if not as powerful as CRC to detect errors, it can maintain a considerable low error rate even for high channel BER values for which a pure detection ARQ scheme is no longer feasible.
Chapter 7

Conclusions

7.1. Main achievements

When considering possible methods to introduce error protection mechanisms in high performance wireless mobile communications it is obvious that none of the two usual ARQ schemes (Pure detection and Type I Hybrid) is appropriate. The combined effects of channel fading and multipath signal propagation are such that these schemes require a considerable number of retransmissions, almost proportional to the channel bit error rate, making it difficult to timely combat the errors generated.

Type II/III HARQ schemes are very efficient schemes but for communications under adverse conditions there is no mechanism to guarantee their normal operation, which makes it impracticable.

Hence, one of the central line actions taken in this work has been finding techniques that enable Type II/III HARQ schemes to operate almost normally, even in considerably unfavorable circumstances. In order to guarantee their normal operation in wireless LAN communications, it has been proposed to convey the very important packet control information (i.e., the Sequence Numbers and the Info/Parity indication) using extra protected methods, but requiring almost no modifications to current specifications.
As for the Sequence Number information, usually located in the packet header, it has been proposed that before actual packet transmissions a "forward direction" SN packet list should be created and conveyed by the most reliable physical modes already defined for the 5 GHz WLANs.

In HIPERLAN/2 the implementation of this mechanism is not excessively complex since it may utilize one Short Transport Channel type, from the set reserved for future use. The rules for the composition of "forward direction" SN packet lists can also be identical to current ARQ acknowledgement strategy using bitmap blocks. This further minimizes the implementation differences to HL/2.

As for the Info/Parity indication, it has been proposed to convey it directly in the packet header, together with its necessary protection. In fact, according to the new defined strategy for the safe delivery of packet control information, Info/Parity indication and associated protection can now occupy the entire DLC User-PDU field reserved for the SN.

Using these two proposed protection methods, the packet control information protection is significantly increased making feasible the use of Type II/III HARQ schemes with their recognized advantages. This improvement is one of the relevant achievements of this work.

To confirm and characterize the effective performance gains between the different ARQ schemes a relatively large system simulation model was developed together with other computational tools. A substantial number of simulations has been performed using different parameterization choices for radio channel conditions, including nominal bit rates and MAC frame usage.

The results obtained show, invariably, that Type II/III HARQ schemes always achieve an equal or better performance than other ARQ schemes. This is especially obvious when the radio channel is characterized by a high BER. The results collected constitute another significant contribution of the work presented in this thesis.

Another important result is the confirmation that a Type III HARQ scheme associated with a concatenated coding format (such as inner BCH – outer BCH) presents extremely favorable low delays for a large channel BER range, making it a very efficient method for delay-constrained audio/video services.

As a final conclusion, it should be specially emphasized that the implementation of the proposed SN protection mechanism is not only important for Type II/III HARQ schemes but
also for normal ARQs, if a packet delay-aware scheme is to be implemented. In fact, a
differentiated treatment for errored copies of the same packet can only be done if a reliable
conveying method, as the one proposed, allows a correct knowledge of corresponding
Sequence Numbers.

7.2. Further work

A great challenge is now put in the global convergence of the two wireless LAN main
standards, IEEE 802.11x and HIPERLAN/2. The first steps are being taken in the radio
regulatory convergence, which will allow the operation of HL/2 and 802.11a radio devices
irrespective of the geographical region.

The main regulatory convergence step to allow HIPERLAN/2 use in North America is
concerned with less band availability. This implies that HL/2 systems have to limit themselves
to operate in the allocated U-NII frequency bands.

The main regulatory convergence steps to allow 802.11a in Europe are:

- Implementation of the Dynamic Frequency Selection (DFS) mechanism,
- Implementation of the Transmit Power Control (TPC) mechanism,
- Support of the upper part of HIPERLAN bands (5470-5725 MHz), not just the
  lower 200 MHz portion (5150-5350 MHz).

The above actions will permit the operation of the systems in both regulatory domains
but do not avoid the harmful radio interference if operated in the same coverage area. To
enable a simultaneous operation it is necessary a coexistence mechanism between both
systems.

A straightforward coexistence mechanism may force the systems to operate in different
channels using a DFS-like strategy. But coexistence can be extended if operation in the same
channel is permitted. This may be set by using a standardized mechanism enabling devices of
both types to efficiently share the same channel.
In the case of an extended coexistence mechanism, any wireless terminal can talk to any Access Point that is multi-mode using only one RF block. This means that dual protocol stack terminals, as the one shown in Figure 104, can have an enhanced use besides alternating the protocol stacks when roaming between different wireless network types. In this case, distinct kinds of services may use the two protocol stacks simultaneously, thus representing an enormous flexibility of use for wireless users. Coexistence mechanisms will also contribute to the faster development of terminal’s integration.

![Diagram of IEEE 1394 and TCP/IP layers](image)

**Figure 104. A dual stack 5 GHz wireless LAN terminal.**

Beyond coexistence mechanisms, there is another convergence step for 802.11a and HL/2 standards. This consists in the interworking possibility, which will enable terminals of one standard to exchange data with Access Points of another standard.

Nevertheless, the ultimate goal will be the existence of a single global standard for the 5 GHz wireless LANs. In this case any wireless terminal can communicate to any AP and to any terminal. This includes the direct data exchange even when operating on ad hoc configurations.

Currently there are two trends to achieve that expected single global standard. One consists in the establishment of a partnership project, which will conduct to the global standard. The corresponding roadmap is depicted in Figure 105.
Figure 105. 5 GHz WLANs standardization roadmap (option 1).

The other trend consists in making additions to different standards after the work of joint study groups. This would lead to two identical standards allowing the final transition to the single global standard in a seamless way. The corresponding roadmap is depicted in Figure 106.

In relation to the application of the proposed error control mechanisms, the convergence of the two standards puts extra challenges in their adaptation. The extension of this adaptation will largely depend on the achieved single global standard and its “distance” from actual HIPERLAN/2 specification.

On one side, this signifies a very close following of international technical activities, not just in one but also in diverse (and some still emerging) fora dealing with the increasingly important 5 GHz WLAN theme.

On the other side, the use of the proposed error control mechanisms for such single global standard will be an extremely valuable contribution. An even broader application range is thus foreseen.
Concluding, the possible areas for further research work include:

- The full adaptation of the proposed mechanisms to high-speed wireless systems other than HIPERLAN/2 and the development of respective simulation models,
- The simulation of the proposed mechanisms under different traffic mixes,
- The inclusion of radio channel models other than AWGN and GE models in the simulation system,
- Running simulations with broader ranges in what concerns the radio transmission conditions.
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