# New High-Rate Wireless LAN Standards

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**ABSTRACT** After the IEEE 802.11 standardization group established the first wireless LAN standard two years ago, several efforts were started to increase data rates and also to use other bands. This article describes the new wireless LAN standards developed by IEEE 802.11, ETSI BRAN, and MMAC. The new standards are targeting data rates up to 11 Mb/s in the 2.4 GHz band and up to 54 Mb/s in the 5 GHz band.

Since the beginning of the 1990s, wireless local area networks (WLANs) for the 900 MHz, 2, 4, and 5 GHz industrial, scientific, and medical (ISM) bands have been available based on a range of proprietary products. In June 1997, the Institute of Electrical and Electronics Engineers approved an international interoperability standard (IEEE 802.11) [1]. The standard specifies both medium access control (MAC) procedures and three different physical layers (PHY). There are two radio-based PHYs using the 2.4 GHz band. The third PHY uses infrared light. All PHYs support a data rate of 1 Mb/s and optionally 2 Mb/s. The 2.4 GHz frequency band is available for license exempt use in Europe, the United States, and Japan. Table 1 lists the available frequency bands and the restrictions to devices which use this band for communications.

User demand for higher bit rates and international availability of the 2.4 GHz band has spurred the development of a higher-speed extension to the 802.11 standard. In July 1998 a proposal was selected for standardization, which describes a PHY providing a basic rate of 11 Mb/s and a fallback rate of 5.5 Mb/s. This PHY can be seen as a fourth mode, to be used in conjunction with the already standardized MAC. Practical products, however, are expected to support both the high-speed 11 and 5.5 Mb/s rate modes as well as the 1 and 2 Mb/s modes.

A second IEEE 802.11 working group has moved on to standardize yet another PHY option, which offers higher bit rates in the 5.2 GHz band. This development was motivated by the adoption, in January 1997, by the U.S. Federal Communications Commission of an amendment to Part 15 of its rules. The amendment made available 300 MHz of spectrum in the 5.2 GHz band, intended for use by a new category of unlicensed equipment called *unlicensed national information infrastructure* (UNII) devices. Table 1 lists the frequency bands and corresponding power restrictions.

In July 1998, the IEEE 802.11 standardization group decided to select orthogonal frequency-division multiplexing (OFDM) [2] as the basis for their new 5 GHz standard, targeting a range of data rates from 6 up to 54 Mb/s. This new standard is the first to use OFDM in packet-based communications; the use of OFDM was previously limited to continuous transmission systems like digital audio broadcasting (DAB) and digital video broadcasting (DVB). Following the IEEE 802.11 decision, High-Performance LAN (HIPERLAN) type 2 and Multimedia Mobile Access Communication (MMAC) also adopted OFDM for their PHY standards. The three bodies have worked in close cooperation since then to ensure that differences between the various standards are kept to a minimum, thereby enabling the manufacturing of equipment that can be used worldwide.

Like the IEEE 802.11 standard, the European Telecommunications Standards Institute (ETSI) HIPERLAN type 1 standard [3] specifies both MAC and PHY. However, unlike IEEE 802.11, no HIPERLAN type 1 compliant products are available in the marketplace. A newly formed ETSI working group, Broadband Radio Access Networks (BRAN), is now working on the following extensions to the HIPERLAN standard: HIPERLAN type 2, a wireless indoor LAN with quality of service (QoS) provision; HiperLink, a wireless indoor backbone; and HiperAccess, an outdoor, fixed wireless network providing access to a wired infrastructure. There are two main differences between HIPERLAN types 1 and 2. First, HIPERLAN type 1 has a distributed MAC without QoS provisions, while HIPERLAN type 2 does have these provisions using a centralized scheduled MAC. Second, the PHY of HIPERLAN type 1 is based on single-carrier Gaussian minimum shift keying (GMSK), while HIPERLAN type 2 uses OFDM.

In Japan, the Ministry of Post and Telecommunications started a standardization effort of MMAC systems which includes ultra-high-speed indoor WLANs supporting large-volume data transmission at speeds up to 156 Mb/s using frequencies in the 30–300 GHz band and high-speed wireless access at 25–30 Mb/s in the super-high frequency (SHF) band (3–60 GHz).

This article can be divided in three parts. The first part describes the extension of the existing IEEE 802.11 standard to higher bit rates in the 2.4 GHz band. The second part describes a new OFDM-based standard intended for the 5 GHz band, providing bit rates up to 54 Mb/s. The third part describes the PHY and MAC of a prototype wireless LAN developed in the Magic Wireless Access Network Demonstrator (WAND) project, which can be seen as a precursor to HIPERLAN type 2.

The focus of this article is on the PHY. In the IEEE 802.11 standard, the MAC layer for the higher data rates will remain the same as for the currently supported 1 and 2 Mb/s rates. A description of this MAC can be found in [1].

## NEW HIGH-RATE IEEE 802.11 EXTENSION FOR THE 2.4 GHZ BAND

In July 1998 the IEEE 802.11b working group adopted complementary code keying (CCK) as the basis for the high-rate PHY extension to deliver data rates up to 11 Mb/s [4]. This high rate extension was adopted, in part, because it provides an easy path for interoperability with the existing 1 and 2 Mb/s networks by maintaining the same bandwidth and utilizing the same preamble and header. The new extension now provides multirate operation at 1, 2, 5.5, and 11 Mb/s.

## 802.11 DSSS 1-and-2 Mb/s Overview

This section provides a brief review of the 1 and 2 Mb/s direct-sequence spread-spectrum (DSSS) signal structure. This review is important because it shows how the 5.5 and 11 Mb/s CCK signaling scheme is a natural extension of the legacy DSSS system. This harmony provides an easy extension from the lower data rates to the higher ones. Also, interoperability is naturally provided.

The packet structure is shown in Fig. 1. The complete packet (PPDU) comprises three segments. The first segment is the preamble, which is used for signal detection and synchronization. The second segment is the header, which contains data rate and packet length information. The third segment (MPDU) contains the information bits. The preamble and header are transmitted at 1 Mb/s, while the data portion is sent at one of four possible rates.

| Region | Frequency Range | Maximum Output Power |
|---|---|---|
| North America | 2.400–2.4835 GHz | 1000 mW |
| Europe | 2.400–2.4835 GHz | 100 mW (EIRP[1]) |
| Japan | 2.471–2.497 GHz | 10 mW |
| United States (UNII lower band) | 5.150–5.250 GHz | Minimum of 50 mW or 4 dBm + $10\log_{10} B^2$ |
| United States (UNII middle band) | 5.250–5.350 GHz | Minimum of 250 mW or 11 dBm + $10\log_{10} B$ |
| United States (UNII upper band) | 5.725–5.825 GHz | Minimum of 1000 mW or 17 dBm + $10\log_{10} B$ |

Notes: [1] EIRP: Effective isotropic radiated power.
[2] $B$: –26 dB emission bandwidth in MHz.

**Table 1.** *2.4 and 5 GHz bands.*

The preamble is formed from a SYNC field and a sync field delimiter (SFD). The SYNC field is generated using 128 scrambled ones. The SYNC field is used for clear channel assessment, signal detection, timing acquisition, frequency acquisition, multipath estimation, and descrambler synchronization.

The 1 and 2 Mb/s DSSS signal is created using a fixed spreading sequence (signature) formed from an 11 chips Barker code. This contrasts with military systems, which typically use long pseudo-random spreading sequences. For 1 Mb/s, the fixed spreading sequence is used to spread a 1 Mb/s binary phase shift keying (BPSK) signal, while for 2 Mb/s the same spreading sequence is quaternary PSK (QPSK) modulated. For all data rates of 1–11 Mb/s, the chip rate is 11 Mchips/s.

### A Description of CCK

Complementary codes were originally conceived by M. J. E. Golay for infrared multislit spectrometry [5]. However, their properties also make them useful in radar applications and more recently for discrete multitone communications and OFDM [6]. The original publication defines a complementary series as a pair of equally long sequences composed of two types of elements which have the property that the number of pairs of like elements with any given separation in one series is equal to the number of pairs of unlike elements with the same separation in the other series. Another way to define a pair of complementary codes is to say that the sum of their aperiodic autocorrelation functions is zero for all delays except zero delay.

The CCK codes voted in at the July 1998 IEEE 802.11 conference are defined in [6]. More background information on these codes can be found in [7]. The following equation represents the eight complex chip values for the CCK code set, with the phase variables being QPSK phases.

$$c=\left\{e^{j(\varphi_1+\varphi_2+\varphi_3+\varphi_4)}, e^{j(\varphi_1+\varphi_3+\varphi_4)}, e^{j(\varphi_1+\varphi_2\varphi_4)}, -e^{j(\varphi_1+\varphi_4)}, e^{j(\varphi_1+\varphi_2+\varphi_3)}, e^{j(\varphi_1+\varphi_3)}, -e^{j(\varphi_1+\varphi_2)}, e^{j(\varphi_1)}\right\} \quad (1)$$

Basically, the three phases $\varphi_2$, $\varphi_3$, and $\varphi_4$ define 64 different codes of 8 chips, with $\varphi_1$ giving an extra phase rotation to the entire code word. Actually, the latter phase is differentially encoded across successive codewords, equivalent to 1 and 2 Mb/s DSSS differential phase encoding. This feature allows the receiver to use differential phase decoding, eliminating a carrier-tracking phase-locked loop (PLL) if desired. Each of the four phases $\varphi_1$- $\varphi_4$ represents 2 bits of information, so a total of 8 bits is encoded per 8-chip CCK code word.

At 5.5 Mb/s, the processing is similar: 4 information bits are consumed per 8-chip CCK codeword transmission. The codeword rate is still 1.375 MHz, since the chip rate is 11 Mchips/s. Two bits select one of four CCK subcodes. The other 2 information bits quadriphase modulate (rotate) the whole codeword. The four CCK subcodes are contained in the larger 64-subcode set of 11 Mb/s. At the receiver, the CCK codes can be decoded using a modified fast Walsh transform as described in [8].

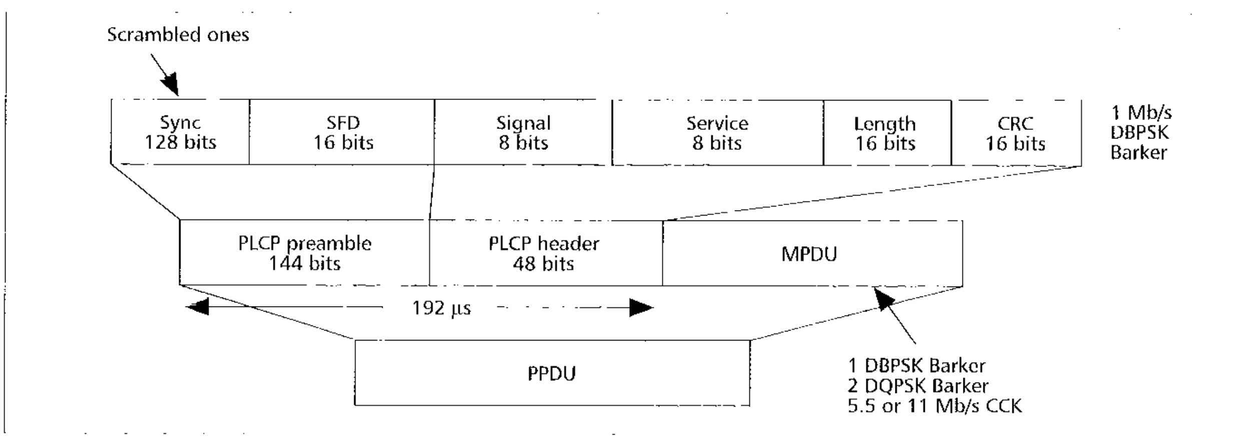


**Figure 1.** *The packet structure used for 802.11 DSSS 1 and 2 Mb/s with the extension to 5.5 and 11 Mb/s shown.*

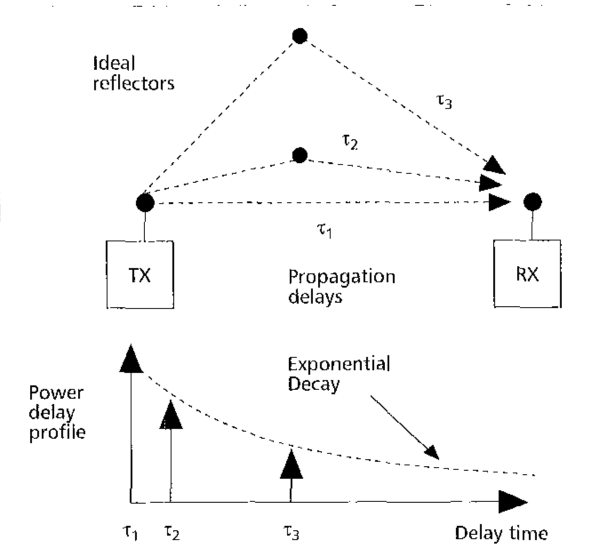


**Figure 2.** *Exponentially decayed power delay profile (PDF)*

### The Indoor WLAN Channel Model

Before examining some receiver architectures, it is important to describe the types of multipath impairments the receiver must combat. Multipath is the dominant impairment for the indoor wireless signal. The other is thermal noise, which is established predominantly by the low-noise amplifier (LNA) in the receiver frontend.

Multipath in indoor environments is characterized by Rayleigh fading paths with an exponentially decaying power delay profile. The power delay profile measures the mean signal power relative to its dispersion across time. An example power delay profile is drawn in Fig. 2. The mean power level establishes the variance of the corresponding Rayleigh components. The chief feature one should note about exponentially-decayed multipath is that on-average the strongest paths arrive earliest in time. If weaker paths do precede the channel impulse response peak on a particular stochastic realization, on average they are few relative to the number of components which follow the impulse response peak.

The root mean squared (RMS) delay spread of multipath channels can range from 20–50 ns for small office/home office (SOHO) environments to 50–100 ns for large office buildings and 100–200 ns for factory environments [9]. For an exponentially decaying power delay profile, the RMS delay spread is equal to the exponential decay constant.

### Implementation Architectures

This section provides some implementation details. It was important for 802.11 to define a high-rate signaling scheme which can be implemented with relatively low complexity, without compromising performance too much. A receiver architecture which is relatively simple to implement is the conventional RAKE receiver, which correlates with all possible codes and with the estimated channel response, and then picks the code that gives the largest correlation output. The RAKE architecture performs well at low signal-to-noise ratios (SNRs) and moderate delay spread values, but tends to break down at high levels of multipath delay spread. For 1000-byte packets and a 10 percent packet error ratio, a RAKE receiver with 6 taps can tolerate a delay spread of about 60 ns at 11 Mb/s and about 200 ns at 5.5 Mb/s.

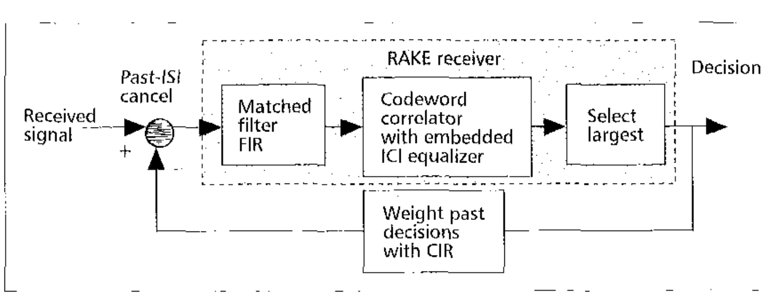


**Figure 3.** *A RAKE receiver enhanced with both ISI and ICI equalization.*

In order to deal with large delay spreads, some form of equalization has to be used. An example of a CCK equalizer is shown in Fig. 3. It consists of a modified RAKE receiver with a feedback path which subtracts intersymbol interference (ISI) components, based on an estimate of the previous symbol. After this cancellation, the signal is correlated with an estimate of the channel response by a matched filter and then correlated with all possible CCK codes. In order to correct for intracodeword interference (ICI) — which is also caused by multipath — a correction factor is subtracted from each correlation output. The correction factors can be precomputed during the training after the channel impulse response (CIR) has been estimated. This receiver structure enhances the delay spread robustness of the 11 Mb/s mode to more than 200 ns, which means it can be used in almost any indoor environment, including large factory halls.

## OFDM for the New 5 GHz Wireless LAN Standards

The basic principle of OFDM is to split a high-rate data stream into a number of lower-rate streams which are transmitted simultaneously over a number of subcarriers. Since the symbol duration increases for lower-rate parallel subcarriers, the relative amount of time dispersion caused by multipath delay spread is decreased. ISI is eliminated almost completely by introducing a guard time in every OFDM symbol. In the guard time, the OFDM symbol is cyclically extended to avoid inter carrier interference. Figure 4 shows an example of four subcarriers from one OFDM symbol. In practice, the most efficient way to generate the sum of a large number of subcarriers is by using inverse fast Fourier transform (IFFT). At the receiver side, FFT can be used to demodulate all subcarriers. It can be seen in Fig. 4 that all subcarriers differ by an integer number of cycles within the FFT integration time, which ensures orthogonality between the different subcarriers. This orthogonality is maintained in the presence of multipath delay spread, as illustrated by Fig. 4. Because of multipath, the receiver sees a summation of time-shifted replicas of each OFDM symbol. As long as the delay spread is smaller than the guard time, there is no ISI or intercarrier interference within the FFT interval of an OFDM symbol. The only remaining effect of multipath is the random phase and amplitude of each subcarrier, which has to be estimated in order to do coherent detection. In order to deal with weak subcarriers in deep fades, forward error correction is applied across the subcarriers.

### OFDM Parameters

Table 2 lists the main parameters of the new OFDM standard. A key parameter which largely determined the choice of the other parameters is the guard interval of 800 ns. This guard interval provides robustness to RMS delay spreads up

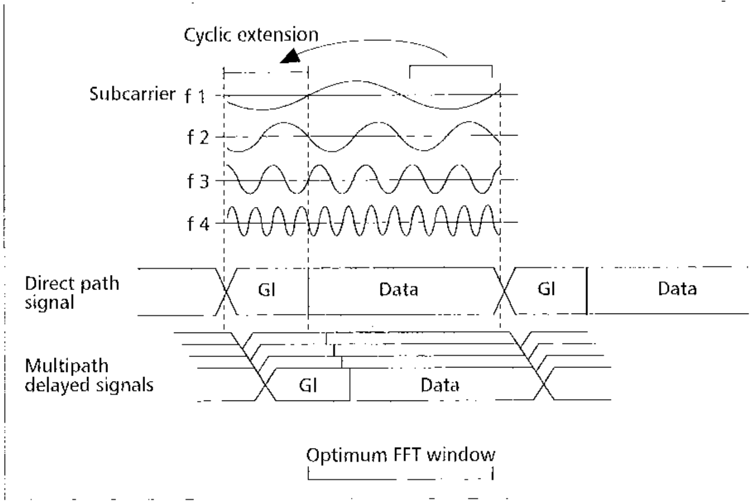


**Figure 4.** *An OFDM symbol with cyclic extension.*

to several hundreds of nanoseconds, depending on the coding rate and modulation used. In practice, this means that the modulation is robust enough to be used in any indoor environment, including large factory buildings. It can also be used in outdoor environments, although directional antennas may be needed in this case to reduce the delay spread to an acceptable amount and increase the range.

In order to limit the relative amount of power and time spent on the guard time to 1 dB, the symbol duration was chosen to be 4 μs. This also determined the subcarrier spacing of 312.5 kHz, which is the inverse of the symbol duration minus the guard time. By using 48 data subcarriers, uncoded data rates of 12–72 Mb/s can be achieved by using variable modulation types from BPSK to 64-quadrature amplitude modulation (QAM). In addition to the 48 data subcarriers, each OFDM symbol contains an additional four pilot subcarriers, which can be used to track the residual carrier frequency offset that remains after an initial frequency correction during the training phase of the packet.

In order to correct for subcarriers in deep fades, forward error correction is used across the subcarriers with variable coding rates, giving coded data rates from 6–54 Mb/s. Convolutional coding is used with the industry standard rate 1/2, constraint length 7 code with generator polynomials (133,171). Higher coding rates of 2/3 and 3/4 are obtained by puncturing the rate 1/2 code.

## Channelization

For the 200 MHz wide spectrum in the lower and middle UNII bands, eight OFDM channels are available with a channel spacing of 20 MHz. The outermost channels are spaced 30 MHz from the band edges in order to meet the stringent FCC restricted band spectral density requirements. The FCC also defined an upper UNII band from 5.725 to 5.825 GHz, which carries another four OFDM channels. For this upper band, the guard spacing from the band edges is only 20 MHz, since the out-of-band spectral requirements for the upper band are less severe than those of the lower and middle UNII bands. In Europe the same spectrum as the lower and middle UNII band is available, plus an extra band from 5.470–5.725 GHz. In Japan, it is expected that a 100 MHz wide band from 5.15–5.25 GHz will become available in mid-2000. This band will contain four OFDM channels with 20 MHz guard spacings from both band edges.

| | |
|---|---|
| Data rate | 6, 9, 12, 18, 24, 36, 48, |
| | 54 Mb/s |
| Modulation | BPSK, QPSK, 16-QAM, |
| | 64-QAM |
| Coding rate | 1/2, 2/3, 3/4 |
| Number of subcarriers | 52 |
| Number of pilots | 4 |
| OFDM symbol duration | 4 μs |
| Guard interval | 800 ns |
| Subcarrier spacing | 312.5 kHz |
| –3 dB bandwidth | 16.56 MHz |
| Channel spacing | 20 MHz |

**Table 2.** *Main parameters of the OFDM standard.*

## OFDM Signal Processing

The general block diagram of the baseband processing of an OFDM transceiver is shown in Fig. 5. In the transmitter path, binary input data is encoded by a standard rate 1/2 convolutional encoder. The rate may be increased to 2/3 or 3/4 by puncturing the coded output bits. After interleaving, the binary values are converted into QAM values. To facilitate coherent reception, four pilot values are added to each 48 data values, so a total of 52 QAM values/OFDM symbol is reached, which are modulated onto 52 subcarriers by applying IFFT. To make the system robust to multipath propagation, a cyclic prefix is added. Furthermore, windowing is applied to get a narrower output spectrum. After this step the digital output signals can be converted to analog signals, which are then upconverted to the 5 GHz band, amplified, and transmitted through an antenna.

The OFDM receiver basically performs the reverse operations of the transmitter, together with additional training tasks. First, the receiver has to estimate frequency offset and symbol timing, using special training symbols in the preamble. Then it can do an FFT for every symbol to recover the 52 QAM values of all subcarriers. The training symbols and pilot subcarriers are used to correct for the channel response as well as remaining phase drift. The QAM values are then demapped into binary values, after which a Viterbi decoder can decode the information bits.

Figure 6 shows the time-frequency structure of an OFDM packet, where all known training values are marked gray. It illustrates how the packet starts with 10 short training symbols, using only 12 subcarriers, followed by a long training symbol and data symbols, with each data symbol containing four known pilot subcarriers used for estimating the reference phase. The preamble, which is contained in the first 16 μs of each packet, is essential to perform start-of-packet detection, automatic gain control, symbol timing, frequency estimation, and channel estimation. All of these training tasks have to be performed before the actual data bits can be successfully decoded. More detailed information on OFDM signal processing as well as performance results can be found in [10].

## Differences between IEEE, ETSI, and MMAC

The main differences between IEEE 802.11 and HIPERLAN type 2 — which is standardized by ETSI BRAN — are in the MAC. IEEE 802.11 uses a distributed MAC based on carrier sense multiple access with collision avoidance (CSMA/CA), while HIPERLAN type 2 uses a centralized and scheduled MAC based on wireless ATM. MMAC supports both of these

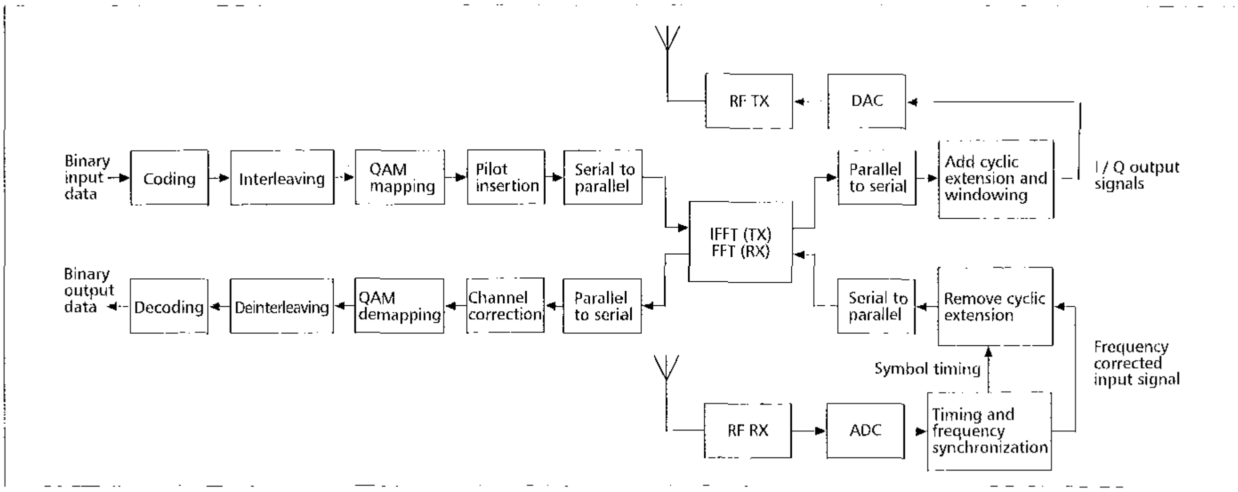


**Figure 5.** *A block diagram of an OFDM transceiver.*

MACs. As far as the PHY is concerned, there are only a few minor differences:

- HIPERLAN uses extra puncturing to accommodate the tail bits in order to keep an integer number of OFDM symbols in 54-byte packets [11].
- In the case of 16-QAM, HIPERLAN uses rate 9/16 instead of rate 1/2 — giving a bit rate of 27 instead of 24 Mb/s — in order to get an integer number of OFDM symbols for packets of 54 bytes. The rate 9/16 is made by puncturing 2 out of every 18 coded bits.
- HIPERLAN uses different training sequences. The long training symbol is the same as for IEEE 802.11, but the preceding sequence of short training symbols is different. A downlink transmission starts with 10 short symbols as in IEEE 802.11, but the first five symbols are different in order to detect the start of the downlink frame. Uplink packets may use five or ten identical short symbols, with the last short symbol being inverted.

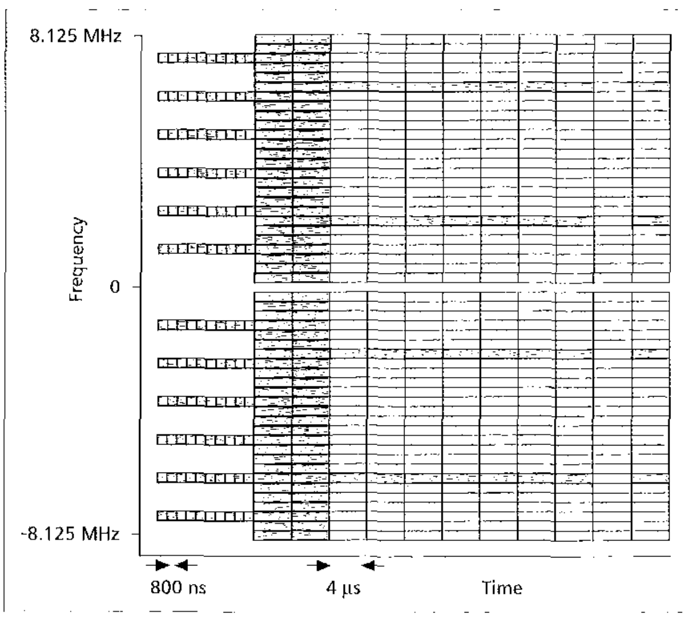


**Figure 6.** *The time-frequency structure of an OFDM packet. Darker subcarriers contain known training values.*

## Magic WAND

The Magic WAND project was part of the European Advanced Communications Technologies and Services (ACTS) program [12]. The Magic WAND consortium members implemented a prototype wireless ATM network based on OFDM modulation. This prototype had a large impact on the current standardization activities in the 5 GHz band. First, by employing OFDM-based modems, Magic WAND helped gain acceptance for OFDM as a viable modulation type for high-rate wireless communications. Second, the wireless ATM-based approach of Magic WAND forms the basis for the current standardization of the HIPERLAN type 2 data link layer.

### The Magic WAND Physical Layer

The WAND modulation scheme is described in [12]. It is based on 16 subcarriers, each with 8-PSK modulation. A special coding scheme is employed, which provides both error control and peak power control [6]. These codes, known as *complementary codes*, reduce the peak power of the transmit signal to just four times the average power. Interestingly, the length 8 complementary codes used in the 2.4 GHz CCK standard are a subset of the 8-PSK codes used in WAND. The code set has a minimum distance of four symbols, which means that three out of eight values may be erased without causing errors. There are two length 8 code words in each OFDM symbol, so it is possible for the receiver to erase up to six of the 16 subcarriers if these are subject to fading. The number of 16 subcarriers was chosen to facilitate implementation, providing a delay spread tolerance of about 50 ns. While this is sufficient for most office buildings and the WAND trial site, a real product would require more delay spread robustness to also cover large office buildings and factory halls.

The OFDM symbol period is 1.2 μs, which includes a guard time of 400 ns. There are 16 subcarriers, which are 8-PSK modulated. At a symbol rate of 13.3 Msymbols/s, this gives a raw bit rate of 40 Mb/s. The rate 1/2 complementary coding reduces the data rate to 20 Mb/s. The subcarrier spacing is 1.25 MHz, which gives a total (3 dB) bandwidth of 20 MHz. The PHY payload holds an odd number of half-slots. Each half-slot consists of 27 bytes. This number was chosen so that a full slot of 54 bytes can hold an ATM cell (which is 52 bytes long), and is also a multiple of 3 bytes, which is imposed by the PHY's modulation scheme.

To support packet-based communication effectively, each data unit must be transferred independent of other data units. The implication is that a PHY data unit (a transmission burst) must be self-contained. All overheads for channel estimation, automatic gain control, timing recovery, and so on must be included in every burst. The packet preamble is 8.4 μs in duration, and consists of one OFDM symbol repeated seven times. This preamble is used for frame detection, automatic gain control, frequency estimation, timing, and channel estimation.

Figure 7 shows a prototype Magic WAND 5 GHz modem demonstrating wireless video playback and Web browsing applications at the Demo '98 exhibition in Berlin, October 1998.

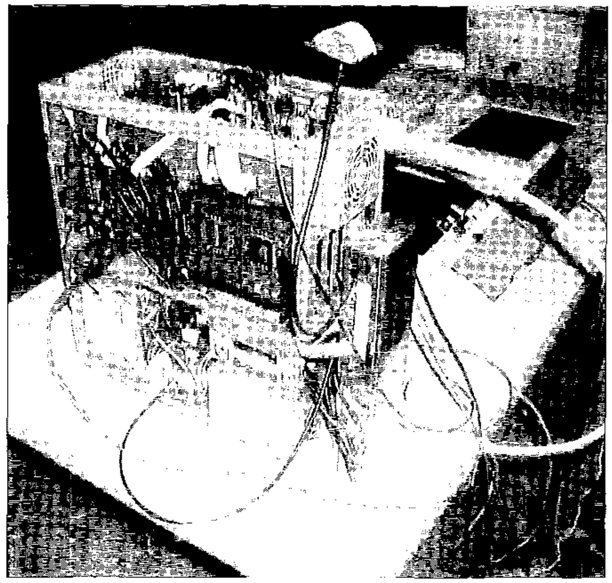

**Figure 7.** *The Magic WAND prototype 5 GHz modem.*

### THE MAGIC WAND MEDIUM ACCESS CONTROL LAYER

The MAC and data link control (DLC) layers of the WAND system have been combined in one layer, bearing the name Mobile Access Scheme Based on Contention and Reservation for ATM (MASCARA). The underlying concept is based on the following set of ideas and requirements, elaborated on in subsequent paragraphs.

- QoS-aware, reservation-based demand-assigned protocol
- Multiple virtual connections per terminal
- Power efficiency
- Cell transfer service for optimal interworking with ATM
- Amortization of PHY overhead over multiple ATM cells
- Contention-mode request and control channel
- Automatic repeat request (ARQ)-based cell loss recovery

ATM is designed to offer service to wireline users with guaranteed QoS. To extend ATM service to mobile terminals, the wireless access network needs to be QoS-aware as well. A centralized algorithm allotting transmission time to users on the basis of their explicit demands seems to be an obvious way to provide QoS and isolation between users' traffic streams. We note that the disadvantage over contention-based algorithms as used in wireless LANs and wireless private branch exchanges (PBXs) is that they do not inherently support multicellular operation. To function correctly, they require a cellular frequency reuse topology and perfect separation between radio cells with identical frequencies. As usual for wireless LANs, time-division duplex between uplink and downlink is chosen, primarily to support traffic asymmetry.

Mobile terminals draw power from batteries, and to extend battery life the protocols need to be energy aware. A frame-based MAC, in which the access point notifies all associated terminals about their expected transmissions and receptions in the entire frame, helps to conserve power: terminals switch on their radios only when necessary. From the energy perspective, the frame duration should be made as long as possible. QoS considerations, on the other hand, put a bound on the maximal frame length. For this scheme to work, a frame structure by itself is insufficient. A common time base among terminals and access point is required as well. For practical reasons the granularity of time must be bounded. The unit of time in MASCARA is a time slot, and all packet transmissions commence on a time slot boundary.

To provide seamless interworking with the ATM backbone and transparency to the user, packets must carry ATM cells. It makes sense to choose the slot duration equal to a cell's transmission time. The same length of time is imposed on the packet header (radio preamble and MAC header) as well. In the WAND system, the first half of the overhead slot is used for the preamble, the other for the MAC header.

If each packet were to contain just one cell, the protocol efficiency would be merely 50 percent. To increase efficiency, a longer packet size can be adopted. On the other hand, QoS-driven restrictions on cellization delay put an upper bound on packet length. In the case of 64 kb/s speech traffic, for instance, cellization delay is 6 ms/cell, which restricts the packet length to one or two cells. The logical decision is to allow packets of variable length, depending on the connection's delay requirements, with a payload of an integer number of cells.

Demand-assigned algorithms assign time slots to terminals, based on terminal demand. Uplink packets contain fields in which a terminal can put its request. If a terminal cannot piggyback its request because no time slots were assigned to it (a deadlock situation), or because it cannot afford to wait for the next packet, the terminal can transmit its request in an unreserved time slot. A contention period is scheduled at the end of every frame. Contention slots can be used for incidental control packets as well.

Adverse radio propagation conditions affect the cell loss ratio (CLR) QoS. By its nature, a radio network cannot provide the same QoS consistently. To sustain a negotiated CLR QoS as long as possible, the DLC layer adds ARQ capability to the system. ARQ can help retain the agreed-on CLR, at the cost of an increase in delay and data overhead.

Figure 8 depicts an example frame. Two mobile terminals (MTs) and one access point (AP) are engaged in the exchange of packets. For instructive purposes, the frame duration is shorter than typically encountered in practice. The AP initiates every frame by broadcasting a frame header (FH) containing the slot map to all associated MTs. The FH has a long preamble, allowing MTs to synchronize to the AP. Subsequently, the AP sends its downlink data, one packet in this example. The channel remains idle for one slot to allow the AP to turn around its radio from transmitting to receiving. Then the MTs are allowed to transmit their packets. After the uplink period, a contention period is scheduled, which in this example is used by both terminals. Terminal 1 is transmitting two request packets, and terminal 2 is transmitting a two-slot control packet. In the example two packets collide, resulting in the loss of the control packet and one of the request packets. The second request packet is transmitted successfully in the third slot. After the contention period and before the next frame, an idle slot is inserted to allow the MT radios to turn around.

The second important measure of QoS, besides delay and

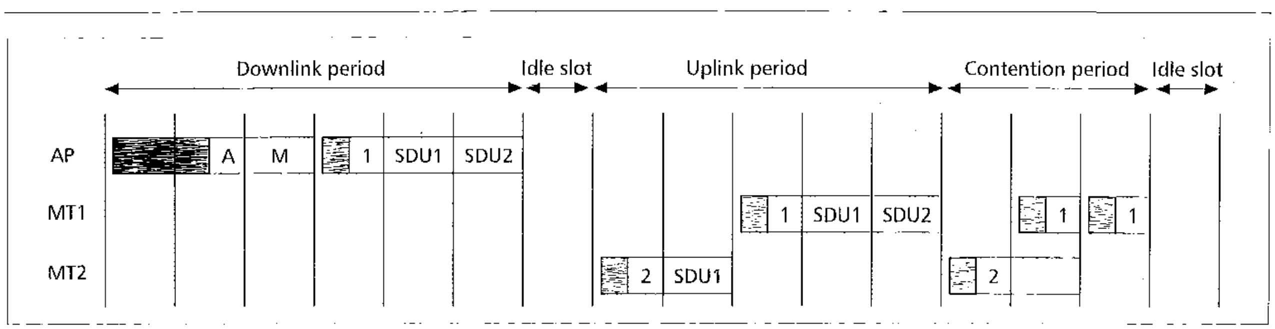


**Figure 8.** *A Magic WAND MAC frame.*

delay jitter, is the connection's error performance over the wireless ATM link. In WAND the radio PHY provides a constant service that can meet typical real-time service requirements (e.g., for voice service). TCP/IP-based data connections cannot tolerate high cell loss ($> 10^{-2}$) and are protected by ARQ. Furthermore, services such as video require real-time service with low error rates. The solution applied in WAND is to apply ARQ with a limited number of retransmissions.

## Conclusions

The new IEEE 802.11 CCK standard makes it possible to enhance wireless LAN data rates in the 2.4 GHz band from 2–11 Mb/s. CCK modulation was chosen especially for its robustness against multipath delay spread, so high data rates can be used in difficult environments with large delay spreads, such as factory halls. Furthermore, since the chip rate and hence the RF bandwidth remain the same as for the 1 and 2 Mb/s direct-sequence data rates, it is relatively easy to make products that support all rates from 1–11 Mb/s. CCK-based products are already available from several manufacturers, who together formed the Wireless Ethernet Compatibility Alliance in order to ensure interoperability between products of different vendors.

The new OFDM standard for the 5 GHz band provides more channels and higher bit rates than the 2.4 GHz band. Bit rates of 6 up to 54 Mb/s are specified with a delay spread robustness sufficient for most indoor wireless applications. This new standard is the first to use OFDM in packet-based wireless communication, after projects like Magic WAND demonstrated the viability of OFDM. With simultaneous standardization efforts going on in the United States, Europe, and Japan, a final worldwide OFDM physical layer standard for the 5 GHz band is expected in the beginning of 2000.

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