

The Last Mile: Wireless Technologies for Broadband and Home Networks

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Until recently, limitations of the access networks have been the major obstacle to the “digital networked house”. The well-known “last mile problem” has hindered an effortless broadband access at home and, therefore, has impacted the home networking applications. However, recent advances in transmission and broadband access technologies are very promising and are capable of bringing information superhighway to the houses worldwide. More notably, broadband wireless access and home networking technologies are being warmly accepted by homeowners because of ease of installation, low cost, and high bandwidth. With this in mind, in this short course we investigate the concepts and technologies needed in between the consumers and the service provider, also known as last mile technologies. In other words, the focus of this chapter is to cover mainly WLL, WLAN, and WPAN systems. We begin with a discussion on the general concepts of broadband wireless communication, and then we delve into the enabling technologies of WLL such as MMDS, LMDS, satellite communications, the newly developed IEEE standard 802.16, HIPERACCESS, and so on. Next, we move on to WLAN technologies including IEEE 802.11a, 802.11b, and HIPERLAN. Finally, we depict the prominent WPAN systems such as Bluetooth, IrDA, HomeRF, and the IEEE standards 802.15.3 and 802.15.4.

1. Introduction

Broadband communications and home networking are becoming household words as more and more homes are utilizing many network-enabled devices. On one hand, the term broadband implies high-speed digital communications, requiring wider bandwidth for transmission, and can be employed for the distribution of high-speed data, voice, and video throughout the home. Therefore, the last mile broadband access specifies the connectivity mechanism from the local signal distributor and the home (or the end user). Several companies are providing methods to connect and provide services of voice, data, music, video, and other forms of communication. They include wired solutions such as Public Switched Telephone Network (PSTN), cable, and fiber optics, as well as wireless options such as fixed wireless and satellite.

Home networking has become a convergence point for the next generation digital infrastructure. As technology has advanced, household appliances, televisions, stereos, home security systems, and nearly everything that operates on electrical energy is becoming digitally controlled and potentially connectable to a network. It is becoming a key technology that will enable new-breed of information appliances to connect to, and communicate over, rapidly expanding digital network.

Until recently, limitations of the access networks have been the major obstacle to the “digital networked house”. The well-known “last mile problem” has hindered an effortless broadband access at home and, therefore, has impacted the home networking applications. However, recent advances in transmission and broadband access technologies are very promising and are capable of bringing information superhighway to the houses worldwide. More notably, broadband wireless access technologies are being warmly accepted by homeowners because of ease of installation, low cost, and high bandwidth.

Along with the advances on wireless access to the home, explosion of the Internet, increasing demand for intelligent home devices, and availability of plenty in-home computing resources, calls for home networking solutions. These solutions should provide connectivity between in-home devices, must efficiently exploit the high-speed access to the Internet and could establish a new home paradigm. More importantly, the truly revolutionary potential for home networking lies in its ability to extend the Internet access everywhere directly into the hands of consumers, what has been called as *pervasive computing*. This could also open up a new mass market and could set the ground for a vast range of new home applications. Therefore, last mile broadband access and home networking are highly coupled and a thorough discussion of one is incomplete without covering the other.

To make both broadband wireless access and home networking widely acceptable, reliability, performance, installation ease and cost are the most crucial factors that need to be addressed efficiently. Indeed, performance and reliability are known to be key concerns for residential users. Also, complex wiring and expensive networking devices are considered significant barriers to extensive deployment of home-networked products. Especially, installing new wires in an existing home environment is commonly a cumbersome process and usually the source of several problems. For this reason, increased focus has been recently concentrated on the so-called “no-new-wires” innovations. These home networking solutions include technologies that either re-use existing in-home cables or employ wireless connectivity.

This chapter is devoted to the candidate wireless technologies to be employed for the last mile broadband access and for home networking. The purpose is to provide comprehensive information about recent advances and activities in these fields, and serve as a complete and updated reference. In this context, the concepts, challenges, and applications of the technologies that enable the broadband wireless access and wireless home networking are addressed in detail.

2. Chapter Organization

In the near future, fourth-generation (4G) wireless technologies will be able to support Internet-like services. This provision will be achieved through a seamless integration of different types of wireless networks with different transmission speeds and ranges interconnected through a high-speed backbone. 4G wireless networks include Wireless Personal Area Networks (WPANs), Wireless Local Area Networks (WLANs), Wireless Local Loops (WLLs), cellular wide area networks and satellite networks (see Figure 1). Ultimately, the goal is to efficiently reach the users either directly or through Customer Premises Equipments (CPEs). The widespread use of wireless networks will increase the deployment of new wireless applications, especially multimedia applications such as video-on-demand, audio-on-demand, voice over IP, streaming media, interactive gaming and other applications.

In this chapter, we investigate the concepts and technologies needed in between the consumers and the service provider, also known as last mile technologies. In other words, the

focus of this chapter is to cover mainly WLL, WLAN, and WPAN systems. We first discuss some general concepts of broadband wireless communication, and then we delve into the enabling technologies of such WLL systems, then covering WLAN, and finally WPAN systems.

3. A Broadband Home Access Architecture

A broadband home access (BHA) architecture represents an ultimate technical solution that could bring the vision of pervasive computing to fruition at home. It serves as an economic conduit that connects the next generation of Internet-based vendors with consumers located in the comfort of their own homes.

In general, there are four distinct technological components of the BHA architecture (see Figure 2) which must be deployed as an integrated and interoperable system in order to successfully penetrate the mainstream marketplace: the broadband local loop, the residential gateway (RG), the Home Area Network (HAN), and electrodomestic network devices (END). In what follows, we investigate the role of each of these components.

3.1 The Broadband Local Loop

Originally developed to support telephony traffic, the *local loop* of a telecommunications network now supports a much larger number of subscriber lines transmitting both voice and Internet traffic. Similar to “last mile”, the term “local loop” is widely used to describe the connection from the local provider to the consumers. Broadly speaking, there are five methods of bringing information to the home: telephone wire, coaxial cable, fiber optics, wireless RF, and satellite communications. The basic requirement for all of these methods is to bring high-speed information to homes as well as offices.

There are many techniques that use a combination of the above methods for a complete system to provide complete coverage of both stationary and mobile users and applications. In the next section, we cover the most prominent solutions to providing broadband wireless access to the home or office environments.

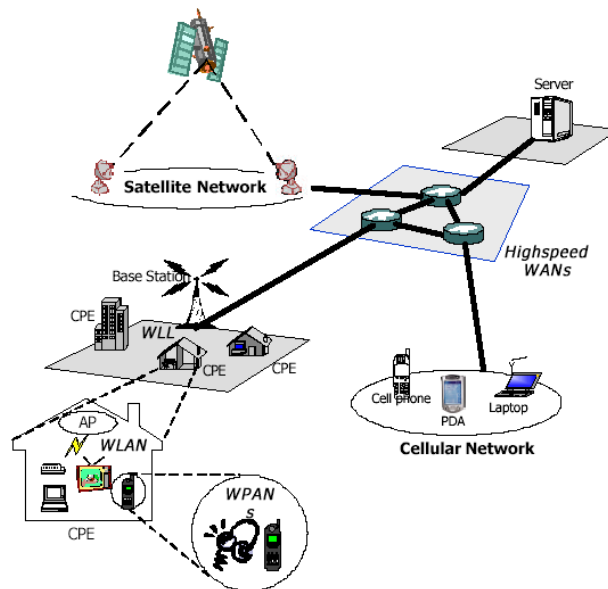


Figure 1 – The envisioned communication puzzle of 4G

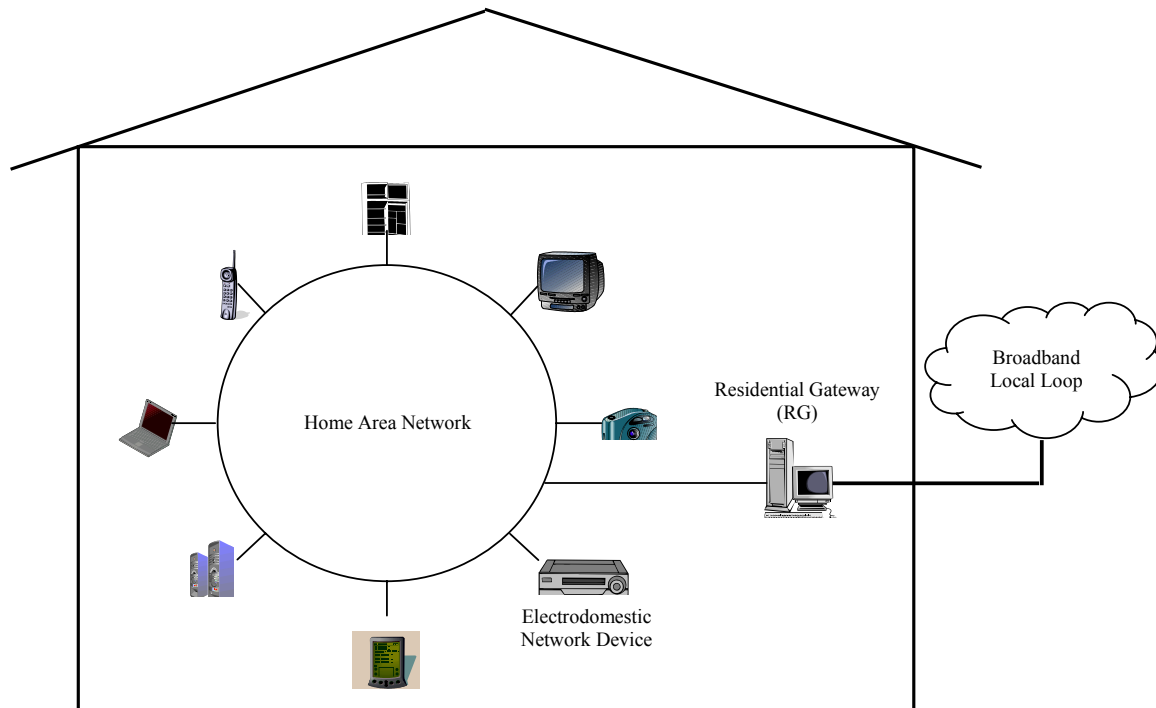


Figure 2 – Broadband home access architecture

3.2 Residential Gateway (RG)

The residential gateway (RG) is the interface device that interconnects the broadband local loop to the in-home network. It offers an effective bi-directional communication channel to every networked device in the home. Since it serves as the centralized access point between the home and the outside world, the RG represents an important technological component in the BHA architecture. Moreover, the RG serves as the convergence point that will bridge the different broadband and local area network (LAN) technologies, and also personal area networks (PANs).

3.3 The Home Area Network (HAN)

The home area network (HAN) is the high-speed in-home network that distributes the information to the ENDs. It provides interconnectivity for all ENDs within the home premises. A wide variety of technologies exist for interconnecting devices within the home, but no single technology meets all of the requirements for the diversity of applications that could be envisioned. While traditional 10Base-T/Cat5 Ethernet offers a robust and proven solution, most consumers do not have the time, interest, or knowledge to rewire their homes. Fortunately, the emergence of “no-new-wires” technologies offers alternatives for solving the mass-market home networking issue. The new technologies include wireless, phonline, and powerline solutions. In section 5, we discuss the wireless home networking solutions that are considered to represent a large fraction of this market.

3.4 Electrodomestic Network Devices (ENDs)

Electrodomestic network devices (ENDs) can be described as a set of “intelligent” processing tools used in home environments. They include computers, appliances, and electronics that have embedded “intelligence” and capability to communicate with other devices. These devices will not only be able to communicate with other in-home devices, but

also to connect to the outside world (e.g., Internet) in case in-home network is connected to a broadband local loop. These will enable development of new applications such as remote administration and web-based home control and automation.

4. The Last Mile Broadband Wireless Access

Rapid growth in demand for high-speed Internet/Web access and multiline voice for residential and small business customers has created a demand for last mile broadband access. Typical peak data rates for a shared broadband pipe for residential customers and small offices/home offices (SOHO) are around 5–10 Mb/s on the downlink (from the hub to the terminal) and 0.5–2 Mb/s on the uplink (from the terminal to the hub). This asymmetry arises from the nature and dominance of Web traffic. Voice and videoconferencing exhibit symmetric traffic. While long-term evolution of Internet services and the resulting traffic is hard to predict, demand for data rates and quality of broadband last mile services will certainly increase dramatically in the near future.

There are many wireless systems in several bands competing for the “last mile”. Methods considered include point-to-point, point-to-multipoint, and multipoint-to-multipoint for bringing broadband communications information and provide networking capabilities amongst the end users.

Broadband access is currently offered through digital subscriber line (xDSL) [47, 48], cable, and broadband wireless access (BWA), which can also be referred to as fixed broadband wireless access (FBWA) networks. Each of these techniques has their own unique cost, performance, and deployment trade-offs. While cable and DSL are already being deployed on a large scale basis, BWA is emerging as an access technology with several advantages. These include avoiding distance limitations of DSL and high costs of cable, rapid deployment, high scalability, lower maintenance and upgrade costs, and incremental investment to match market growth. Nevertheless, a number of important issues including spectrum efficiency, network scalability, self-installable CPE antennas, and reliable non-line-of-sight (NLOS) operation need to be resolved before BWA can penetrate the market successfully. In this section we characterize BWA, and outline its major features, including important issues at both physical and medium access control (MAC) layers, while in the next section we discuss the major technologies available for BWA.

4.1 Basic Principles

We start our discussions on BWA with a discussion of the basic principles involving wireless communications. In wireless technology, data is transmitted over the air and these are ideal platforms for extending the concept of home networking into the area of mobile devices around the home. Consequently, wireless technology is portrayed as a new system that complements phone-line and powerline networking solutions. While it is not clear if wireless technology will be used as a home network backbone solution (as suggested by some proponents of the IEEE 802.11 standard), it will definitely be used to interconnect class of devices that could constitute a subnetwork with mobile communications. These mobility subnetworks will interface with other subnetworks and with the Internet by connecting to the home network backbone regardless of if it is wired or wireless.

Wireless networks transmit and receive data over the air, minimizing the need for expensive wiring systems. With a wireless-based home network, you can access and share expensive entertainment devices without installing new cables through walls and ceilings. At the core of wireless communication is a device called a transmitter and another called a receiver. The user interacts with the transmitter – for example, if someone inputs a URL into

their PC, this input is converted by the transmitter to electromagnetic waves and sent to the receiver. For two-way communication, each user requires a transmitter and a receiver. Therefore, many of the many manufacturers build the transmitter and receiver into a single unit called transceiver. The operation and functionality of a wireless and wired network remains the same; however, there are subtle differences in the technologies that are used to achieve a similar objective.

The two main propagation technologies used in wireless networks are Infrared and Radio Frequency and are described below.

4.1.1 Infrared (IR)

Most of us today are familiar with everyday devices that use IR technology such as remote controls for TVs, VCRs, DVD and CD players. IR transmission is categorized as a line-of-sight (LOS) wireless technology. This means that the workstations and digital appliances must be in a direct line to the transmitter in order to establish communication link successfully. An infrared-based network suits environments where all the digital appliances that require network connectivity are in one room. There are, however, new diffused IR technologies that can work without LOS inside a room, so expect to see these products in the very near future. IR networks can be implemented reasonably quickly; however, people walking or moisture in the air can weaken the signals. IR in-home technology is promoted by an international association of companies called IrDA (Infrared Data Association) [1]. Further details on the IrDA system are given later in this chapter.

4.1.2 Radio Frequency (RF)

Another main category of wireless technology is the radio frequency. RF is a more flexible technology, allowing consumers to link appliances that are distributed throughout the house. RF can be categorized as narrow band or spread spectrum. Narrow band technology includes microwave transmissions which are high-frequency radio waves that can be transmitted to distances up to 50 Km. Microwave technology is not suitable for home networks, but could be used to connect networks in separate buildings. Spread spectrum technology (SST) is one of the most widely used technologies in wireless networks. SST was developed during World War II to provide greater security for military applications. As it entails spreading the signal over a number of frequencies, spread spectrum technology makes the signal harder to intercept. There are a couple of techniques used to deploy SST. For instance, a system called frequency-hopping spread spectrum (FHSS) is the most popular technology for operating wireless home networks. FHSS constantly hop over entire bands of frequencies in a particular sequence. To a remote receiver not synchronized with the hopping sequence, these signals appear as a random noise. A receiver can only process the signal by tuning to the appropriate transmission frequency. The FHSS receiver hops from one frequency to another in tandem with the transmitter. At any given time, there may a number of transceivers hopping along the same band of frequencies. Each transceiver uses a different hopping sequence that is carefully chosen to minimize interference. Later in this chapter, we cover the Bluetooth technology which employs the FHSS technique. Because wireless technology has roots in military applications, security has been a design criterion for wireless devices. Security provisions are normally integrated with wireless network devices, sometimes making them more secure than most wireline-based networks.

4.2 Services, Deployment Scenarios and Architectures of BWA

Typical BWA services include Internet access, multiline voice, audio, and streaming video. Quality of service (QoS) guarantees for data and voice are needed. Carrier requirements include meeting the Federal Communications Commission (FCC) regulations on power emission and radio interoperability, scalability using a cellular architecture wherein throughput per square mile can be increased by cell splitting, low-cost CPE and infrastructure equipment, high coverage and capacity per cell which could reduce infrastructure costs, self-installability of CPE antennas, and finally, portability evolution.

Three different deployment scenarios can be considered for BWA: supercells, macrocells, and microcells.

4.2.1 Supercells

In this scenario, a large service area with a radius of up to 30 mi is covered. The base transceiver station (BTS) antenna height is typically in excess of 1000 ft, and a high-gain rooftop directional CPE antenna is needed with a LOS connection between transmitter and receiver. This is a single-cell configuration which is not scalable. The same cell frequency reuse in angle and polarization may be feasible with sectorization. Due to LOS propagation, carrier-to-noise ratio (C/N) values of around 30 dB can be sustained, which makes the use of high-order modulation possible. Due to a strict need for LOS links, full coverage cannot generally be guaranteed.

4.2.2 Macrocells

Macrocells typically use cellular architecture with spatial frequency reuse between cells. The BTS antenna height is significantly lower than in the supercell case, typically 50–100 ft. Low BTS heights induce severe path loss and possibly NLOS propagation. A cell radius of around 5 mi may be possible. Due to NLOS propagation and co-channel interference (CCI) from other cells, significantly lower C/N and carrier-to-interference ratio (C/I) values could be supported as compared to supercells, and lower-order modulation has to be used. Directional CPE antennas can still be employed. The architecture is scalable in both capacity and coverage, and high coverage is possible since NLOS propagation is supported.

4.2.3 Microcells

Microcells are similar to macrocells with the difference that much smaller cells (typical cell radius of 1 mi) are used. The BTS towers are lower than in the macrocell case, typically below rooftop, and may be 20–40 ft high. To support portability, the CPE architecture has omnidirectional indoor antennas. Small cell size offers sufficient link margin to provide indoor coverage.

4.2.4 Challenges in Fixed Wireless Networks

We shall next outline major challenges in fixed wireless networks and discuss the main differences between fixed broadband and current mobile wireless access networks. Essentially, the quality and data rate requirements in the fixed case are *significantly* higher than in the mobile case. Due to the requirements for *higher data rates*, the link budget shrinks by roughly 15 dB, assuming that fixed transmit power remains the same as in the mobile

cellular case. The requirements for higher quality increase needed fade margins for C/N and C/I by roughly 15 dB each. Taking into account that the use of directional antennas provides a gain of roughly 15 dB in link budget against noise, this translates into a 15 dB disadvantage in link budget against noise and a 15 dB disadvantage against CCI. The former means much smaller coverage or cell radius (1/5 of the mobile cell radius); the latter requires much higher reuse factors (20–30 instead of 3 in mobile) and hence 1/6 cell capacity.

Hence, new sophisticated physical and radio link layers are needed in order to maintain coverage and retain a reuse factor of 3. The use of multiple antennas, discussed in more detail later, provides significant leverage in terms of link budget against noise and CCI, and seems to be very promising in meeting these requirements. Coverage influences network economics since good coverage reduces the infrastructure costs during initial setup. Extra capacity improves network cost effectiveness by delaying the need for cell splitting.

4.3 BWA Channels

Wireless transmission is limited by available radio spectrum while impaired by path loss, interference, and multipath propagation, which cause fading and delay spread. Because of these limitations, in general much greater challenges are present in wireless than wired systems. In this subsection, we discuss BWA channels.

4.3.1 Path Loss and Delay Spread

The path loss in BWA channels depends on the type of terrain. It is observed that the COST 231-Hata model gives reasonable estimates of the path loss for a flat terrain and high base station antenna heights for a wide frequency range. In moderate or hilly terrain and for lower base station antenna heights, the Hata model may not be adequate, and other models may have to be used. Measurements in the 1.9 GHz band representing the macro/microcell cases have been reported in [2]. These measurements show differences in path loss on the order of tens of decibels for different terrain categories, which makes it very important to have a distinction.

The amount of delay spread in fixed wireless channels depends strongly on the antenna characteristics. In [3], median root mean square (RMS) delay spreads for directional antennas in suburban environments of approximately 75 ns have been reported; with omnidirectional antennas in the same terrain a delay spread of 175 ns has been found [3]. The reason for the difference in delay spread for directional and omnidirectional antennas is that echoes at longer delays tend to arrive at angles farther away from the direct path and are thus more attenuated by the side lobes in the case of directional antennas. Measurements conducted mostly in the 900 MHz band [4] with omnidirectional antennas in suburban, urban, and mountainous environments show delay spreads of up to 16 μ s. The fading rates encountered in fixed wireless environments are between 0.1 and 2 Hz.

4.3.2 The K-Factor

The path gain of a fixed BWA channel can be represented as having a fixed component plus a fluctuating (scatter) component. The ratio of the average energy in the fixed component to the average energy in the scatter component is called the K-factor. The value of the K-factor has significant implications on the system design and its performance. Generally it is found that the K-factor in fixed wireless applications can be very low, which is due to low BTS and CPE antenna heights (under the eave CPE antennas). Figure 3 shows K-factor

measurements conducted by the Smart Antennas Research Group at Stanford University. In these measurements performed in the 2.4 GHz band, the transmit antenna has been 10 and 20 m high, respectively, and the CPE antenna with a 50° 3 dB beamwidth in azimuth has been 3 m high. It is found that the K-factor decreases significantly with increasing distance between transmitter and receiver. We note that the K-factor shown in Figure 3 has been averaged over time and frequency. In practice, significant fluctuations in K-factor can occur due to wind and traffic. In Figure 3, we also show the Greenstein-Erceg model for the median K-factor vs. distance [5] assuming 20 m transmit and 3 m receive antenna heights. The experimental data and the model are shown to be in an excellent agreement.

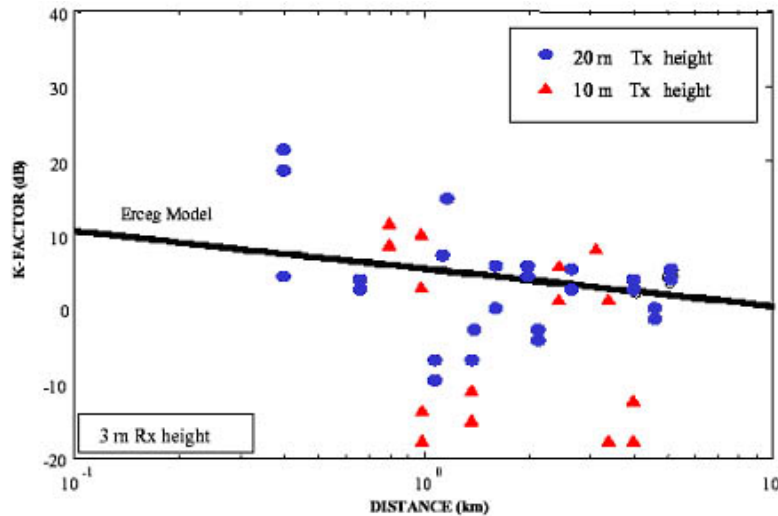


Figure 3 – K-factor as a function of distance between transmitter and receiver

To summarize, in a fixed BWA system design, very low K-factors (almost purely Rayleigh fading conditions) have to be assumed in order to provide large cell coverage and reliable operation at the edge of the cell.

4.4 Physical Layer, MAC Layer, and Radio Link Protocols

In this subsection, we discuss issues regarding the physical layer, MAC layer, and Radio Link Protocol (RLP) of a BWA system.

4.4.1 The Physical Layer

4.4.1.1 Modulation

We consider three alternative modulation formats: single-carrier (SC) modulation with equalization, direct sequence code-division multiple access (DS-CDMA) [50] with a rake receiver, and orthogonal frequency-division multiplexing (OFDM) with interleaving and coding, and briefly mention the new technique of ultra-wideband modulation (UWB). We assume that the transmitter does not know the channel.

4.4.1.2 Single-Carrier Modulation with Equalization

Several equalization options with different performance and implementation tradeoffs exist for SC modulation. Maximum-likelihood (ML) equalization yields optimum performance, but is computationally very complex. Decision-feedback equalization (DFE) is generally considered as an attractive option in practical. Simpler alternatives include linear equalizers such as zero-forcing or MMSE. However, linear equalization does not properly exploit the frequency diversity in the channel created by delay spread. In practice, for high delay spread and/or high data rate case the computational complexity of SC equalizers and the complexity required for equalizer adaptation can impose limits on the performance of SC systems.

4.4.1.3 DS-CDMA

DS-CDMA uses a spreading code sequence which is multiplied with the digital baseband transmitted symbol. This spreading code sequence has a much higher rate than the information bearing symbol which spreads the symbol in frequency. A RAKE receiver can be employed to exploit frequency diversity. With increasing data rate, both the symbol and chip rates increase, which allows the system to resolve finer differences in physical path delays, but leads to an increased number of discrete-time baseband channel impulse response taps and hence increases necessary number of elements in the rake combiner, which, in turn, results in increased computational complexity.

4.4.1.4 Orthogonal Frequency-Division Multiplexing

OFDM eliminates the need for equalization by inserting a guard interval (cyclic prefix) which is a copy of the last part of the OFDM symbol and must be long enough to accommodate the largest possible delay spread. The transmitter and the receiver employ an Inverse Fast Fourier Transform (IFFT) and FFT, respectively, and equalization reduces to simple scalar multiplications on a tone-by-tone basis. In OFDM, frequency diversity is obtained by coding and interleaving across tones. For increasing delay spread and/or data rate, the cyclic prefix must increase proportionally so that it remains longer than the channel impulse response. Thus, in order to maintain a constant overhead due to the CP, the number of tones N must increase proportionally. This results in increased computational complexity due to the increased FFT size. Summarizing, the ease of equalization seems to favor OFDM over SC and DS-CDMA from a pure complexity point of view.

4.4.1.5 Ultra-Wideband Modulation

Recently, UWB has attracted a lot of interest for wireless broadband communications. In UWB, a train of modulated sub-nanosecond pulses are used to convey information. A RAKE receiver realizes the path diversity. The result of the pulses transmitted across an ultra-wideband spectrum means that UWB may be able to coexist with other narrowband systems since the interference energy per system may be small and may only increase the noise floor. Recently, UWB has received some encouragement from the FCC. Several industry efforts are underway to commercialize the technology.

4.4.1.6 Hardware Considerations

From a pure complexity point of view, OFDM seems to be more attractive than SC and DS-CDMA. In practice, however, OFDM signals make the system sensitive to power

amplifier nonlinearities. Therefore, in the OFDM case, the power amplifier cost is higher. The decision as to whether SC, DS-CDMA, or OFDM should be used is therefore driven by two factors: the cost of silicon required for the transmit and receive signal processing operations, and the cost of power amplifier.

4.4.1.7 Channel Coding

Channel coding adds redundancy to the transmitted data to allow the receiver to correct transmission errors. As mentioned above, in the OFDM case, channel coding combined with interleaving also provides frequency diversity. Typical, BWA channel coding schemes employ concatenated Reed-Solomon (RS)/convolutional coding schemes, where RS codes are used as outer codes and convolutional codes as inner codes. Soft decoding and iterative decoding techniques can provide additional gain.

4.4.1.8 Synchronization

The timing and frequency offset sensitivity of SC and DS-CDMA systems is theoretically the same as long as they use the same bandwidth and data throughput. OFDM is more sensitive to synchronization errors than SC and DS-CDMA.

4.4.1.9 Link Adaptation

In BWA systems, channel conditions may vary significantly due to fading. It is therefore desirable to adapt the modulation and coding scheme according to the channel conditions. While voice networks are designed to deliver a fixed bit rate, data services can be delivered at a variable rate. Voice networks are engineered to deliver a certain required worst case bit rate at the edge of the cell. Most users, however, have better channel conditions. Therefore, data networks can take advantage of adaptive modulation and coding to improve the overall throughput. In a typical adaptive modulation scheme, a dynamic variation in the modulation order (constellation size) and forward error correction (FEC) code rate is possible. In practice, the receiver feeds back information on the channel, which is then used to control the adaptation. Adaptive modulation can be used in both up- and downlinks. The adaptation can be performed in various ways and can be user-specific only, user- and time-specific, or QoS-dependent.

4.4.1.10 Multiple Access

Time Division Multiple Access (TDMA) [50] is performed by assigning different disjoint time slots to different users, or equivalently the transmission time is chopped up into sequentially accessed time slots. Each user, then takes turns transmitting and receiving in a round-robin sequence. For data networks, where channel use may be very bursty, TDMA is modified to reservation-based schemes where time slots are allocated only if there is data to be transmitted. In CDMA, all the users transmit at the same time with different users employing different quasi-orthogonal signature sequences. While there is little theoretical difference in terms of capacity between TDMA and CDMA, CDMA offers unique advantages in terms of realizing signal and interference diversity. In BWA, however, *fixed spreading* CDMA is not attractive since the operating bandwidth due to a high spreading factor (typically larger than 32) becomes very high. For example, for a data rate of 10 Mb/s an operating bandwidth of 160 MHz is required for a spreading factor of 32. In third-

generation (3G) mobile systems for high-data-rate links, the spreading factor drops to 4 in order to keep the bandwidth at 4 MHz. Such a low spreading factor makes CDMA almost look like TDMA. Other practical approaches include multicode CDMA modulation.

4.4.1.11 TDD vs. FDD

The BWA industry is currently debating the merits of time-division duplexing (TDD) vs. frequency-division duplexing (FDD) in point-to-multipoint networks. FDD is the legacy used in the fixed wireless industry in point-to-point links originally designed for transporting analog voice traffic, which is largely symmetric and predictable. TDD, on the other hand, is being used in the design of point-to-multipoint networks to transport digital data, which is asymmetric and unpredictable. While TDD requires a single channel for full duplex communications, FDD systems require a paired channel for communication, one for the downlink and one for the uplink. In TDD, transmit/receive separation occurs in the time domain, as opposed to FDD, where it happens in the frequency domain. While FDD can handle traffic that has relatively constant bandwidth requirements in both communications directions, TDD effectively handles varying uplink/downlink traffic asymmetry by adjusting time spent on up- and downlinks. Given that Internet traffic is bursty (i.e., time-varying), the uplink and downlink bandwidths need to vary with time, which favors TDD. TDD requires a guard time equal to the round-trip propagation delay between the hub and the remote units. This guard time increases with link distance. Timing advance can be employed to reduce the required guard time. In FDD, sufficient isolation in frequency between the uplink and downlink channels is required. In brief, FDD seems to be simpler to implement while it offers less efficient solution.

4.4.2 The MAC Layer and RLP

The MAC layer and RLP work with the physical (PHY) layer to deliver the best possible QoS in terms of throughput, delay, and delay jitter to the users. The major task of the MAC layer is to associate the transport and QoS requirements with different applications and services, and appropriately prioritize and schedule transmission over uplink and downlink. A wireless MAC protocol should therefore provide differentiated grades and quality of service, dynamic bandwidth allocation, and scheduling for bursty data. An important feature of the MAC layer is the ability to perform retransmission, which allows operation at higher error rates and hence better frequency reuse, increases robustness, and improves TCP performance. The major MAC functions are:

- Controlling uplink and downlink *transmission schedules*, which allows support of multiple service flows (i.e., distinct QoS) on each CPE-BTS link.
- *Admission control* to ensure that adequate channel capacity is available to accommodate QoS requirements of the new flow, and to enforce policy constraints like verifying that a CPE is authorized to receive the QoS requested for a service flow.
- *Link initialization* and maintenance like channel choice, synchronization, registration, and various security issues.
- *Support for integrated voice/data transport*. Typical data requirements are bandwidth on demand, very low packet error rates, and type-of-service differentiation. Voice requirements are bandwidth guarantees, and bounded loss, delay, and jitter.

- Support for *fragmentation*, *automatic repeat request* (ARQ), and *adaptive modulation and coding*.

We shall next summarize some MAC features, which are specifically desirable in the wireless scenario:

- *Fragmentation* of packet data units (PDUs) into smaller packets. This helps to reduce the packet error rate and limit the latency for voice communication.
- *Retransmission* on the level of fragmented PDUs.
- *Scheduling support* for multiple modulation/coding schemes.
- Wireless-specific *link maintenance and control* like uplink power control and adaptive modulation and coding.

4.5 Multiple Antennas in BWA

As outlined previously, fixed BWA systems face two key challenges: providing high-data-rate and high-quality wireless access over fading channels as close to wireline quality as possible. The high requirement for quality arises because wireless BWA systems compete with cable modems and asynchronous DSL (ADSL), which operate over fixed channels and hence provide very good quality.

This high quality requirement constitutes a major difference from existing mobile cellular networks, where customers are accustomed to low QoS. Also, in existing mobile cellular networks, the requirements for data rate are much lower than in the fixed BWA case. The use of multiple antennas at the transmit and receive sides of a wireless link in combination with signal processing and coding is a promising means to satisfy all these requirements. Note that in fixed BWA as opposed to mobile cellular communications, the use of multiple antennas at the CPE is possible.

The leverages provided by the use of multiple antennas at both the BTS and CPE are as follows:

- *Array gain*: Multiple antennas can coherently combine signals to increase the C/N value and hence improve coverage. Coherent combining can be employed at both the transmitter and receiver, and requires channel knowledge. Since channel knowledge is hard to obtain in the transmitter, array gain is more likely to be available in the receiver.
- *Diversity gain*: Spatial diversity through multiple antennas can be used to combat fading and significantly improve the link reliability. Diversity gain can be obtained both at the transmitter and receiver. A recently developed space-time codes [6] realize transmit diversity gain without knowing the channel in the transmitter.
- *Interference suppression*: Multiple antennas can be used to suppress CCI and hence increase the cellular capacity.
- *Multiplexing gain*: The use of multiple antennas at both the transmitter and receiver allows opening up parallel spatial data pipes within the same bandwidth, which leads to a linear (in the number of antennas) increase in data rate [7–9, 52].

Summarizing, the use of multiple antennas at both the BTS and CPE can improve cellular capacity and link reliability. More details on the impact of multiple antennas on cellular networks can be found in [10].

5. Last Mile Broadband Wireless Access Technologies

In the previous section, we have studied the general concepts and issues involved in broadband data delivery to offices and homes. We now turn our attention to the specific technologies proposed to achieve this.

In recent years there has been increasing interest shown in wireless technologies for subscriber access, as an alternative to traditional wired (e.g., twisted-pair, cable, fiber optics, etc) local loop. These approaches are generally referred to as wireless local loop (WLL), or fixed wireless access, or even Last Mile Broadband Wireless Access. Last Mile Broadband Wireless Access technologies are a relatively new service that is being used by telecommunication companies to carry IP data from central locations on their networks to small low-cost antennas that are mounted on their subscribers' roofs. Wireless cable Internet access is enabled through the use of a number of distribution technologies. In the following subsections, we investigate these broadband wireless technologies and their characteristics.

5.1 Multichannel Multipoint Distribution System (MMDS)

Analog-based MMDS [11, 12] began in the mid-seventies with the allocation of two television channels for sending business data. This service became popular, and applications were made to allocate part of the ITFS (Instructional Television Fixed Service) band to wireless cable TV. Once the regulations had been amended, it became possible for a wireless cable system to offer up to thirty-one 6 MHz channels in the 2.5 to 2.7 GHz frequency band. During this timeframe, nonprofit organizations used the system to broadcast educational and religious programs. In 1983, the FCC allocated frequencies in both of these spectrums, providing 200 MHz bandwidth for licensed network providers, and having the output power up to 30 watts. The basic components of a digital MMDS system providing broadband connectivity to a home network are shown in Figure 4.

An MMDS broadband system consists of a head-end that receives data from a variety of sources including Internet Service Providers (ISPs) and TV broadcast stations. At the head-end, data is processed, converted to the 2.1 and 2.7 GHz frequency range and sent to microwave towers. Quadrature Amplitude Modulation (QAM) is the most commonly used format employed in sending data over an MMDS network, however some operators use a modulation format called Coded Orthogonal Frequency Division Multiplexing (COFDM). This format operates extremely well in conditions likely to be found in heavily built-up areas where digital transmissions become distorted by line of sight obstacles, such as buildings, bridges, and hills. The signals are then rebroadcast from low-powered base stations in a diameter of 35 miles from your home place. This provides up to 10 Mbps during peak use and can provide speeds up to 37.5 Mbps to a single user. Signals are received with home rooftop antennas.

The receiving antenna has a clear line of site to the transmitting antenna. A down converter, usually a part of the antenna, converts the microwave signals into standard cable channel frequencies. From the antenna the signal travels to a gateway device where it is routed and passed onto the various devices that are connected to the in-home network. Today, there are MMDS systems in use all around the United States and in many other countries.

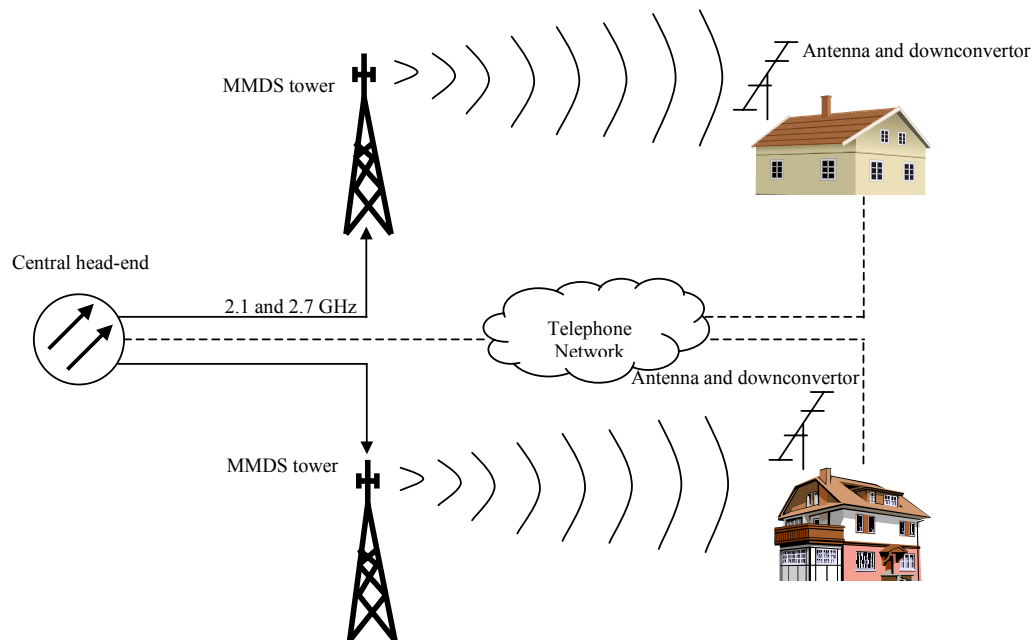


Figure 4 – MMDS broadband connectivity

5.2 Local Multipoint Distribution Service (LMDS)

LMDS [13, 14] is a “last mile” point-to-multipoint distribution service (not a LAN), which propagates communications signals with a relatively short RF range to multiple end-users. In this multipoint system, the base station or hub transmits signals in a point-to-multipoint (PMP) method that resembles a broadcast mode. The return path from the subscriber to the base station or hub is accomplished by a point-to-point (PTP) link. Overall, the architecture of LMDS is similar to that of the MMDS system.

LMDS combines high-capacity radio-based communications and broadcast systems with interactivity operated at millimeter frequencies. Other systems, however, have been primarily used for analog TV distribution (e.g., MMDS), and it all started with Cellular Vision and Bernard Bossard proposing a system for TV distribution in central New York City [19]. Digital television opened up a combined mechanism for transport of data representing TV programs, data, and communication. The possibility of implementing a full-service broadband access network by rebuilding a broadcast network into an interactive network by functionally adding a communications channel for the return has, been a perfect match with the growth of the Internet and data services. Broadband interactivity has been possible with digitalization.

The transmitter site should be on top of a tall building or on a tall pole, overlooking the service area. The transmitter covers a sector typically 60–90° wide. Full coverage thus requires 4–6 transmitters. The streams transmitted contain 34–38 Mb/s of data addressed to everybody (typical TV) in the coverage zone, subgroups or individuals (typical communication, Internet). The capacity of the PTP return channels is determined by the requirements of individual users.

Operation of LMDS in an area normally requires a cluster of cells with separate base stations for co-located transmitter/receiver sites. One of the base station sites will serve as coordination center for the franchise area and connect the LMDS cells to external networks.

Inter-cell networking may be implemented using fiber or short hop radio relay connections. Co-location with mobile base stations allows for infrastructure sharing.

Operation in the millimeter range imposes some restrictions. Precipitation effects lead to severe attenuation, and depending on the climatic zone and the frequency of operation the reliable range of operation could be limited to 3–5 km. Line of sight is also required. Full coverage will however not be possible, and numbers quoted are normally in the 40–70 percent range, while something in excess of 95 percent is a minimum for a service offered to the public. Improved coverage is thus required and may be obtained in different ways. The numbers quoted refer to a single cell. By introducing some overlapping between cells it may be possible to obtain coverage in shielded areas in one cell from the neighboring cell transmission site. Use of repeaters and reflectors are other possibilities, but that requires some additional equipment, which could be compensated for by increasing the number of users. Thus, site dependent ways of operation could solve the coverage problem. The most severe restriction may be the attenuation caused by transmission through vegetation. Buildings completely shielded by vegetation need an elevated rooftop antenna or some broadband connection to an unshielded site. Propagation issues are by now well understood and are not considered as a serious obstacle for reliable operation of millimeter systems. The problems are known and proper precautions can be taken [20].

5.2.1 Operating Frequencies

Even though the capacity in the millimeter part of the spectrum is considerable, there are many systems competing for frequency allocations, and it has been difficult to obtain a worldwide allocation for LMDS.

In the United States, 1.3 GHz in the 28–29 GHz band has been allocated, while European countries are allocating frequencies in different bands. The major high-capacity band is presently 40.5–42.5 GHz with a possible extension to 43.5 GHz.

Licensing and deployment in Europe indicate that there will be systems in different frequency bands from 24 GHz up to 43.5 GHz. The frequency band 24.5–26.6 GHz with subbands of 56 MHz has been opened for PMP applications in many European countries. These bands may then be used for either LMDS or other related fixed wireless access system which can then represent a typical multipoint business system with some capacity for private users. Only systems addressing the business domain are typically based on the Asynchronous Transfer Mode (ATM) technology.

The 40 GHz band is normally to be shared among two or three licenses, limiting the available spectrum per operator to 500–2000 MHz with two polarizations. The licensing policy may vary from country to country, with stimulation to competition as the main guideline. LMDS has a potential of becoming the high-capacity access domain for private users.

5.2.2 Technologies Employed

Proven technologies required for service startup exist, and different companies have products available addressing the needs of small business customers and to some extent, also demanding private users.

In LMDS, a high-capacity broadcast-based downlink is shared among several users in a flexible way. The front-end technology is still expensive at millimeter frequencies, but

existing high electron mobility transistor (HEMT) module offers the required performance. The output power level needed per 36 Mb/s transport beam is about 25 dBm. A technology allowing for final stage amplification of several transport beams reduces the equipment complexity and the cost. The hub transmitters, however, are shared by many users and cost is not that critical.

The front-end technology at 40 GHz is more expensive than at 28–29 GHz and attenuation by precipitation increases with frequency, favoring the lower frequency ranges. Higher capacity offered at 40 GHz may compensate for these effects in the long run.

The number of transport streams is determined by demand and limitations set by available spectrum. This gives a scalable architecture, starting with relatively low capacity and adding transmitter modules as demand increases.

The transmission format for Digital Video Broadcasting (DVB) satellite transmission based on quadrature phase shift keying (QPSK) modulation has been adopted by both Digital Audio/Visual Council (DAVIC) and the DVB project, and with the same Input Frequency (IF) interface between the outdoor and indoor units in the range 950–2150 MHz. This allows for application of set-top boxes developed for reception of digital TV by satellite with data included in the transport multiplex. The IF is then fed into a set-top box interfacing a TV or a PC or both in parallel, depending on user's orientation. Both options allow for interactivity since set-top boxes are also equipped with a return channel connection to the PSTN/ISDN. However, there are some significant differences. In DVB, IP or ATM data are included in the MPEG transport stream in combination with TV programs. DAVIC has separate high-capacity ATM-based data transmissions. Until now, the PC-oriented user has dominated the interactive world; while the manipulation of contents, inclusion of more advanced text TV, possibilities for e-commerce, different games, and active participation in competitions, have led to an increased interest in interactive television with a low-capacity return channel.

The uplink is the individual connection, and different technologies may be used depending on the demand. Two of the broadband driving applications, namely, interactive TV and the Internet, will require only low-capacity return links, and technologies like General Packet Radio Service (GPRS) [46] and PSTN/ISDN will be adequate. For more demanding customers, an in-band radio return link with on-demand capacity is required. The radio-based solutions for small and medium-sized enterprises do have a radio-link-type return link, allowing for symmetric connections or connections which may be asymmetric in either direction. However, it is felt that existing radio return solutions, with their requirement for isolation between transmit and receive implemented through the use of appropriate filtering in allocated bands impose limitations on operation flexibility and efficient management of resources. A combined use of systems in broadcast and data for both private users and business organizations will necessarily result in strong variations in capacity for the two directions. Possible future TDD operation could solve this problem.

The main technological challenge is the large-scale production of a real low-cost two-way user terminal for the private market as the mass market depends on it. The total capacity of a system is mainly determined by the available frequency resource. In a cellular system employing QPSK modulation, the capacity of a 2 GHz system is around 1.5 Gb/s per cell for downlink and uplink channels.

5.2.3 Applications

LMDS is the first system with high flexibility, allowing for increased capacity on demand. Changing the cell size through reduction of either cell diameter or illumination angle

increases the total capacity. Its flexibility with respect to on-demand high capacity in both directions makes it well suited to home offices and teleteaching in a local domain. The first major applications are TV-, Internet-, and business-oriented; thus combining professional and entertainment use. In Europe, LMDS has been considered a supplement/alternative to cable TV and has actually been referred to as a *wireless cable*. With digital television, the possibility for converging TV, data, and communications has opened up development of new broadband applications. Hopefully, availability of broadband capacity will stimulate the growth of their usefulness such as telemedicine and teleteaching, which have been recognized for quite some time even though it is yet to really take off.

From Television to Interactive Television – The TV business has had strong growth, but the time spent by individuals watching TV has not changed very much. Digital TV introduces new possibilities. The first step is the introduction and development of interactive TV and adding new and interesting functionality. More local TV programs will take advantage of LMDS. Interactive TV will stimulate growth in e-commerce; and the local activities such as property trading, apartment renting, car buying and selling, and many other transactions, will take advantage of the possibilities offered by broadband networking. Telebanking and vacation planning are applications where interactive TV offers added functionality.

Teleteaching – Education and life-long learning are one of the major challenges in many countries today. Lack of educated and skilled teachers, particularly in current technologies, is a common concern. The local focus of LMDS makes it excellent for high-capacity connections to schools at different levels, connecting a group of local schools as well as providing connections to remote sites. Locally, it would also be possible to connect to homes and have lessons stored for the use of both the students and the parents. Broadband access will offer many possibilities in educational area we have barely started to explore. In this connection, the advantage of LMDS is the flexibility in capacity allocation and the multicast property of the downlink, allowing very efficient delivery for such type of applications.

5.3 Satellite Communications

Satellite communications [15, 16] allows the most remote places to receive Internet, telephones, faxes, videos and telecommunications via satellite signals. The infrastructure, bandwidth, and the possibility of combining satellite communications with other types of systems makes this method an ideal candidate for providing ubiquitous communications to everyone worldwide, thus representing a major player in the BWA arena.

Communication satellites are, in effect, orbiting microwave relay stations, located about 35,000 Km above the surface of the earth, used to link two or more earth-based microwave stations (also called *earth stations* or *ground stations*). Communications satellite providers typically lease some or all of a satellite's channels to large corporations, which use them for long-distance telephone traffic, private data networks, and distribution of television signals. Leasing these huge communications “pipes” can be very expensive, therefore they are not suitable for the mass residential marketplace. Consequently, a new suite of services, called the direct broadcast satellite (DBS) system, has been developed to provide consumers with a range of high-speed Internet access services.

A DBS system consists of a minidish that connects in-home networks to satellites with the ability to deliver multimedia data to a home network at speeds in excess of 45 Mbps. However, this speed can only be achieved when downloading content. To upload or send

information to the Internet, the system uses a slow telephone line connection. Satellite systems normally use the QPSK modulation scheme to transmit data from the dish in the sky to the minidish located on the top of the roof.

5.3.1 Operational Frequencies

Five different bands of operation are used for satellite communications. The lowest band is called the *L-band*. It operates with an uplink at 1.6 GHz and a downlink at 1.5 GHz using a narrow bandwidth. The next band is the *C-band* and operates around 6 GHz for the uplink to the satellite and 4 GHz for the downlink from the satellite to the ground station. The next band, which is generally used by the military, is called the *X-band* and operates around 8 GHz for the uplink and 7 GHz for the downlink. Next it comes the *Ku-band*, which has become popular for telecommunications, operating around 14 GHz for the uplink and 11 to 12 GHz for the downlink. The highest band of operation, the *Ka-band*, is becoming popular for broadband communications and other applications and operates at 30 GHz for the uplink and 20 GHz for the downlink. The *Ka-band* provides a much higher bandwidth for high-speed data and allows for more simultaneous end-users. A summary of different frequency bands, including the bandwidth, is shown in Table 1.

Table 1 shows approximate frequencies that represent bands that are in use. Band expansion is continuously changing so these numbers may not be exact and may vary slightly. Along with the frequency changes, bandwidths also change for different systems and uses. The most widely used bands are the 6/4 GHz C-band and the 14/11 – 12 GHz Ku-band. However, the 30/20 GHz band has become very popular in recent years for commercial use and is growing rapidly due to added interest in broadband communications.

5.3.2 Multiple Access Schemes

Multiple access allows various users to share the same bandwidth, satellite, and antenna systems. Two basic methods are used to allow for multiple users.

The first method is a multiplexing scheme called *preassigned multiple access* (PAMA). This mechanism permanently assigns a channel or time to a user. An example of a PAMA is using time slots and assigning a given time slot to each end user. Since they are permanently assigned, the users will have that given time slot and will be multiplexed with all of the other users similar to a Time Division Multiplex (TDM) used in other communication links.

Table 1 – Satellite frequency bands

Frequency band	Uplink	Downlink	Bandwidth
L-band 1.6/1.5 GHz	1.6 GHz	1.5 GHz	Narrowband
C-band 6/4 GHz	5.850-6.425 GHz	3.625-4.200 GHz	500/500 MHz
X-band 8/7 GHz	7.925-8.425 GHz	7.250-7.750 GHz	500/500 MHz
Ku-band 14/12 GHz	14-14.5 GHz	11.5-12.75 GHz	500/500 MHz
Ka-band 30/20 GHz	27.5-31 GHz	17.7-21.2 GHz	3.5/3.5 GHz

The second method of multiplexing is *demand assigned multiple access* (DAMA) [49]. This system is a true multiple access scheme similar to TDMA used in other communication systems (e.g., some cellular systems). It is used on an “as needed basis”, i.e., each user takes any time slot when needed.

Another method of providing multiple users is Frequency Division Multiplex (FDM)/FDMA [50]. These methods use frequency division to provide multiple users in one band. In systems that incorporate FDMA, channels are separated using different frequency slots for different users.

5.3.3 Propagation Delay

One of the problems with real-time communications using satellites is the large distance between the earth station and the satellite. The approximate propagation delay equals 275 ms and the two-way propagation delay is double that time (i.e., 550 ms). Since this propagation delay is so long, echo cancellation is vital to the quality of the communication link, especially for voice applications. Video applications, in particular one way broadcasting, generally do not need echo cancellation techniques.

5.4 IEEE Standard 802.16

To provide a standardized approach to WLL, the IEEE 802 committee set up the 802.16 working group [43] in 1999 to develop broadband wireless standards. IEEE 802.16 [17] standardizes the WirelessMANTM air interface and related functions for wireless metropolitan area networks (MANs). This standard serves as a major driving force in linking businesses and homes to local telecommunication networks.

A wireless MAN provides network access to buildings through exterior antennas, communicating with central radio base stations (BSs). The wireless MAN offers an alternative to cabled access networks, such as fiber optic links, coaxial systems using cable modems, and DSL links. This technology may prove less expensive to deploy and may lead to more ubiquitous broadband access, as wireless systems have the capacity to address broad geographic areas without the costly infrastructure development required in deploying cable links to individual sites. Such systems have been in use for several years, but the development of the new standard marks the maturation of the industry and forms the basis of new industry success using second-generation equipment.

In this scenario, with WirelessMAN technology bringing the network to a building, users inside the building can be connected to it with conventional in-building networks such as Ethernet or wireless LANs. However, the fundamental design of the standard may eventually allow for an efficient extension of the WirelessMAN networking protocols directly to the individual user. For instance, a central BS may someday exchange MAC protocol data with an individual laptop computer in a home. The links from the BS to the home receiver and from the home receiver to the laptop would likely use quite different physical layers, but design of the WirelessMAN MAC could accommodate such a connection with full QoS. With the technology expanding in this direction, it is likely that the standard will evolve to support nomadic and increasingly mobile users such as a stationary or slow-moving vehicle.

IEEE Standard 802.16 was designed to evolve as a set of air interfaces based on a common MAC protocol but with physical layer specifications dependent on the spectrum of use and the associated regulations. The standard, as approved in 2001, addresses frequencies from 10 to 66 GHz, where a large spectrum is currently available worldwide but at which the short wavelengths introduce significant deployment challenges. A new project, currently in the balloting stage, has just completed an amendment denoted IEEE 802.16a [18] which extends the air interface support to lower frequencies in the 2–11 GHz band, including both licensed and license-exempt spectra. Compared to the higher frequencies, such spectra offer a less expensive opportunity to reach many more customers, although at generally lower data rates.

This suggests that such services will be oriented toward individual homes or small to medium-sized enterprises.

5.4.1 MAC Layer

The IEEE 802.16 MAC protocol has been designed for point-to-multipoint broadband wireless access applications. It addresses the need for very high bit rates, both uplink and downlink. Access and bandwidth allocation algorithms must accommodate hundreds of terminals per channel, with terminals that may be shared by multiple end users. The services required by these end users are varied in their nature and include legacy TDM voice and data, IP connectivity, and packetized voice over IP (VoIP). To support this variety of services, the 802.16 MAC must accommodate both continuous and bursty traffic. Additionally, these services are expected to be assigned QoS in keeping with the traffic types. The 802.16 MAC provides a wide range of service types analogous to the classic ATM service categories as well as newer categories such as guaranteed frame rate (GFR).

The 802.16 MAC protocol must also support a variety of backhaul requirements, including both ATM and packet-based protocols. Convergence sublayers are used to map the transport-layer-specific traffic to a MAC that is flexible enough to efficiently carry any traffic type. Through such features as payload header suppression, packing, and fragmentation, the convergence sublayers and MAC work together to carry traffic in a form that is often more efficient than the original transport mechanism.

Issues of transport efficiency are also addressed at the interface between the MAC and the PHY layer. For example, modulation and coding schemes are specified in a burst profile that may be adjusted to each subscriber station adaptively for each burst. The MAC can make use of bandwidth-efficient burst profiles under favorable link conditions but shift to more reliable, though less efficient, alternatives as required to support the planned 99.999 percent link availability.

The request-grant mechanism is designed to be scalable, efficient, and self-correcting. The 802.16 access system does not lose efficiency when presented with multiple connections per terminal, multiple QoS levels per terminal, and a large number of statistically multiplexed users. It takes advantage of a wide variety of request mechanisms, balancing the stability of contentionless access with the efficiency of contention-oriented access.

Along with the fundamental task of allocating bandwidth and transporting data, the MAC includes a privacy sublayer that provides authentication of network access and connection establishment to avoid theft of service, and it provides key exchange and encryption for data privacy. To accommodate more demanding physical environment and different service requirements of the frequencies between 2 and 11 GHz, the 802.16a project is upgrading the MAC to provide automatic repeat request (ARQ) and support for mesh, rather than only point-to-multipoint, network architectures.

5.4.1.1 MAC Layer Details

The MAC includes service specific convergence sublayers that interface to higher layers, above the core MAC common part sublayer that carries out the key MAC functions. Below the common part sublayer is located the privacy sublayer.

I) Service Specific Convergence Sublayers

IEEE Standard 802.16 defines two general service-specific convergence sublayers for mapping services to and from 802.16 MAC connections. The ATM convergence sublayer is defined for ATM services, and the packet convergence sublayer is defined for mapping packet services such as IPv4, IPv6, Ethernet, and virtual local area network (VLAN). The primary task of the sublayer is to classify service data units (SDUs) to the proper MAC connection, preserve or enable QoS, and enable bandwidth allocation. The mapping takes various forms depending on the type of service. In addition to these basic functions, the convergence sublayers can also perform more sophisticated functions such as payload header suppression and reconstruction to enhance airlink efficiency.

II) Common Part Sublayer

Introduction and General Architecture — In general, the 802.16 MAC is designed to support a point-to-multipoint architecture with a central BS handling multiple independent sectors simultaneously. On the downlink, data to the subscriber stations (SSs) are multiplexed in TDM fashion. The uplink is shared between SSs in TDMA fashion.

The 802.16 MAC is connection-oriented. All services, including inherently connectionless services, are mapped to a connection. This provides a mechanism for requesting bandwidth, associating QoS and traffic parameters, transporting and routing data to the appropriate convergence sublayer, and all other actions associated with the contractual terms of the service. Connections are referenced with 16-bit connection identifiers (CIDs) and may require continuous availability of bandwidth or bandwidth on demand.

Each SS has a standard 48-bit MAC address, but this serves mainly as an equipment identifier, since the primary addresses used during operation are the CIDs. Upon entering the network, the SS is assigned three management connections in each direction. These three connections reflect the three different QoS requirements used by different management levels. The first of these is the basic connection, which is used for the transfer of short, time-critical MAC and radio link control (RLC) messages. The primary management connection is used to transfer longer, more delay-tolerant messages such as those used for authentication and connection setup. The secondary management connection is used for the transfer of standard-based management messages such as Dynamic Host Configuration Protocol (DHCP), Trivial File Transfer Protocol (TFTP), and Simple Network Management Protocol (SNMP).

The MAC reserves additional connections for other purposes. One connection is reserved for contention-based initial access. Another is reserved for broadcast transmissions in the downlink as well as for signaling broadcast contention-based polling of SS bandwidth needs. Additional connections are reserved for multicast, rather than broadcast, contention-based polling. SSs may be instructed to join multicast polling groups associated with these multicast polling connections.

MAC PDU Formats — The MAC PDU is the data unit exchanged between the MAC layers of the BS and its SSs. A MAC PDU consists of a fixed-length MAC header, a variable-length payload, and an optional cyclic redundancy check (CRC). Two header formats, distinguished by the HT field, are defined: the generic header (Figure 5) and the bandwidth request header. Except for bandwidth containing no payload, MAC PDUs have either MAC management messages or convergence sublayer data.

Three types of MAC subheader may be present. A grant management subheader is used by SS to convey bandwidth management needs to its BS. A fragmentation subheader indicates the presence and orientation within the payload of any fragments of the SDUs. The packing subheader is used to indicate packing of multiple SDUs into a single PDU. Immediately following the generic header a grant management and fragmentation subheaders may be inserted in MAC PDUs if so indicated by the Type field. The packing subheader may be inserted before each MAC SDU if shown by the Type field.

Transmission of MAC PDUs — The IEEE 802.16 MAC supports various higher-layer protocols such as ATM or IP. Incoming MAC SDUs from corresponding convergence sublayers are formatted according to the MAC PDU format, possibly with fragmentation and/or packing, before being conveyed over one or more connections in accordance with the MAC protocol. After traversing the airlink, MAC PDUs are reconstructed back into the original MAC SDUs so that the format modifications performed by the MAC layer protocol are transparent to the receiving entity.

IEEE 802.16 takes advantage of packing and fragmentation processes, and their effectiveness, flexibility and efficiency are maximized by the bandwidth allocation process. Fragmentation is the process in which a MAC SDU is divided into one or more MAC SDU fragments. Packing is the process in which multiple MAC SDUs are packed into a single MAC PDU payload. Both processes may be initiated by either a BS for a downlink connection or for an SS for an uplink connection. IEEE 802.16 allows simultaneous fragmentation and packing for efficient use of the bandwidth.

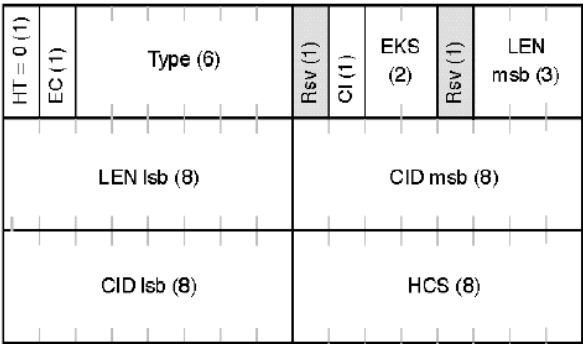


Figure 5 – Generic header for MAC PDU

PHY Support and Frame Structure — The IEEE 802.16 MAC supports both TDD and FDD. In FDD, both continuous and burst downlinks are possible. Continuous downlinks allow for certain robustness enhancement techniques, such as interleaving. Burst downlinks (either FDD or TDD) allow the use of more advanced robustness and capacity enhancement techniques, such as subscriber-level adaptive burst profiling and advanced antenna systems.

The MAC builds the downlink subframe starting with a frame control section containing the DL-MAP (downlink MAP) and UL-MAP (uplink MAP) messages. These indicate PHY transitions on the downlink as well as bandwidth allocations and burst profiles on the uplink. The DL-MAP is always applicable to the current frame and is always at least two FEC blocks long. To allow adequate processing time, the first PHY transition is expressed in the first FEC block. In both TDD and FDD systems, the UL-MAP provides allocations starting no

later than the next downlink frame. The UL-MAP can, however, start allocating in the current frame, as long as processing times and round-trip delays are observed.

Radio Link Control — The advanced technology of the 802.16 PHY requires equally advanced radio link control (RLC), particularly a capability of the PHY to change from one burst profile to another. The RLC must control this capability as well as the traditional RLC functions of power control and ranging. RLC begins with periodic BS broadcast of the burst profiles that have been chosen for the uplink and downlink. Among the several burst profiles used on a channel, one particular is chosen based on a number of factors, such as rain region and equipment capabilities. Burst profiles for the downlink are each tagged with a Downlink Interval Usage Code (DIUC) and those for the uplink are tagged with an Uplink Interval Usage Code (UIUC).

During initial access, the SS performs initial power leveling and ranging using ranging request (RNG-REQ) messages transmitted in initial maintenance windows. The adjustments to the SS's transmit time advance, as well as power adjustments, are returned to the SS in ranging response (RNG-RSP) messages. For ongoing ranging and power adjustments, the BS may transmit unsolicited RNG-RSP messages instructing the SS to adjust its power or timing. During initial ranging, the SS can also request service in the downlink via a particular burst profile by transmitting its choice of DIUC to the BS. The selection is based on received downlink signal quality measurements performed by the SS before and during initial ranging. The BS may confirm or reject the choice in the ranging response. Similarly, the BS monitors the quality of the uplink signal it receives from the SS. The BS commands the SS to use a particular uplink burst profile simply by including the appropriate burst profile UIUC with the SS's grants in ULMAP messages.

After initial determination of uplink and downlink burst profiles between the BS and a particular SS, RLC continues to monitor and control the burst profiles. Harsher environmental conditions, such as rain fades, can force the SS to request a more robust burst profile. Alternatively, exceptionally good weather may allow an SS to temporarily operate with a more efficient burst profile. The RLC continues to adapt the SS's current UL and DL burst profiles, ever striving to achieve a balance between robustness and efficiency. Because the BS is in control and directly monitors the uplink signal quality, the protocol for changing the uplink burst profile for an SS is simple by BS merely specifying the profile's associated UIUC whenever granting the SS bandwidth in a frame. This eliminates the need for an acknowledgment, since the SS will always receive either both the UIUC and the grant or neither. Hence, there exists no chance of uplink burst profile mismatch between the BS and the SS.

In the downlink, the SS is the entity that monitors the quality of the receive signal and therefore knows when its downlink burst profile should change. The BS, however, is the entity in control of the change. There are two methods available to the SS to request a change in downlink burst profile, depending on whether the SS operates in the grant per connection (GPC) or grant per SS (GPSS) mode. The first method would typically apply (based on the discretion of the BS scheduling algorithm) only to GPC SSs. In this case, the BS may periodically allocate a station maintenance interval to the SS. The SS can use the RNG-REQ message to request a change in downlink burst profile. The preferred method is for the SS to transmit a downlink burst profile change request (DBPC-REQ). In this case, which is always an option for GPSS SSs and can be an option for GPC SSs, the BS responds with a downlink burst profile change response (DBPC-RSP) message confirming or denying the change.

Because messages may be lost due to irrecoverable bit errors, the protocols for changing SS's downlink burst profile must be carefully structured. The order of the burst profile change actions is different when transitioning to a more robust burst profile than when transitioning to a less robust one. The standard takes advantage of the fact that any SS is always required to listen to more robust portions of the downlink as well as the profile that has been negotiated.

Channel Acquisition — The MAC protocol includes an initialization procedure designed to eliminate the need for manual configuration. Upon installation, SS begins scanning its frequency list to find an operating channel. It may be programmed to register with one specific BS, referring to a programmable BS ID broadcasted by each. This feature is useful in dense deployments where the SS might hear a secondary BS due to selective fading or when the SS picks up a side-lobe of a nearby BS antenna.

After deciding on which channel or channel pair to start communicating, the SS tries to synchronize to the downlink transmission by detecting the periodic frame preambles. Once the physical layer is synchronized, the SS looks for periodic DCD and UCD broadcast messages that enable the SS to learn the modulation and FEC schemes used on the carrier.

IP Connectivity — After registration, the SS attains an IP address via DHCP and establishes the time of day via the Internet Time Protocol. The DHCP server also provides the address of the TFTP server from which the SS can request a configuration file. This file provides a standard interface for providing vendor-specific configuration information.

5.4.2 Physical Layer

5.4.2.1 10-66 GHz

In the design of the PHY specification for 10–66 GHz, line-of-sight propagation has been deemed a practical necessity. With this condition assumed, single-carrier modulation could be easily selected to be employed in designated air interface “WirelessMAN-SC.” However, many fundamental design challenges remained. Because of a point-to-multipoint architecture, BS basically transmits a TDM signal, with individual subscriber stations allocated time slots sequentially. Access in the uplink direction is by TDMA. Following extensive discussions on duplexing, a burst design has been selected that allows both TDD (in which the uplink and downlink share a channel but do not transmit simultaneously) and FDD (in which the uplink and downlink operate on separate channels, sometimes simultaneously). This burst design allows both TDD and FDD to be handled in a similar fashion. Support for half-duplex FDD subscriber stations, which may be less expensive since they do not simultaneously transmit and receive, was added at the expense of some slight complexity. Both TDD and FDD alternatives support adaptive burst profiles in which modulation and coding options may be dynamically assigned on burst-by-burst basis.

5.4.2.2 2-11 GHz

The 2–11 GHz bands, both licensed and license-exempt, are addressed in IEEE Project 802.16a. The standard is in ballot but is not yet complete. The draft currently specifies that

compliant systems implement one of three air interface specifications, each of which can provide interoperability. Design of the 2–11 GHz physical layer is driven by the need for NLOS operation. Because residential applications are expected, rooftops may be too low for a clear sight line to the antenna of a BS, possibly due to obstruction by trees. Therefore, significant multipath propagation must be expected. Furthermore, outdoor-mounted antennas are expensive due to both hardware and installation costs.

The three 2–11 GHz air interface included in 802.16a Draft 3 specifications are:

- *WirelessMAN-SC2*: This uses a single-carrier modulation format.
- *WirelessMAN-OFDM*: This uses orthogonal frequency-division multiplexing with a 256-point transform. Access is by TDMA. This air interface is mandatory for license-exempt bands.
- *WirelessMAN-OFDMA*: This uses orthogonal frequency-division multiple access with a 2048-point transform. In this system, multiple access is provided by addressing a subset of the multiple carriers to individual receivers.

Because of the propagation requirements, the use of advanced antenna systems is supported. It is premature to speculate on further details of the 802.16a amendment prior to its completion. While the draft seems to have reached a level of maturity, the contents could significantly change by ballots. Modes could even be deleted or added.

5.4.2.3 Physical Layer Details

The PHY specification defined for 10–66 GHz uses burst single-carrier modulation with adaptive burst profiling in which transmission parameters, including the modulation and coding schemes, may be adjusted individually to each SS on a frame-by-frame basis. Both TDD and burst FDD variants are defined. Channel bandwidths of 20 or 25 MHz (typical U.S. allocation) or 28 MHz (typical European allocation) are specified, along with Nyquist square-root raised-cosine pulse shaping with a rolloff factor of 0.25. Randomization is performed for spectral shaping and ensuring bit transitions for clock recovery.

The FEC used is Reed-Solomon GF(256), with variable block size and appropriate error correction capabilities. This is paired with an inner block convolutional code to robustly transmit critical data, such as frame control and initial accesses. The FEC options are paired with QPSK, 16-state QAM (16-QAM), and 64-state QAM (64-QAM) to form burst profiles of varying robustness and efficiency. If the last FEC block is not filled, that block may be shortened. Shortening in both the uplink and downlink is controlled by the BS and is implicitly communicated in the uplink map (UL-MAP) and downlink map (DL-MAP).

The system uses a frame of 0.5, 1, or 2 ms. This frame is divided into physical slots for the purpose of bandwidth allocation and identification of PHY transitions. A physical slot is defined to be 4 QAM symbols. In the TDD variant of the PHY, the uplink subframe follows the downlink subframe on the same carrier frequency. In the FDD variant, the uplink and downlink subframes are coincident in time but are carried on separate frequencies.

The downlink subframe starts with a frame control section that contains the DL-MAP for the current downlink frame as well as the UL-MAP for a specified time in future. The downlink map specifies when physical layer transitions (modulation and FEC changes) occur

within the downlink subframe. The downlink subframe typically contains a TDM portion immediately following the frame control section. Downlink data are transmitted to each SS using a negotiated burst profile. The data are transmitted in order of decreasing robustness to allow SSs to receive their data before being presented with a burst profile that could cause them to lose synchronization with the downlink.

In FDD systems, the TDM portion may be followed by a TDMA segment that includes an extra preamble at the start of each new burst profile. This feature allows better support of half-duplex SSs. In an efficiently scheduled FDD system with many half-duplex SSs, some may need to transmit earlier in the frame than they are received. Due to their half-duplex nature, these SSs may lose synchronization with the downlink. The TDMA preamble allows them to regain synchronization.

Due to the dynamics of bandwidth demand for a variety of services that may be active, the mixture and duration of burst profiles and the presence or absence of a TDMA portion vary dynamically from frame to frame. Since the recipient SS is implicitly indicated in the MAC headers rather than in the DL-MAP, SSs listen to all portions of the downlink subframes they are capable of receiving. For full-duplex SSs, this means receiving all burst profiles of equal or greater robustness than they have negotiated with the BS.

Unlike the downlink, the UL-MAP grants bandwidth to specific SSs. The SSs transmit in their assigned allocation using the burst profile specified by the Uplink Interval Usage Code (UIUC) in the UL-MAP entry granting them bandwidth. The uplink subframe may also contain contention-based allocations for initial system access and broadcast or multicast bandwidth requests. The access opportunities for initial system access are sized to allow extra guard time for these SSs that have not resolved the transmit time advances necessary to offset the round-trip delay to the BS.

Between the PHY and MAC is a transmission convergence (TC) sublayer. This layer performs the transformation of variable length MAC PDUs into the fixed length FEC blocks (plus possibly a shortened block at the end) of each burst. The TC layer has a PDU sized to fit in the FEC block currently being filled. It starts with a pointer indicating where the next MAC PDU header starts within the FEC block (see Figure 6).

The TC PDU format allows resynchronization to the next MAC PDU in the event that the previous FEC block had irrecoverable errors. Without the TC layer, a receiving SS or BS would potentially lose the entire remainder of a burst when an irrecoverable bit error occurs.

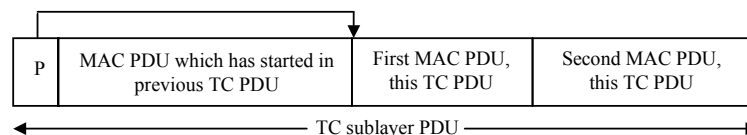


Figure 6 – TC PDU format

5.5 IEEE 802.11 as a Last Mile Alternative

Some companies are exploring the possibility of employing IEEE 802.11 WLAN standard (described in detail in the next section) as an alternative delivery platform to last mile broadband communication [21]. Originally designed to be used in office and even home environments, 802.11, and in particular 802.11b standard, is now starting to be considered as a last mile technology because of its extremely low cost as compared to existing BWA technologies.

If 802.11b wireless network is used as a last mile distribution technology and it does not solve all of BWA problems, it does certainly emphasize the importance of its business case. Since the IEEE 802.11b standard operates in the unlicensed 2.4 GHz band, the cost effectiveness of 802.11b and its largely unregulated operating band becomes a double edged-sword. Therefore, good network design approach and friendly co-operation ought to be employed amongst carriers.

Recent experiments [21] have shown that by employing standard components and a readily available antenna, a 802.11b network achieves reliable broadband access. In distances of 1 Km, a terminal with a standard 802.11b wireless card and a fixed antenna can receive data at the maximum 7.66 Mb/s data rate (802.11b portends to operate at 11 Mb/s but with the protocol overheads it effectively means the maximum data transfer rate is around 7.66 Mb/s). As a matter of fact, the range has been shown to be extendable to up to 7 Km although the quality of service suffers over such distances. The fact that the network is operating at a high quality speed over distance of greater than 1 Km, offers a great potential for the BWA market.

5.6 Various Standards

Broadband radio access standards and architectures are currently under serious discussion in Europe, Japan, and the United States. Different regions and countries use different terms when referring to these standards. In Europe, they are referred to as Broadband Radio Access Networks (BRAN); in the United States, as LMDS, IEEE 802.16, and BWA systems, among other terms. In Canada and some other countries, they are also referred to as Local Multipoint Communication Systems (LMCS). Their applications, however, are varied: from fixed to mobile, local to wide area, and include promising applications such as High-speed Internet access, two-way data communications (peer-to-peer or client/server), private or public telephony, two-way multimedia services such as videoconferencing and video commerce, and broadcast video.

For BRAN, broadband access consists of what is termed as High-Performance Radio Access (HIPERACCESS), HIPERLAN (covered in detail later in this chapter), and HIPERLINK, as shown in Figure 7. HIPERACCESS systems connect mainly residential, SOHO, and small to medium enterprise (SME) premises and allows access to a variety of telecommunications services such as voice, data, and multimedia services, with transmission rates varying from about 2 Mb/s to 25 Mb/s. HIPERACCESS is primarily to be used as a broadband remote access network. The radio spectrum can be in the 2–40 GHz range.

The second application referred to above, HIPERLAN, provides local access with controlled QoS for broadband applications (e.g., Internet and videoconferencing) to portable computers for use within buildings and on campus using mainly unlicensed radio spectrum in the 5 GHz band.

The third application of BRAN is called HIPERLINK, and is primarily a network–network radio interconnection which will support a variety of protocols and all the aforementioned traffic scenarios. This application would use bit rates of up to 155 Mb/s in parts of the 17 GHz radio spectrum.

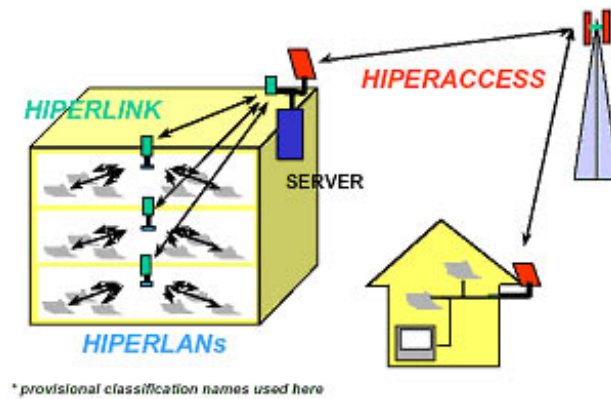


Figure 7 – Broadband wireless access

IEEE 802.16 covers more issues than HIPERACCESS, including WirelessMAN and Wireless High-Speed Unlicensed Metropolitan Area Networks (HUMANS), which include frequencies from 2 up to 66 GHz.

The International Telecommunication Union (ITU) initiated a working group called ITU JRG 8A-9B in charge of broadband wireless access system standardization. This group receives input from BRAN and IEEE 802.16 and tries to deliver a global consensus on this technology from the standpoint and function of the ITU. For details, see [44].

6. Wireless Local Area Networking

Wireless network technologies are expected to become more widespread than the current popular wired solutions. In the context of home networking, wireless communications present an ideal framework, while these do have a variety of technical and deployment obstacles. Among the technologies for wireless home networking, WLANs and WPANs systems are the key enablers, each one having its own characteristics and suitability for specific areas. Therefore, in this section we investigate the most prominent solutions for WLAN systems while later on we delve into WPAN technologies.

6.1 Wireless Home Networking Application Requirements

Today's home networking applications are driving the need for high-performance wireless network protocols with highly usable (effective) speed and isochronous, multimedia-capable services. Factor driving the need for high performance are:

- *Home networks incorporate multimedia* – Existing and emerging digital devices such as televisions, DVD players, digital video recorders, digital audio/MP3 players, DBS systems, flat-panel displays, digital set-top boxes, and PCs create a need to support multimedia content at home. The home network ought to support all types of digital content, including local content (e.g., DVD, MP3) and broadcast content (e.g., video on demand, streaming media). Such multimedia traffic encompasses video, audio, voice, and data. Internet multimedia broadcasting is already prevalent. An ability to support multimedia is expected to be the “killer app” that would encourage a massive acceptance and adoption of home networks. Therefore, a home network must support the coexistence of data (e.g., printing, file transfer) and isochronous content (e.g.,

voice, video). The consumer needs to choose products today that could provide a solid foundation for multimedia network services in the near future.

- *Consumers are adding more nodes to their home networks* – As mentioned earlier, the rapid growth of multi-PC homes indicates that the number of nodes in a PC network will continue to raise as new home network appliances are introduced. Wireless appliances may share the same bandwidth. Consequently, higher network throughput and adequate speed are necessary to accommodate additional home network devices. Choosing a wireless network with an access mechanism that supports multiple nodes without significantly degrading performance is essential to supporting a growing home wireless network.
- *The need to preserve high-speed broadband Internet access* – As we have seen in preceding sections, the desire for faster Internet access is driving a massive deployment of high-speed broadband access. Hence, consumers need to avoid any bottleneck and a high-performance wireless network is needed to maintain high-speed broadband access to devices.

6.2 IEEE Standard 802.11 for WLANs

The sky appears to be the limit for WLAN technologies. WLANs provide an excellent usage model for high-bandwidth consumers, and they are quite appealing for their low infrastructure cost and high data rates compared to other wireless data technologies such as 3G cellular or point-to-multipoint distribution systems.

In June 1997, IEEE approved the 802.11 standard [22, 35, 42] for WLANs, and in July 1997, IEEE 802.11 has been adopted as a worldwide International Standards Organization (ISO) standard. The standard consists of three possible physical (PHY) layer implementations and a single common MAC layer supporting data rates of 1 Mb/s or 2 Mb/s. The alternatives for PHY layer in the original standard include a FHSS system using 2 or 4 Gaussian frequency-shift keying (GFSK) modulation and a direct sequence spread spectrum (DSSS) system using differential binary phase-shift keying (DBPSK) or differential quadrature phase-shift keying (DQPSK) baseband modulation.

The IEEE 802.11 standard has been widely employed, as it can be easily adapted for business or residential use and for low-mobility environments such as airports, coffee shops, hotels and other locations where a need for broadband Internet access exists. Therefore, we now discuss this standard, its peculiarities, and its relevance with respect to the field of broadband wireless access.

6.2.1 Network Architecture

WLANs can be used either to replace wired LANs, or as an extension of the wired LAN infrastructure. The basic topology of an 802.11 network is shown in Figure 8(a). A Basic Service Set (BSS) consists of two or more wireless nodes, or stations (STAs), which have established communication after recognizing each other. In the most basic form, stations communicate directly with each other on a peer-to-peer mode, sharing a given cell coverage area. This type of network is often formed on a temporary instantaneous basis, and is commonly referred to as an *ad hoc* network [42], or Independent Basic Service Set (IBSS).

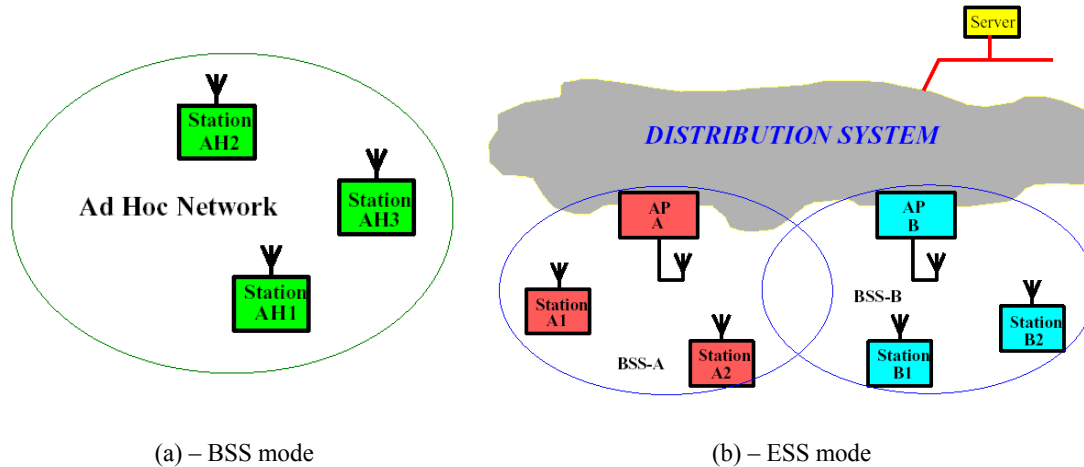


Figure 8 – Possible network topologies

The main function of an Access Point (AP) is to form a bridge between wireless and wired LANs. In most instances, each BSS contains an AP which is analogous to a BS used in cellular phone networks. When an AP is present, stations do not communicate on a peer-to-peer basis. All communications between stations or between a station and a wired network client go through the AP. AP's are not mobile, and form a part of the wired network infrastructure. A BSS in this configuration is said to be operating in the *infrastructure mode*. The Extended Service Set (ESS) shown in Figure 8(b) consists of a series of overlapping BSSs (each containing an AP) connected together by means of a Distribution System (DS) which could be any type of network and is almost invariably an Ethernet LAN. Mobile nodes can roam between APs and seamless coverage is possible.

6.2.2 MAC Layer

The IEEE 802 group has adopted the same MAC layer for both 802.11a [23, 35, 42] and 802.11b [22, 35]. The basic access method for 802.11 is the Distributed Coordination Function (DCF) which uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) [15]. This requires each station to listen for other potential users. If the channel is idle, the station may transmit. However if it is busy, each station waits until the current transmission completes, and then enters into a random back off procedure. This prevents multiple stations from seizing the medium immediately after completion of the preceding transmission.

Packet reception in DCF requires acknowledgement as shown in Figure 9(a). The period between completion of packet transmission and start of the ACK frame is one Short Inter Frame Space (SIFS). ACK frames have a higher priority over other traffic. Fast acknowledgement is one of the salient features of the 802.11 standard, because it requires ACKs to be handled at the MAC sublayer. Transmissions other than ACKs must wait at least one DCF inter frame space (DIFS) before transmitting data. If a transmitter senses a busy medium, it determines a random back-off period by setting an internal timer to an integer number of slot times. Upon expiration of a DIFS, the timer begins to decrement. If the timer reaches zero, the station may begin transmission. However, if the channel is seized by another station before the timer reaches zero, the timer setting is retained at the decremented value for subsequent transmission.

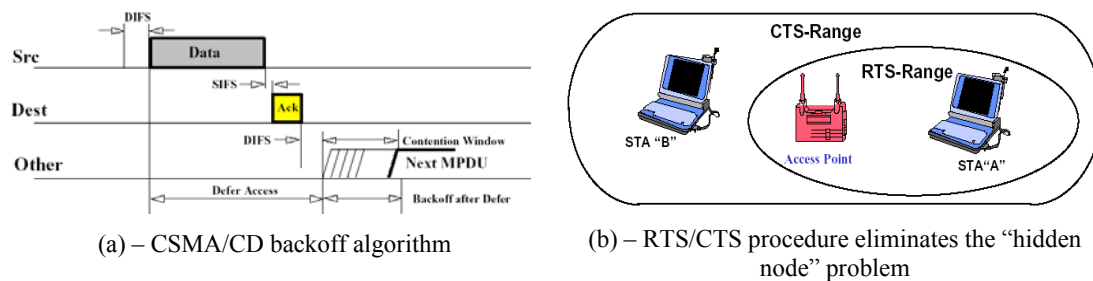


Figure 9 – CSMA/CD and RTS/CTS exchange in 802.11

The method described above relies on the *Physical Carrier Sense*. The underlying assumption is that every station can “hear” all other stations. This is not always the case. Referring to Figure 9(b), the AP is within range of the STA-A, but STA-B is out of range. STA-B would not be able to detect transmissions from STA-A, and the probability of collision is greatly increased. This is known as the *Hidden Node*.

To combat this problem, a second carrier sense mechanism is available. *Virtual Carrier Sense* enables a station to reserve the medium for a specified period of time through the use of RTS/CTS frames. In the case described above, STA-A sends an RTS frame to the AP. The RTS will not be heard by STA-B. The RTS frame contains a duration/ID field which specifies the period of time for which the medium is reserved for a subsequent transmission. The reservation information is stored in the Network Allocation Vector (NAV) of all stations detecting the RTS frame.

Upon receipt of the RTS, the AP responds with a CTS frame, which also contains a duration/ID field specifying the period of time for which the medium is reserved. While STA-B did not detect the RTS, it will detect the CTS and update its NAV accordingly. Thus, collision is avoided even though some nodes are hidden from other stations. The RTS/CTS procedure is invoked according to a user specified parameter. It can be used always, never, or for packets which exceed an arbitrarily defined length.

A PHY layer convergence procedure (PLCP) maps a MAC PDU into a frame format. Figure 10(c) shows the format of a complete packet (PPDU) in 802.11a, including the preamble, header, and PHY layer service data unit (PSDU or payload):

- The header contains information about the length of the payload and the transmission rate, a parity bit, and six zero tail bits. The header is always transmitted using the lowest-rate transmission mode in order to ensure robust reception. Hence, it is mapped onto a single binary phase shift keying (BPSK) modulated orthogonal frequency-division multiplexed (OFDM) symbol.
- The rate field conveys information about the type of modulation and the coding rate used in the rest of the packet.
- The length field takes a value between 1 and 4095, and specifies the number of bytes in the PSDU.
- The parity bit is a positive parity for the first 17 bits of the header.

- The 6 tail bits are used to reset the convolutional encoder and terminate the code trellis in the decoder.
- The first 7 bits of the service field are set to zero and used to initialize the descrambler. The remaining 9 bits are reserved for future use.
- The pad bits are used to ensure that the number of bits in the PPDU maps to an integer number of OFDM symbols.

As mentioned above, DCF is the basic media access control method for 802.11 and it is mandatory for all stations. The Point Coordination Function (PCF) is an optional extension to DCF. PCF provides a time division duplexing capability to accommodate time bounded, connection-oriented services such as cordless telephony.

6.2.3 Physical Layer

Knowing what some of the physical layer terminology means is essential to understanding the intricacies of 802.11.

- GFSK is a modulation scheme in which the data are first filtered by a Gaussian filter in the baseband, and then modulated with a simple frequency modulation. “2” and “4” represent the number of frequency offsets used to represent data symbols of one and two bits, respectively.
- DBPSK is phase modulation using two distinct carrier phases for data signaling providing one bit per symbol.
- DQPSK is a type of phase modulation using two pairs of distinct carrier phases, in quadrature, to signal two bits per symbol. The differential characteristic of the modulation schemes indicates the use of the difference in phase from the last change or symbol to determine the current symbol’s value, rather than any absolute measurements of the phase change.

Both the FHSS and DSSS modes are specified for operation in the 2.4 GHz industrial, scientific and medical (ISM) band, which has sometimes been jokingly referred to as the “interference suppression is mandatory” band because it is heavily used by various electronic products. The third physical layer alternative is an infrared system using near-visible light in the 850 nm to 950 nm range as the transmission medium.

At the forefront of the new WLAN options that will enable much higher data rates are two supplements to the IEEE 802.11 standard: 802.11b and 802.11a, as well as a European Telecommunications Standards Institute (ETSI) standard called as High Performance LAN (HIPERLAN/2). Both 802.11 and HIPERLAN/2 have similar physical layer characteristics operating in the 5 GHz band and use the modulation scheme OFDM, but the MAC layers are considerably different. The focus here, however, is to discuss and compare the physical layer characteristics of 802.11a and 802.11b. HIPERLAN/2 shares several of the same physical properties as 802.11a, and will be covered later in this chapter.

Another standard that warrants mention in this context is IEEE 802.11g. With a ruling from the FCC that will now allow OFDM digital transmission technology to operate in the

ISM band, and the promise of interoperability with a large installed base of 802.11b products, the 802.11g extension to the standard begins to garner the attention of WLAN equipment providers. Although not detailed here, it will offer data rates equal to or exceeding 22 Mb/s with products available late in 2002.

6.2.3.1 802.11b Details

802.11b, approved by the IEEE in 1999, is an extension of the 802.11 DSSS system mentioned earlier and supports 5.5 and 11 Mb/s of higher payload data rates in addition to the original 1 and 2 Mb/s rates. Many commercial products are now available, and the systems base is growing rapidly. 802.11b also operates in the highly populated 2.4 GHz ISM band (2.40 to 2.4835 GHz), which provides only 83 MHz of spectrum to accommodate a variety of other products, including cordless phones, microwave ovens, other WLANs, and PANs. This makes susceptibility to interference a primary concern. The occupied bandwidth of the spread-spectrum channel is 22 MHz, so the ISM band accommodates only three non-overlapping channels spaced 25 MHz apart. To help mitigate interference effects, 802.11b designates an optional frequency agile or hopping mode using the three non-overlapping channels or six overlapping channels spaced at 10 MHz.

802.11b uses eight-chip complementary code keying (CCK) as the modulation scheme to achieve higher data rates. Instead of the Barker codes used to encode and spread the data for the lower rates, CCK uses a nearly orthogonal complex code set called complementary sequences. The chip rate remains consistent with the original DSSS system at 11 Mchip/s, while the data rate varies to match channel conditions by changing the spreading factor and/or the modulation scheme.

To achieve data rates of 5.5 and 11 Mb/s, the spreading length is first reduced from 11 to eight chips. This increases the symbol rate from 1 Msym/s to 1.375 Msym/s. For the 5.5 Mb/s bit rate with a 1.375 MHz symbol rate, it is necessary to transmit 4 bits/symbol ($5.5 \text{ Mb/s} / 1.375 \text{ Msym/s}$) and for 11 Mb/s, an 8 bits/symbol. The CCK approach taken in 802.11b, keeps the QPSK spread-spectrum signal and still provides the required number of bits/symbol, uses all but two of the bits to select from a set of spreading sequences and the remaining two bits to rotate the sequence. The selection of the sequence, coupled with the rotation, represents the symbol conveying the four or eight bits of data. For all 802.11b payload data rates, the preamble and header are sent at the 1 Mb/s rate.

6.2.3.2 802.11a Details

While 802.11a has been approved in September 1999, new product development has proceeded much more slowly than 802.11b. This is due to the cost and complexity of implementation. This standard employs 300 MHz bandwidth in the 5 GHz unlicensed national information infrastructure (UNII) band. The spectrum is divided into three “domains,” each having restrictions imposed on the maximum allowed output power. The first 100 MHz in the lower frequency portion is restricted to a maximum power output of 50 mW. The second 100 MHz has a higher 250 mW maximum, while the third 100 MHz is mainly intended for outdoor applications and has a maximum of 1.0 W power output.

OFDM, employed by 802.11a, operates by dividing the transmitted data into multiple parallel bit streams, each with relatively lower bit rates and modulating separate narrowband carriers, referred to as sub-carriers. The sub-carriers are orthogonal, so each can be received without interference from another. 802.11a specifies eight non-overlapping 20 MHz channels

in the lower two bands; each of these are divided into 52 sub-carriers (four of which carry pilot data) of 300-kHz bandwidth each. Four non-overlapping 20 MHz channels are specified in the upper band. The receiver processes the 52 individual bit streams, reconstructing the original high-rate data stream. Four complex modulation methods are employed, depending on the data rate that can be supported by channel conditions between the transmitter and the receiver. These include BPSK, QPSK, 16-QAM, and 64-QAM.

Quadrature amplitude modulation is a complex modulation method where data are carried in symbols represented by the phase and amplitude of the modulated carrier. 16-QAM has 16 symbols. Each represents four data bits. 64-QAM has 16 symbols with each representing four data bits.

BPSK modulation is always used on four pilot sub-carriers. Although it adds a degree of complication to the baseband processing, 802.11a includes forward error correction (FEC) as a part of the specification. FEC, which does not exist within 802.11b, enables the receiver to identify and correct errors occurring during transmission by sending additional data along with the primary transmission. This nearly eliminates the need for retransmissions when packet errors are detected. The data rates available in 802.11a are noted in Table 2, together with the type of modulation and the coding rate.

Table 2 – 802.11a data rate description

Data Rate (Mbit/s)	Modulation Type	Coding Rate (Convolutional Encoding & Puncturing)	Coded bits per sub-carrier symbol	Coded bits per OFDM symbols	Data bits per OFDM symbol
6*	BPSK	1/2	1	48	24
9	BPSK	3/4	1	48	36
12*	QPSK	1/2	2	96	48
18	QPSK	3/4	2	96	72
24*	16-QAM	1/2	4	192	96
36	16-QAM	3/4	4	192	144
48	64-QAM	2/3	6	288	192
54	64-QAM	3/4	6	288	216

* Support for these data rates is required by the 802.11a standard

802.11a products were expected to begin arriving in the first half of 2002. Some of the companies developing 802.11a chipset solutions are touting the availability of operational modes that exceed the 54 Mb/s stated in the specification. Of course, because faster data rates are out of the specification's scope, they require the use of equipment from a single source throughout the entire network.

Considering the composite waveform resulting from the combination of 52 sub-carriers, the format requires more linearity in the amplifiers because of the higher peak-to-average power ratio of the transmitted OFDM signal. In addition, enhanced phase noise performance is required because of the closely spaced, overlapping carriers. These issues add to the implementation complexity and cost of 802.11a products. Application-specific measurement tools aid in the design and troubleshooting of OFDM signals and systems.

6.2.3.3 Pros and Cons of 802.11b and 802.11a

The 5 GHz band has received considerable attention, but its drawback is the shorter wavelength. Higher-frequency signals will have more trouble propagating through physical obstructions encountered in an office (walls, floors, and furniture) than those at 2.4 GHz. An advantage of 802.11a is its intrinsic ability to handle delay spread or multipath reflection effects. The slower symbol rate and placement of significant guard time around each symbol, using a technique called cyclical extension, reduces the inter-symbol interference (ISI) caused by multipath interference. (The last one-quarter of the symbol pulse is copied and attached to the beginning of the burst. Due to the periodic nature of the signal, the junction at the start of the original burst will always be continuous.). In contrast, 802.11b networks are generally range-limited by multipath interference rather than the loss of signal strength over distance.

When it comes to deployment of a wireless LAN, operational characteristics have been compared to those of cellular systems, where frequency planning of overlapping cells minimizes mutual interference, supports mobility as well as provides seamless channel handoff. The three non-overlapping frequency channels available for IEEE 802.11b are at a disadvantage as compared to the greater number of channels available to 802.11a. The additional channels allow more overlapping access points within a given area while avoiding additional mutual interference.

Both 802.11b and 802.11a use dynamic rate shifting where the system will automatically adjust the data rate based on the condition of the radio channel. If the channel is clear, then the modes with the highest data rates are used. But as interference is introduced into the channel, the radio will fall back to a slower, albeit more robust, transmission scheme.

6.3 HIPERLAN/2 Standard for WLANs

While 802.11 is the standard defined by IEEE, the ETSI BRAN has developed the HIPERLAN/2 standard [24] which also operates at 5 GHz frequency band similarly to 802.11a. These two standards primarily differ in the MAC layer [25 – 28], however some minor differences also occur in the PHY layers. Here, we discuss the HIPERLAN/2 standard as a means to providing a foundation to broadband access to the home and office environment.

The HIPERLAN/2 radio network is defined in such a way that there are core-independent PHY and data link control (DLC) layers as well as a set of convergence layers (CLs) for interworking. The CLs include Ethernet, ATM, and IEEE 1394 infrastructure [29], and technical specifications for HIPERLAN/2–third generation (3G) interworking are expected to be completed mid-2002. IEEE 802.11a defines similarly independent PHY and MAC layers (with the MAC common to multiple PHYs within the 802.11 standard). A similar approach to network protocol convergence is expected.

Basically, the network topology of HIPERLAN/2 is the same as in 802.11 (Figure 8). Therefore, following the same approach adopted for 802.11, we first discuss the MAC layer characteristics of HIPERLAN/2 and then move on to its physical layer details. Since we now have an understanding of 802.11, we follow an approach where we discuss HIPERLAN/2 continuously comparing their properties with that of 802.11.

6.3.1 MAC Layer

As we mentioned earlier, the main differences between the IEEE 802.11 and HIPERLAN/2 standards occur at the MAC layer. In HIPERLAN/2, medium access is based on a TDMA/TDD approach using a MAC frame with a period of 2 ms [30]. This frame comprises uplink (to the AP), downlink (from the AP), and direct link (DiL, directly between

two stations) phases. These phases are scheduled centrally by the AP, which informs STAs, at which point in time in the MAC frame they are allowed to transmit their data. Time slots are allocated dynamically depending on the need for transmission resources. The HIPERLAN/2 MAC is designed to provide quality of service support, essential to many multimedia and real-time applications.

On the other hand, IEEE 802.11a uses the distributed CSMA/CA MAC protocol that obviates the requirement for any centralized control. The use of a distributed MAC makes IEEE 802.11a more suitable for ad hoc networking and non-real-time applications. Another significant difference between the two standards is the length of the packets employed. HIPERLAN/2 employs fixed length packets, while 802.11a supports variable length packets.

The HIPERLAN/2 MAC frame structure (Figure 10(a)) comprises time slots for broadcast control (BCH), frame control (FCH), access feedback control (ACH), and data transmission in downlink (DL), uplink (UL), and direct link (DiL) phases, which are allocated dynamically depending on the need for transmission resources. An STA first has to request capacity from the AP in order to send data. This is performed in the random access channel (RCH), where contention for the same time slot is allowed.

DL, UL, and DiL phases consist of two types of PDUs: long and short. The long PDUs (illustrated in Figure 10(b)) have a size of 54 bytes and contain control or user data. The payload comprises of 48 bytes, and the remaining bytes are used for the PDU type, a sequence number (SN), and cyclic redundancy check (CRC-24). Long PDUs are referred to as the long transport channel (LCH).

Short PDUs contain only control data and have a size of 9 bytes. They may contain resource requests, automatic repeat request (ARQ) messages, and so on, and are referred to as the short transport channel (SCH).

Traffic from multiple connections to/from one STA can be multiplexed onto one PDU train, which contains long and short PDUs. A physical burst is composed of the PDU train payload preceded by a preamble, and is the unit to be transmitted via the PHY layer [24].

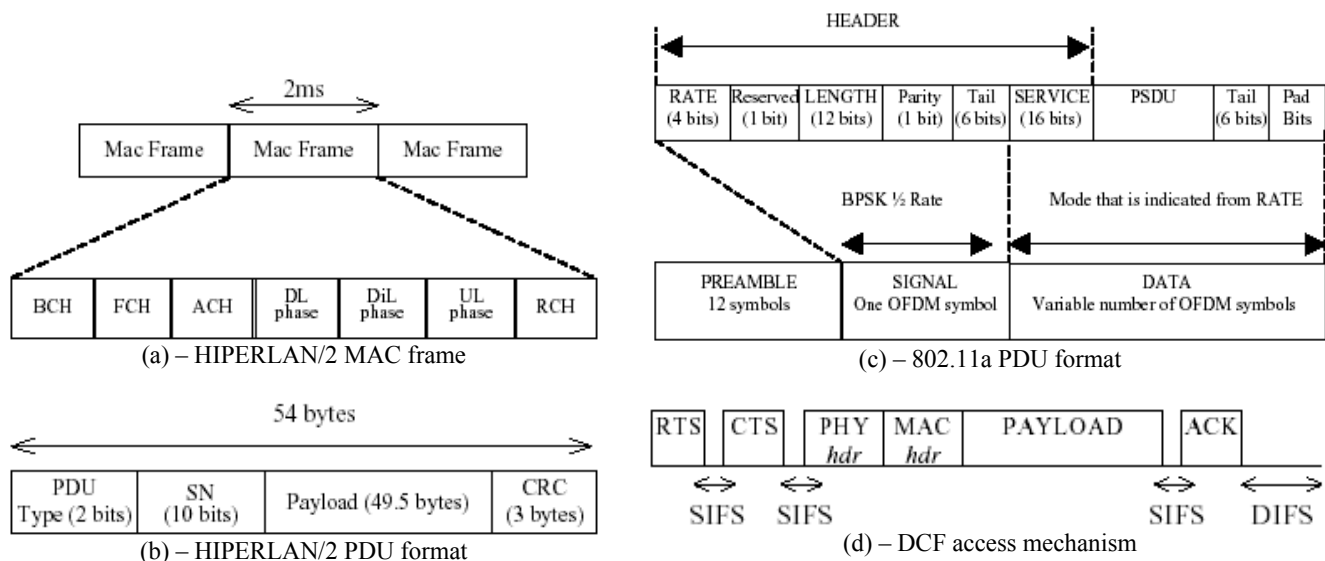


Figure 10 – MAC structures for HIPERLAN/2 and 802.11a

6.3.2 Physical Layer

The PHY layers of both 802.11a and HIPERLAN/2 are very similar and are based on the use of OFDM. As we already know, OFDM is used to combat frequency selective fading and to randomize the burst errors caused by a wideband fading channel. The PHY layer modes (similar to Table 2) with different coding and modulation schemes are selected by a link adaptation scheme [29, 31]. The exact mechanism of this process is not specified in the standards.

Data for transmission is supplied to the PHY layer in the form of an input PDU train or PPDU frame, as explained earlier. This is then input to a scrambler that prevents long runs of 1s and 0s in the input data being sent to the remainder of the modulation process. Although both 802.11a and HIPERLAN/2 scramble the data with a length 127 pseudorandom sequence, the initialization of the scrambler is different.

The scrambled data is input to a convolutional encoder. The encoder consists of a 1/2 rate mother code and subsequent puncturing. The puncturing schemes facilitate the use of code rates 1/2, 3/4, 9/16 (HIPERLAN/2 only), and 2/3 (802.11a only). In the case of 16-QAM, HIPERLAN/2 uses rate 9/16 instead of rate 1/2 in order to ensure an integer number of OFDM symbols per PDU train. The rate 2/3 is used only for the case of 64-QAM in 802.11a. Note that there is no equivalent mode for HIPERLAN/2. HIPERLAN/2 also uses additional puncturing in order to keep an integer number of OFDM symbols with 54-byte PDUs.

The coded data is interleaved in order to prevent error bursts from being input to the convolutional decoding process in the receiver. The interleaved data is subsequently mapped to data symbols according to either a BPSK, QPSK, 16-QAM, or 64-QAM constellation. OFDM modulation is implemented by means of an inverse fast Fourier transform (FFT). 48 data symbols and 4 pilots are transmitted in parallel in the form of one OFDM symbol.

In order to prevent intersymbol interference (ISI) and intercarrier interference (ICI) due to delay spread, a guard interval is implemented by means of a cyclic extension. Thus, each OFDM symbol is preceded by a periodic extension of the symbol itself. The total OFDM symbol duration is $T_{total} = T_g + T$, where T_g represents the guard interval and T the useful OFDM symbol duration. When the guard interval is longer than the excess delay of the radio channel, ISI is eliminated.

The OFDM receiver basically performs the reverse operations of the transmitter. However, the receiver is also required to undertake AGC (Automatic Gain Control), time and frequency synchronization, and channel estimation. Training sequences are provided in the preamble for the specific purpose of supporting these functions. Two OFDM symbols are provided in the preamble in order to support the channel estimation process. A prior knowledge of the transmitted preamble signal facilitates the generation of a vector defining the channel estimate, commonly referred to as the channel state information (CSI).

The channel estimation preamble is formed such that the two symbols effectively provide a single guard interval of length 1.6 ms. This format makes it particularly robust to ISI. By averaging over two OFDM symbols, the distorting effects of noise on the channel estimation process can also be reduced. HIPERLAN/2 and 802.11a use different training sequences in the preamble. The training symbols used for channel estimation are the same, but the sequences provided for time and frequency synchronization are different. Decoding of the convolutional code is typically implemented by means of a Viterbi decoder.

7. Wireless Personal Area Networking

In this section, we initially explore the consumer applications requirements of wireless home networking. We then present a detailed description of the technologies, companies and industry groups that are seeking to tap into this vast consumer market opportunity with emphasis on the WPAN systems.

7.1 Bluetooth and WPANs

In the past quarter century we have seen the rollout of three generations of wireless cellular systems attracting end-users by providing efficient mobile communications. On another front, wireless technology became an important component in providing networking infrastructure for localized data delivery. This later revolution was made possible by the induction of new networking technologies and paradigms, such as WLANs and WPANs.

WPANs are short to very short-range (from a couple centimeters to a couple of meters) wireless networks that can be used to exchange information between devices in the reach of a person. WPANs can be used to replace cables between computers and their peripherals, to establish communities helping people do their everyday chores making them more productive, or to establish location aware services. WLANs on the other hand provide with a larger transmission range. Although WLAN equipment usually carries the capability to be set up for ad hoc networking, the premier choice of deployment is yet a cellular like infrastructure mode to interface wireless users with the Internet. The best example representing WPANs is the recent industry standard: Bluetooth [32, 42], other examples include Spike [33], IrDA [1], and in the broad sense HomeRF [34]. As we have seen, for WLANs the most well known representatives are based on the standards IEEE 802.11 and HIPERLAN with all their variations.

The IEEE 802 committee has also realized the importance of short-range wireless networking and initiated the establishment of the IEEE 802.15 WG for WPANs [36] to standardize protocols and interfaces for wireless personal area networking. Altogether, the 802.15 WG is formed by four Task Groups (TG):

- IEEE 802.15 WPAN/Bluetooth TG 1 – The TG 1 was established to support applications which require medium-rate WPANs (such as Bluetooth). These WPANs will handle a variety of tasks ranging from cell phones to PDA communications and have a QoS suitable for voice applications.
- IEEE 802.15 Coexistence TG 2 – Several wireless standards, such as Bluetooth and IEEE 802.11b, and appliances, such as microwaves operate, in the unlicensed 2.4 GHz ISM (Industrial-Scientific-Medical) frequency band. The TG 2 is developing specifications on the ISM band due to the unlicensed nature and available bandwidth. Thus, the IEEE 802.15 Coexistence TG 2 (802.15.2) for Wireless Personal Area Networks is developing Recommended Practices to facilitate coexistence of Wireless Personal Area Networks (802.15) and Wireless Local Area Networks (802.11).
- IEEE 802.15 WPAN/High Rate TG 3 – The TG3 for WPANs is chartered to draft and publish a new standard for high-rate (20Mbit/s or greater) WPANs. Besides a high data rate, the new standard will provide for low power, low cost solutions addressing the needs of portable consumer digital imaging and multimedia applications. This developing standard is discussed later in this chapter.

- IEEE 802.15 WPAN/Low Rate TG 4 – The goal of the TG 4 is to provide a standard having ultra-low complexity, cost, and power for a low-data-rate (200Kb/s or less) wireless connectivity among inexpensive fixed, portable, and moving devices. Location awareness is being considered as a unique capability of the standard. The scope of the TG 4 is to define the physical and media access control (MAC) layer specifications. Potential applications are sensors, interactive toys, smart badges, remote controls, and home automation. Further details on 802.15.4 are provided later in this chapter.

One key issue in the feasibility of WPANs is the inter-working of wireless technologies to create heterogeneous wireless networks. For instance, WPANs and WLANs will enable an extension of the 3G cellular networks (i.e., UMTS and cdma2000) into devices without direct cellular access. Moreover, devices interconnected in a WPAN may be able to utilize a combination of 3G access and WLAN access by selecting the access that is best for a given time. In such networks 3G, WLAN and WPAN technologies do not compete against each other but enable the user to select the best connectivity for his/her purpose. Figure 11 [42] clearly shows the operating space of the various 802 wireless standards and activities still in progress.

Given the importance within the WPAN operating space, intensive research activities, and availability of devices, we now devote a little time in, first, giving a brief introduction on Bluetooth and then provide an overview of the Bluetooth standard as defined by the Bluetooth SIG (Special Interest Group).

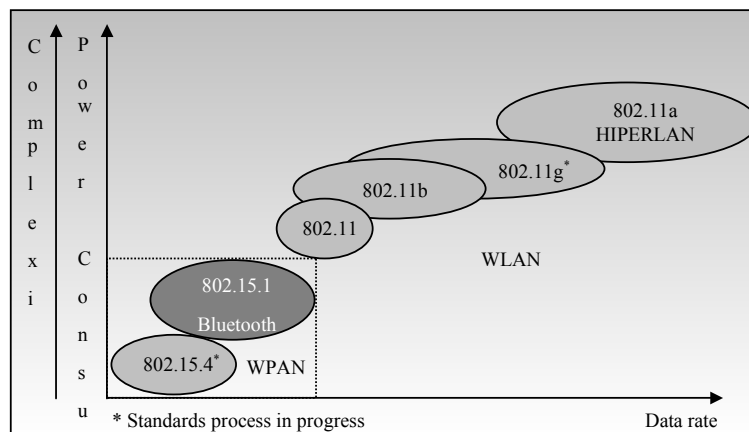


Figure 11 – The scope of the various WLAN and WPAN standards

7.1.1 Brief History and Applications of Bluetooth

In the context of wireless personal area networks, the Bluetooth technology came to light in May 1998, and since then the Bluetooth SIG has steered the development of an open industry specification, called Bluetooth, including both protocols and applications scenarios. A study in July 2001 by Micrologic Research forecasts that, in 2005, *1.2 billion Bluetooth* chips will be shipped worldwide.

The Bluetooth SIG is an industry group consisting of leaders in the telecommunications and computing industries that are driving the development of Bluetooth WPAN technology.

Bluetooth wireless technology has become a de facto standard, as well as a specification for small-form factor, low-cost, short-range radio links between mobile PCs, mobile phones and other portable devices [37]. The Bluetooth SIG includes promoter companies such as 3Com, Ericsson, IBM, Intel, Microsoft, Motorola, Nokia and Toshiba, and many more adopter companies. The goal of Bluetooth is to enable users to easily connect a wide range of computing and telecommunications devices, without a need to buy, carry, or connect cables. It enables rapid ad hoc connections, and the possibility of automatic, unconscious connections between devices. Because Bluetooth can be used for a variety of purposes, it will also potentially replace multiple cable connections via a single radio link [37].

The Bluetooth specification is divided into two parts:

- *The Core* – This portion specifies components such as the radio, baseband (medium access), link manager, service discovery protocol, transport layer, and interoperability with different communication protocols.
- *The Profile* – The Profile portion specifies the protocols and procedures required for different types of Bluetooth applications.

Bluetooth has a tremendous potential in moving and synchronizing information in a localized setting. Potential for Bluetooth applications is huge, because we do business transactions and communicate more frequently with the people who are close by as compared to those who are far away - a natural phenomenon of human interaction.

7.1.2 Bluetooth Details

Bluetooth [32] operates in the ISM frequency band starting at 2.402 GHz and ending at 2.483 GHz in USA and most countries of Europe. A total of 79 RF channels of 1 MHz width are defined, where the raw data rate is 1 Mbit/s. A TDD technique divides the channel into 625 μ s slots and, with a 1Mbit/s symbol rate, a slot can carry up to 625 bits. Transmission in Bluetooth occurs in packets that occupy 1, 3 or 5 slots. Each packet is transmitted on a different hop frequency with a maximum frequency hopping rate of 1600 hops/s. Therefore, a FHSS technique is employed for communication.

The goals of the specifications are to eliminate the need for wires and to simplify ad hoc networking among devices. It utilizes small inexpensive radios for the physical layer and for Master-Slave relationship at the MAC layer between devices. The Master periodically polls the Slave devices for information and only after receiving such a poll, is a Slave is allowed to transmit. Therefore, the Master is responsible for controlling access to the network, providing services to slave nodes and allowing them to conserve power.

A Master device can directly control seven active Slave devices in what is defined as a *piconet*. Piconets are small WPANs that are formed when Bluetooth enabled devices are in proximity to each other and share the same hopping sequence and phase. A total of 79 carriers with 1 MHz spacing and a slot of size 625 μ s allow Bluetooth to support piconets with up to 1 Mbps data rate. Transmitting power levels near 100 mW allows devices to be up to 10 meters apart and if special transceivers are used, networking up to a 100 meters range is also possible.

A node can enter and leave a piconet at any time without disrupting the piconet. More than 8 nodes can be allowed to form a network by making a node act as a bridge between two

piconets and create a larger network called a *scatternet*. Figure 12 [42] illustrates a scatternet composed of four piconets, where each piconet has several slaves (indicated by the letter $S_{i,j}$) and one master (indicated by the letter M_i). Figure 13 depicts the Bluetooth protocol stack, which also shows the application “layer” at the top where the profiles would reside. The protocols that belong to the Core specifications are:

- The Radio – The radio layer, which resides below the Baseband layer, defines the technical characteristics of the Bluetooth radios. The Bluetooth radios come in three power classes. Class 1 radios have transmit power of 20 dBm (100 mW); class 2 radios have transmit power of 4 dBm (2.5 mW); class 3 radios have transmit power of only 0 dBm (1 mW).
- The Baseband – The baseband defines the key medium access procedures that enable devices to communicate with each other using the Bluetooth wireless technology. The baseband defines the Bluetooth piconets and their creation procedure. It also defines the low-level packet types.
- The Link Manager Protocol (LMP) – The LMP is a transactional protocol between two link management entities in communicating Bluetooth devices.
- The Logical Link Control & Adaptation Protocol (L2CAP) – The L2CAP layer shields specifics of the Bluetooth lower layers and provides a packet interface to higher layers. At L2CAP, the concept of master and slave devices does not exist anymore.

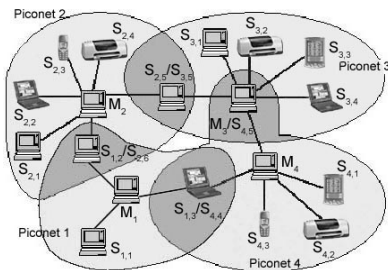


Figure 12 – Four piconets forming a scatternet

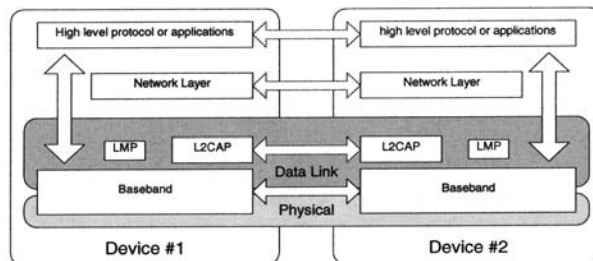


Figure 13 – Bluetooth protocol architecture

The Bluetooth specification defines two distinct types of links for the support of voice and data applications, namely, SCO (*Synchronous connection-oriented*) and ACL (*Asynchronous connectionless*). The first link type supports point to point voice switched circuits while the latter supports symmetric as well as asymmetric data transmission. ACL packets are intended to support data applications and do not have prescribed time slot allocations as opposed to SCO packets, which support periodic audio transmission at 64Kb/s in each direction.

Bluetooth addresses many of the issues such as power, cost, size, simplicity that make it very appealing for use in WPANs. IEEE is looking at Bluetooth and how it addresses the functional requirements of 802.15. As a matter of fact, large portions of Bluetooth have been adopted for recommendation to the 802 Group as the 802.15.1 standard [36].

7.2 Infrared Data Association's (IrDA) Serial Infrared (SIR) Data and Advanced Infrared (AIR) Specifications

The Infrared Data Association (IrDA) [1] has been founded as a non-profit organization in 1993, and is an industry-focused group of device manufacturers that have developed a standard for transmitting data via infrared light waves. Their goal has been to create a low-cost, low-power, half-duplex, serial data interconnection standard that supports a walk-up, point-to-point user model. The latest IrDA SIR core specification is divided into three parts: IrDA Data, IrDA Control and IrDA PC99. Each one is used differently, depending on the type of device to be connected. IrDA PC99 is intended for low speed devices such as keyboards, joysticks and mouse. IrDA Control is recommended in-room cordless peripherals to host PCs such as printers or scanners. IrDA Data is recommended for high-speed, short-range, line of sight, point-to-point cordless data transfer such as local area networking or file sharing.

The IrDA Data architecture has some serious limitations. First, although the architecture can accommodate a point-to-multipoint mode of operation, the IrDA Data specification has never been extended to define the protocols to enable this multipoint functionality. Second, within a given field of view, the establishment of an IrDA Data connection between a single pair of devices inhibits the establishment of connections between other independent devices whose fields of view intersects with that of an established connection. Thus, the use of the medium becomes dedicated to a single pair of devices. Having realized, among other things, that IrDA is not well suited to WPAN environments, the members of the IrDA community have extended the IrDA Data architecture to enable true multipoint connectivity while at the same time limiting the investment in upper layer applications and services. This has resulted in the IrDA AIR specification, which does offer some improvement on mobility freedom to IrDA devices.

7.2.1 IrDA Data and IrDA AIR Details

IrDA Data is one of out three protocols in the Infrared Data Association's (IrDA) Serial Infrared (SIR) Data specification. IrDA Data is recommended for high-speed short-range, line of sight, point-to-point cordless data transfer. IrDA Data has required protocols and optional protocols to meet the connectivity needs of WPAN devices if both implemented. The three required protocols for IrDA Data are PHY (Physical Signaling Layer), IrLAP (Link Access Protocol), and IrLMP (Link Management Protocol and Information Access Service). Table 3 illustrates the IrDA Data protocol stack [4] with the mandatory and optional protocols.

IrDA Data utilizes optical signaling in the 850 nm range for the PHY layer and uses a polling channel access scheme. Data rates for IrDA Data range from 2400 bps to 4 Mbps. The typical distance for IrDA Data devices is about one meter and up to two meters can be reached. IrDA Data has built in tolerances so that devices do have to be perfectly aligned to communicate. IrDA Data is able to support data by utilizing Point-to-Point (PPP) [38] protocol and voice by encapsulating voice into IP packets. IrDA IrLAP is based on High-level Data Link Control (HDLC) [38] and provides a device-to-device connection and ordered transfer of data. IrLAP also has procedures that allow devices to discover each other when first turned on. IrLMP supports a method to multiplex multiple connections onto the IrLAP layer. This feature allows, for example, multiple file transfers to exist between two or more IrDA Data ports. The IrLMP also has a service discovery protocol called Information Access Services (IAS) that enables devices to understand the capabilities of nearby devices.

This feature is very useful in an ad hoc networking environment where devices need services but do not know exactly which device is a printer or an Internet gateway. IrDA Data's optional protocols are summarized in Table 4.

IrDA SIR is a very mature specification that has been included in over 100 million devices. The protocol has all the features that are needed for WPAN today and is very cost effective. The only limitations that are preventing IrDA from taking off are the short-range and blockage issues of infrared optical communication that has been implemented by IrDA. Despite of these shortcomings, it is still being employed in applications where there are no interference from an adjacent devices. Also, high rate devices of up to 16 Mbps are currently being developed.

To cope up with the limitations of IrDA Data such as line of sight requirement, the IrDA association defined the IrDA AIR protocol architecture. IrDA AIR adds a protocol entity called IrLC (Link Controller) that provides multipoint link layer connectivity along side an IrLAP protocol entity, which provides legacy connectivity to IrDA devices. To control access to the shared medium, IrDA AIR employs a MAC protocol called IrMAC which uses a burst reservation CSMA/CA MAC protocol.

Table 3 – IrDA Data Protocol Stack

IrTran-P	IrOBEX	IrLAN	IrCOMM	IrMC
LM-IAS	Tiny Transport Protocol – Tiny TP			
Ir Link Mgmt – IrLMP				
Ir Link Access Protocol – IrLAP				
Async Serial – IR 9600 – 115.2 Kbps		Sync Serial – IR 1.152 Mbps		Sync 4PPM 4 Mbps

Table 4 – IrDA Data Optional Protocols

Optional Protocol	IrDA	Function
Tiny TP		TCP/IP like flow control
IrOBEX		Object exchange services
IrCOMM		Emulates serial and parallel ports to support legacy applications
IrTran-P		Image exchange services for digital photo devices
IrLAN		Provides infrared access to local area networks (LAN)
IrMC		Protocol to provide voice communication and messaging services for mobile devices

IrDA AIR has an interesting feature of actively monitoring the symbol error rates at an AIR decode by which it is possible to estimate the SNR (Signal-to-Noise Ratio) for the channel between the source and sink of a packet. This SNR estimate can be fed back to the sending station in order to maintain a good-quality channel. AIR's base rate is 4 Mbps, reducing through successive halving of data rates to 256 Kbps to yield a doubling range. AIR prototypes have been demonstrated at 4 Mbps up to 5 meters, while at 256 kbps within 10 meters.

Therefore, IrDA AIR offers to improve the freedom of movement to IrDA devices and are freed from 1 meter restriction, 15-30 degree half-angle coverage profile of IrDA DATA, and operate over a greater range and a wider angle.

7.3 HomeRF Working Group's (HRFWG) Shared Wireless Access Protocol – Cordless Access (SWAP-CA)

The HomeRF Working Group (HRFWG) [34] is a consortium of over 100 companies from the computer, electronics, and consumer electronics industries formed in early 1997 to establish an open industry specification for wireless digital communication between PCs and a broad range of interoperable consumer electronic devices anywhere around the house [39]. The HRFWG has developed a specification called the Shared Wireless Access Protocol – Cordless Access (SWAP-CA) [40] that uses RF in the ISM band to support for both managed and ad hoc networks. The specification has combined the data networking elements of 802.11 and voice elements of the Digital European Cordless Telephone (DECT) standard to that allows mobile devices to communicate via voice and data. SWAP-CA has built in mechanisms for small mobile devices in WPANs. SWAP-CA is focused on allowing the users to maximize connectivity to the Internet and the PSTN in as many home devices as possible [39, 22].

7.3.1 SWAP-CA Details

The HomeRF Working Group sees SWAP-CA as one of the methods that could provide connectivity to devices at home. SWAP-CA supports both isochronous clients that are slaves to PCs and an asynchronous network of peer devices that is effectively a wireless Ethernet LAN. The HomeRF Working Group's connectivity vision is to allow computers, cordless phones, and other electronic devices to share resources such as the Internet and the PSTN.

A SWAP-CA system is designed to carry both voice and data traffic and to interoperate with PSTN and data networks such as the Internet. Like Bluetooth, the SWAP protocol operates in the 2.4 ISM band. SWAP-CA utilizes frequency hopping spread spectrum for its relaxed implementation of IEEE 802.11 for data networking services. HRFWG has eliminated the complexities of 802.11 to make SWAP-CA cheaper to implement and manufacture. Voice support in SWAP-CA is modeled after the DECT standard, which has been adapted to the 2.4 GHz ISM band. SWAP-CA utilizes TDMA to provide isochronous voice services and other time-critical services, and CSMA/CA to provide asynchronous services for packet data.

SWAP-CA can support as many as 127 devices per network at a distance of up to 50 meters. There are four types of devices that can operate in a SWAP-CA network [1, 40]:

- A Connection Point (CP) – similar to an 802.11 AP, which functions as a gateway between a SWAP-CA compatible device, the PSTN and a personal computer that could be connected to the Internet.
- Isochronous nodes (I-nodes), which are voice focused devices such as cordless phones.
- Asynchronous nodes (A-Nodes), which are data-focused devices such as personal digital assistants (PDAs) and smart digital pads.
- Combined Asynchronous-Isochronous nodes (AI-nodes).

A SWAP-CA network can operate as a managed network or as a peer-to-peer ad hoc network. In the managed network implementation, the CP controls the network and is the gateway to other devices like the Internet and the PSTN. The CP provides simultaneous

support for voice and data communications by controlling access to the network. In an ad hoc scenario, the SWAP-CA network can only support data and a CP is not required. Figure 14 illustrates the two such scenarios.

When a managed network topology is implemented, SWAP-CA utilizes the frame structure of Figure 15. The existence of contention-free periods (CFP1 and CFP2) using TDMA and a contention period using CSMA/CA allows the managed SWAP-CA network to support both voice and data. The start of the frame is marked by a Connection Point Beacon (CPB) that can be used for network synchronization, controlling the framing format, polling devices to allow access to the TDMA slots, and power management.

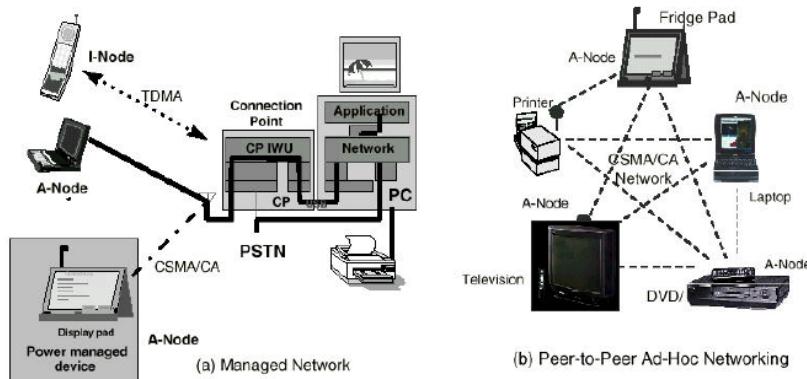


Figure 14 – SWAP-CA Managed and Ad hoc Networks

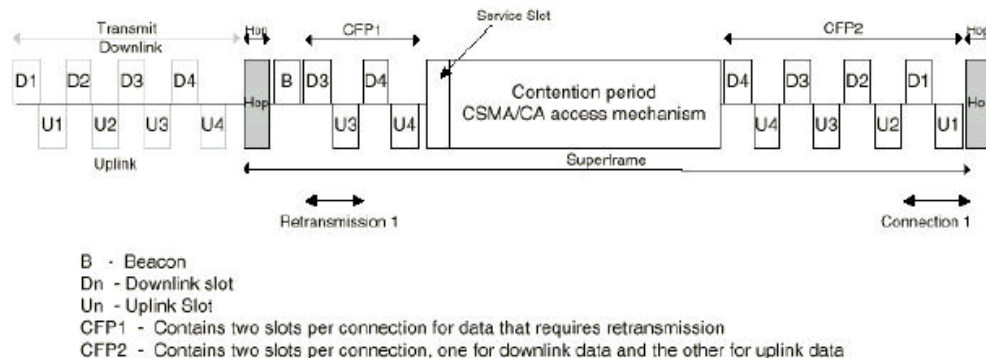


Figure 15 – SWAP-CA hybrid TDMA/CSMA frame

There are variations of the SWAP-CA protocol that are being looked at by the HomeRF Working Group. One is a multimedia protocol SWAP-MM that would focus on video and audio requirements of home networking such as home theater systems. The second is SWAP-lite that focuses on the simple wireless connectivity needs for devices such as keyboards, mouse, remote controls, and joysticks. SWAP-lite is seen as a direct competitor with IrDA and even Bluetooth, widely accepted technologies, and therefore might not receive as much attention as SWAP-MM.

7.4 IEEE 802.15

As we mentioned earlier, the goal for the 802.15 WG is to provide a framework for the development of short-range (less than 10 m), low-power, low-cost devices that wirelessly connect the user within their communication and computational environment. WPANs are intended to be small networks in the home or office with no more than 8 to 16 nodes. Since

the 802.15.1 standard is a derivative of Bluetooth which has already been explained, and 802.15.2 is a recommended practice rather than a standard, we will confine our discussion here to the 802.15.3 and 802.15.4 developing standards.

7.4.1 802.15.3

The 802.15.3 Group [36] has been tasked to develop an ad-hoc MAC layer suitable for multimedia WPAN applications and a PHY capable of data rates in excess of 20 Mbps. The current draft of the 802.15.3 standard (being dubbed Wi-Media) specifies data rates up to 55 Mbps in the 2.4 GHz unlicensed band. The technology employs an ad-hoc PAN topology not entirely dissimilar to Bluetooth, with roles for “master” and “slave” devices. The draft standard calls for drop-off data rates from 55 Mbps to 44 Mbps, 33 Mbps, 22 Mbps and 11 Mbps. We note that 802.15.3 is not compatible with either Bluetooth or the 802.11 family of protocols though it reuses elements associated with both.

7.4.1.1 802.15.3 MAC and PHY Layer Details

The 802.15.3 MAC layer specification is designed from the ground up to support ad hoc networking, multimedia QoS provisions, and power management. In an ad hoc network, devices can assume either master or slave functionality based on existing network conditions. Devices in an ad hoc network can join or leave an existing network without complicated setup procedures. The 802.15.3 MAC specification provides provisions for supporting multimedia QoS. Figure 16 illustrates the MAC superframe structure that consists of a network beacon interval, and a contention access period (CAP) reserves for guaranteed time slots (GTS). The boundary between the CAP and GTS periods is dynamically adjustable.

A network beacon is transmitted at the beginning of each superframe, carrying WPAN-specific parameters, including power management, and information for new devices to join the ad hoc network. The CAP period is reserved for transmitting non-QoS data frames such as short bursty data or channel access requests made by the devices in the network. The medium access mechanisms during the CAP period is CSMA/CA. The remaining duration of the superframe is reserved for GTS to carry data frames with specific QoS provisions. The type of data transmitted in the GTS can range from bulky image or music files to high-quality audio or high-definition video streams. Finally, power management is one of the key features of the 802.15.3 MAC protocol, which is designed to significantly lower the current drain while being connected to a WPAN. In the power saving mode, the QoS provisions are also maintained.

The 802.15.3 PHY layer operates in the unlicensed frequency band between 2.4 GHz and 2.4835 GHz, and is designed to achieve data rates of 11-55 Mb/s that are commensurate with the distribution of high-definition video and high-fidelity audio. The 802.15.3 systems employ the same symbol rate, 11 Mbaud, as used in the 802.11b systems. Operating at this symbol rate, five distinct modulation formats are specified, namely, uncoded QPSK modulation at 22 Mb/s and trellis coded QPSK, 16/32/64-QAM at 11, 33, 44, 55 Mb/s, respectively (TCM) [41]. The base modulation format is QPSK (differentially encoded). Depending on the capabilities of devices at both ends, the higher data rates of 33-55 Mb/s are achieved by using 16, 32, 64-QAM schemes with 8-state 2D trellis coding. Finally, the specification includes a more robust 11 Mb/s QPSK TCM transmission as a fallback mode to alleviate the well-known hidden node problem. The 802.15.3 signals occupy a bandwidth of 15 MHz, which allows for up to four fixed channels in the unlicensed 2.4 GHz band. The transmit power level complies with the FCC rules with a target value of 0 dBm.

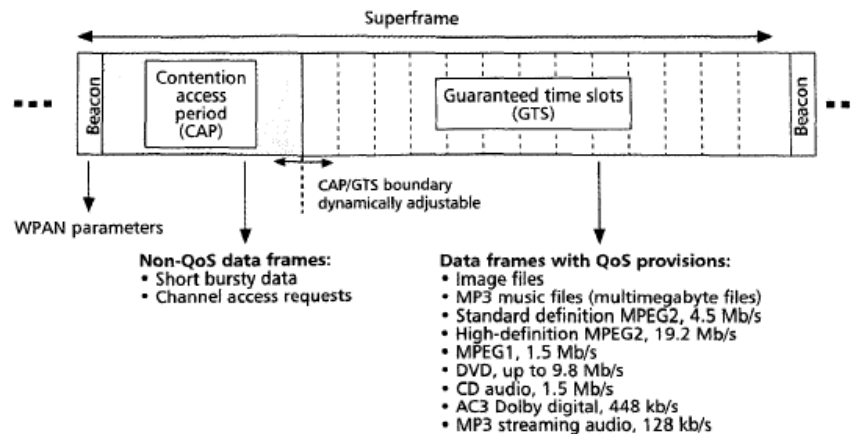


Figure 16 – IEEE 802.15.3 MAC superframe

The RF and baseband processors used in the 802.15.3 PHY layer implementations are optimized for short-range transmission limited to 10 m, enabling low-cost and small-form-factor MAC and PHY implementations for integration in consumer devices. The total system solution is expected to fit easily in a compact flash card. The PHY layer also requires low current drain (less than 80 mA) while actively transmitting or receiving data at minimal current drain in the power saving mode.

From an ad hoc networking point of view, it is important that devices have the ability to connect to an existing network with a short connection time. The 802.15.3 MAC protocol targets connection times much less than 1 s. Reviewing the regulatory requirements, it should be noted that the operation of WPAN devices in the 2.4 GHz band is highly advantageous since these devices cannot be used outdoors in Japan while operating in the 5 GHz band. The outdoor use of most portable WPAN devices prohibits the use of 5 GHz band for worldwide WPAN applications.

7.4.1.2 802.15.3 and Bluetooth

On the face of it, 802.15.3 could be seen as a source of competition to Bluetooth since it too is a WPAN technology using an ad-hoc architecture. In reality this is not the case. Admittedly, the concept of 802.15.3 is to allow for a chipset solution that would eventually be approximately 50% more expensive than a Bluetooth solution. Furthermore, the power consumption and size would be about 50% greater than a Bluetooth solution. However, on the flip-side 802.15.3 would allow for data rates considerably in excess of current sub-1 Mbps Bluetooth solutions. This is the critical differentiating element.

In effect, 802.15.3 is being positioned to be a complementary WPAN solution to Bluetooth. This is particularly the case since the Bluetooth SIG is going slowly on its efforts to develop the next-generation Bluetooth Radio 2, which would allow for data rates between 2 Mbps and 10 Mbps.

7.4.1.3 802.15.3 and WLANs

Some view that there is actually more potential for 802.15.3 to be seen as overlapping with 802.11-based protocols than with Bluetooth. With 802.11-based wireless LANs pushing 54 Mbps and the work being done by the 802.11e TG, it is clear that wireless LANs are also looking to become a serious contender for multimedia applications.

Even though 802.15.3 is being designed from scratch and would theoretically offer superior bandwidth for multimedia applications at favorable cost and power consumption metrics, it will have a challenge distinguishing itself from full-fledged 802.11-based wireless LANs. Even so, one source of differentiation is that 802.15.3 is meant to be optimized for PAN distances (up to 10 meters) while WLAN range is clearly larger.

7.4.2 802.15.4

IEEE 802.15.4 [36, 51] defines a specification for low-rate, low-power wireless personal area networks (LR-WPAN). It is extremely well suited to those home networking applications where the key motivations are reduced installation cost and low power consumption. The home network has varying requirements. There are some applications that require high data rates like shared Internet access, distributed home entertainment and networked gaming. However, there is an even bigger market for home automation, security and energy conservation applications, which typically do not require the high bandwidths associated with the former category of applications. Instead, the focus of this standard is to provide a simple solution for networking wireless, low data rate, inexpensive, fixed, portable and moving devices. Application areas include industrial control, agricultural, vehicular and medical sensors and actuators that have relaxed data rate requirements.

Inside the home, there are several areas where such technology can be applied effectively: PC-peripherals including keyboards, wireless mice, low end PDAs, joysticks; consumer electronics including radios, TVs, DVD players, remote controls; home automation including heating, ventilation, air conditioning, security, lighting, control of windows, curtains, doors, locks; health monitors and diagnostics. These will typically need less than 10 kbps, while the PC-peripherals require a maximum of 115.2 kbps. Maximum acceptable latencies will vary from 10 ms for the PC peripherals to 100 ms to home automation.

Although Bluetooth has been originally developed as a cable replacement technology, it has evolved to handle more typical and complex networking scenarios. Though it has some power saving modes of operation, it is not seen as an effective solution for power constrained home automation and industrial control applications. On the same note, 802.11 is an overkill for applications like temperature or security sensors mounted on a window. Both technologies would require frequent battery changes, which is not suitable for certain industrial applications, like metering systems, which require a battery change once in 2 to 20 years. The tradeoff is a smaller but adequate features set are present in 802.15.4.

As we have seen, 802.15.1 and 802.15.3 are meant for medium and high data rate WPANs respectively. The 802.15.4 effort is geared towards those applications that do not fall in the above two categories, which have low bandwidth requirements, very low power consumption and are extremely inexpensive to build and deploy. These are referred to as LR-PANs. In 2000, two standards groups, the Zigbee alliance [53] (a HomeRF spinoff) and the IEEE 802 working group came together to specify the interfaces and the working of the LR-PAN. In this coalition, the IEEE group is largely responsible for defining the MAC and the PHY layers, while the Zigbee alliance which includes Philips, Honeywell and Invensys Metering Systems, among others, is responsible for defining and maintaining higher layers above the MAC. The alliance is also developing application profiles, certification programs, logos and a

marketing strategy. The specification is based on the initial work done mostly by Philips and Motorola for Zigbee – previously known as PURLnet, FireFly and HomeRF Lite.

The 802.15.4 standard –like all other IEEE 802 standards – specifies those layers up to and including portions of the data link layer. The choice of higher-level protocols is left to the application, depending on specific requirements. The important criteria would be energy conservation and the network topology. The draft, as such, supports networks in both the star and peer-to-peer topology. Multiple address types – both physical (64 bit) and network assigned (8 bit) are allowed. Network layers are also expected to be self-organizing and self-maintaining to minimize cost to the customer.

Currently, the PHY and the DLL (Data Link Layer) have been more or less clearly defined. The focus now is on the upper layers and this effort is largely led by the Zigbee Alliance which aims to bring this innovative and cheap technology to the market by 2003. In the following sections the MAC and PHY layer issues of 802.15.4 are described.

7.4.2.1 802.15.4 Data Link Layer (DLL) Details

The DLL is split into two sublayers – the MAC and the Logical Link Control (LLC). The LLC is standardized in the 802 family while the MAC varies depending on the hardware requirements. Figure 17 shows the correspondence of the 802.15.4 to the ISO-OSI reference model.

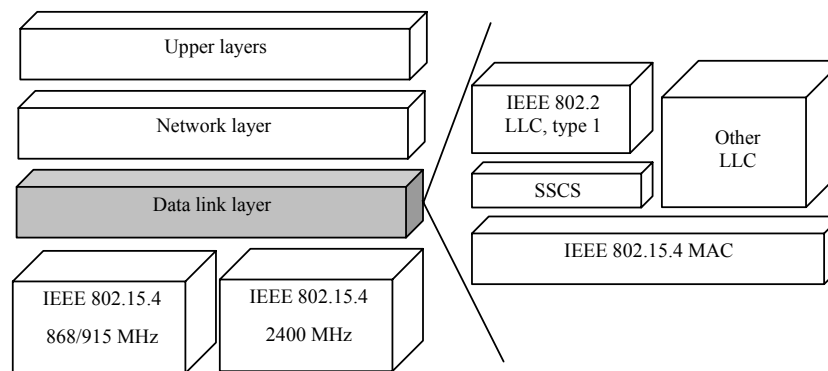


Figure 17 – 802.15.4 in the ISO-OSI layered network model

The IEEE 802.15.4 MAC provides services to an IEEE 802.2 type I LLC through the Service Specific Convergence Sub layer (SSCS). A proprietary LLC can access the MAC layer directly without going through the SSCS. The SSCS ensures compatibility between different LLC sub layers and allows the MAC to be accessed through a single set of access points. MAC protocol allows association and disassociation, acknowledged frame delivery, channel access mechanism, frame validation, guaranteed time slot management and beacon management. The MAC sub layer provides the MAC data service through the MAC common part sub layer (MCPS-SAP), and the MAC management services through the MAC layer management entity (MLME-SAP). These provide the interfaces between the SSCS (or another LLC) and the PHY layer. MAC management service has only 26 primitives as compared to IEEE 802.15.1 which has 131 primitives and 32 events.

The MAC frame structure has been designed in a flexible manner, so that it can adapt to a wide range of applications, while maintaining the simplicity of the protocol. There are 4 types of frames – beacon, data, acknowledgement and command frames. The overview of the frame structure is illustrated in Figure 18.

The MAC protocol data unit (MPDU), or the MAC frame, consists of the MAC header (MHR), MAC service data unit (MSDU) and MAC footer (MFR). The MHR consists of a 2 byte frame control field – that specifies the frame type, the address format and controls the acknowledgement, 1 byte sequence number which matches the acknowledgement frame with the previous transmission, and a variable sized address field (0-20 bytes). This allows either only the source address – possibly in a beacon signal – or both source and destination address like in normal data frames or no address at all as in an acknowledgment frame. The payload field is variable in length but the maximum possible size of an MPDU is 127 bytes. The beacon and the data frames originate at the higher layers and actually contain some data, while the acknowledgement and the command frame originate in the MAC layer and are used to simply control the link at a peer-to-peer level. The MFR completes the MPDU and consists of a frame check sequence (FCS) field which is basically a 16-bit CRC code.

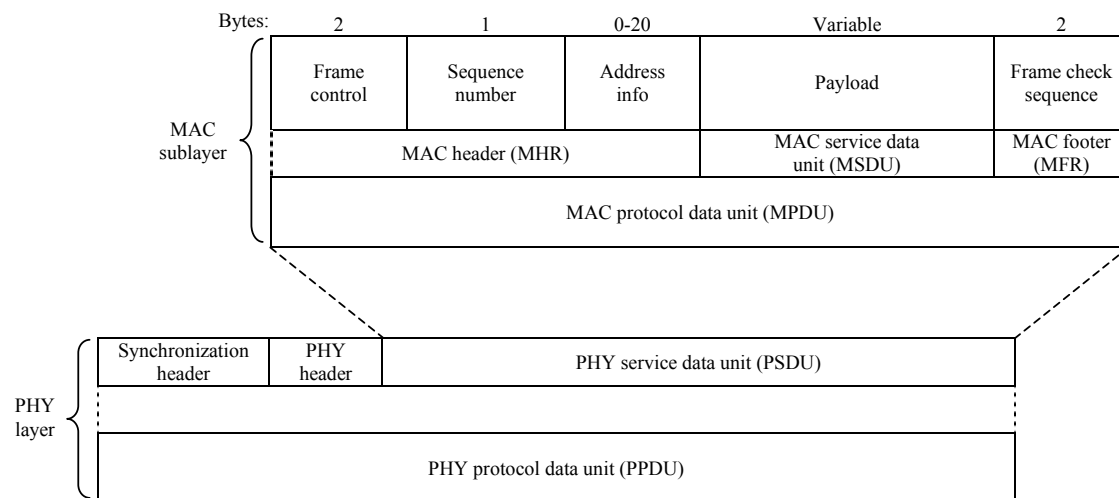


Figure 18 – The general MAC frame format

IEEE 802.15.4 under certain conditions provides dedicated bandwidth and low latencies to certain types of applications, by operating in a *superframe* mode. One of the devices – usually one that is less power constrained than the others – acts as the PAN coordinator, transmitting superframe beacons at predetermined intervals that range from 15 ms to 245 ms. The time between the beacons is divided into 16 equal time slots independent of the superframe duration. The device may transmit at any slot, but must complete its transmission before the end of the superframe. Channel access is usually contention based though the PAN may assign time slots to a single device. This is known as a *guaranteed time slot* (GTS) and introduces a contention free period located immediately before the next beacon. In a beacon enabled superframe network, a slotted CSMA/CA is employed, while in non-beacon networks, the un-slotted or standard CSMA/CA is used.

An important function of MAC is to confirm successful reception of frames. Valid data and command frames are acknowledged; otherwise it is simply ignored. The frame control field indicates whether a particular frame has to be acknowledged or not. IEEE 802.15.4

provides three levels of security: no security, access control lists and symmetric key security using AES-128. To keep the protocol simple and the cost minimum, key distribution is not specified, but may be included in the upper layers.

7.4.2.2 802.15.4 PHY Layer Details

IEEE 802.15.4 offers two PHY layer choices based on the DSSS technique and share the same basic packet structure for low duty cycle low power operation. The difference lies in the frequency band of operation. One specification is for the 2.4 GHz ISM band available worldwide and the other is for the 868/915 MHz for Europe and USA, respectively. These offer an alternative to the growing congestion in the ISM band due to a large-scale proliferation of devices like microwave ovens, etc. They also differ with respect to the data rates supported. The ISM band PHY layer offers a transmission rate of 250 kbps while the 868/915 MHz offers 20 and 40 kbps. The lower rate can be translated into better sensitivity and larger coverage area, while the higher rate of the 2.4 GHz band can be used to attain lower duty cycle, higher throughput and lower latencies.

The range of LR-WPAN is dependant on the sensitivity of the receiver which is -85 dB for the 2.4 GHz PHY and -92 dB for the 868/915 MHz PHY. Each device should be able to transmit at least 1 mW but actual transmission power depends on the application. Typical devices (1 mW) are expected to cover a range of 10-20 m, but with good sensitivity and a moderate increase in power, it is possible to cover the home in a star network topology.

The 868/915 MHz PHY supports a single channel between 868.0 and 868.6 MHz and 10 channels between 902.0 and 928.0 MHz. Since these are regional in nature it is unlikely that all 11 channels ought to be supported on the same network. It uses a simple DSSS in which each bit is represented by a 15-chip maximal length sequence (m-sequence). Encoding is done by multiplying the m-sequence with +1 or -1, and the resulting sequence is modulated by the carrier signal using BPSK.

The 2.4 GHz PHY supports 16 channels between 2.4 GHz and 2.4835 GHz with 5 MHz channel spacing for easy transmit and receive filter requirements. It employs a 16-ary quasi-orthogonal modulation technique based on DSSS. Binary data is grouped into 4-bit symbols, each specifying one of 16 nearly orthogonal 32-bit chip pseudo noise (PN) sequences for transmission. PN sequences for successive data symbols are concatenated and the aggregate chip is modulated onto the carrier using minimum shift keying (MSK). The use of “nearly orthogonal” symbol sets simplifies the implementation, but incurs a minor performance degradation (< 0.5 dB). In terms of energy conservation, orthogonal signaling performs better than differential BPSK. However, in terms of receiver sensitivity, the 868/915 MHz has a 6-8 dB advantage.

The two PHY layers though different, maintain a common interface to the MAC layer, i.e., they share a single packet structure as shown in Figure 19.

The packet or PHY protocol data unit (PPDU) consists of the synchronization header, a PHY header for the packet length, and the payload itself which is also referred to as the PHY service data unit (PSDU). The synchronization header is made up of a 32-bit preamble – used for acquisition of symbol and chip timing and possible coarse frequency adjustment and an 8-bit start of packet delimiter, signifying the end of the preamble. Out of the 8 bits in the PHY header, seven are used to specify the length of the PSDU which can range from 0-127 bytes. Channel equalization is not required for either PHY layer because of the small coverage area and the relatively low chip rates. Typical packet sizes for monitoring and control applications are expected to be in the order of 30-60 bytes.

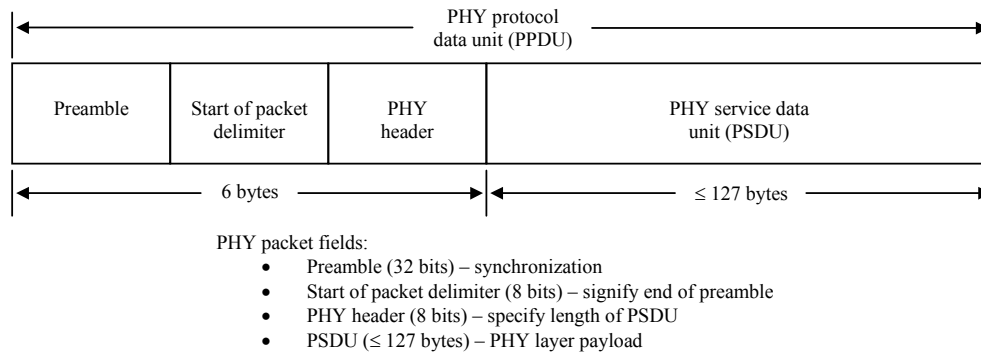


Figure 19 – 802.15.4 PHY layer packet structure

Since the IEEE 802.15.4 standard specifies working in the ISM band it is important to consider the effects of interference that is bound to occur. The applications envisioned by this protocol have little or no QoS requirements. Consequently, data that does not go through on the first attempt will be retransmitted and higher latencies are tolerable. Too many transmissions also increases the duty cycle and therefore affects the consumption of power. Once again the application areas are such that transmissions will be infrequent, with the devices in a passive mode of operation for most of the time.

7.5 Comparison of WPAN Systems

To understand suitability of the aforementioned systems for WPAN applications, it is important to compare the under different aspects. Therefore, Table 5 presents a tabular comparison of the various WPAN technologies discussed so far.

7.6 WLAN versus WPAN

It is important to discuss and clarify the applications and differences between WLAN and WPAN systems as there is a long and continuous debate regarding their distinctions and whether or not they are competing technologies. The only place where it is reasonable to assume WPAN and WLAN are the same is that they both are wireless technologies, i.e., their role is to allow the transmission of information between devices by a radio link. This is something also shared by devices such as cellular phones, walkie-talkies, garage door openers, cordless phones, satellite phones, etc. However, no one would assume that walkie-talkies are in competition with satellite phones. This is because there are several fundamental differences, such as range, price, abilities, primary role, power consumption, etc.

One of the most important issues is the range, and this is one field which is often used (combined with role) to make distinction between wireless technologies. Figure 20 shows the various wireless technologies and their suitability for a given radio coverage and the type of networks. As we can see, WPAN and WLAN systems have completely different scopes and, hence, distinct applications.

There is no question (particularly if cost, size, and power are not the primary factors) about which technology to use for a wireless mobile network. WLANs have been designed for this environment. Yet, it is important to realize that WPAN wireless communication devices are complementary to WLANs. Designed as a cable-replacement technology and not intended as a WLAN competitor, WPAN is not likely to eclipse WLAN and vice-versa. However, WPAN products often have interesting and flexible features not found in WLAN

systems. This includes co-located separate (personal) networks, ad hoc networking (not present in HomeRF only), and synchronous channels that are particularly effective for voice applications and exceptionally low power operation for wireless link members. These connections can range within group, point-to-point, point-to-multipoint, all of which can be accomplished automatically.

Table 5 – Comparison of WPAN systems

Technology	IrDa	HomeRF (SWAP-CA)	Bluetooth (802.15.1)	802.15. x	
				3	4
Operational Spectrum	Infrared 850 nm	2.4 GHz ISM band	2.4 GHz ISM band	2.402 – 2.480 GHz ISM band	2.4 GHz and 868/915 MHz
Physical Layer Details	Optical Rays	FHSS with FSK	FHSS 1600 hops per second	Uncoded QPSK Trellis Coded QPSK or 16/32/64-QAM scheme	DSSS with BPSK or MSK (O-QPSK)
Channel Access	Polling	CSMA-CA and TDMA	Master - Slave Polling, Time Division Duplex (TDD)	CSMA-CA, and Guaranteed Time Slots (GTS) in a Superframe structure	CSMA-CA, and Guaranteed Time Slots (GTS) in a Superframe structure
Maximum Data Rate	4 Mbps	10 Mbps	Up to 1 Mbps	11-55 Mbps	868 MHz - 20, 915 MHz - 40, 2.4 GHz - 250 kbps
Coverage	< 10 m	> 50 m	< 10 m	< 10m	< 20 m
Power Level Issues	Distance Based	< 300 mA peak current	1 mA – 60 mA	< 80 mA	Very Low current drain (20-50 μ A)
Interference	Present	Present	Present	Present	Present
Price	Low (< \$ 10)	Medium	Low (< \$ 10)	Medium	Very Low

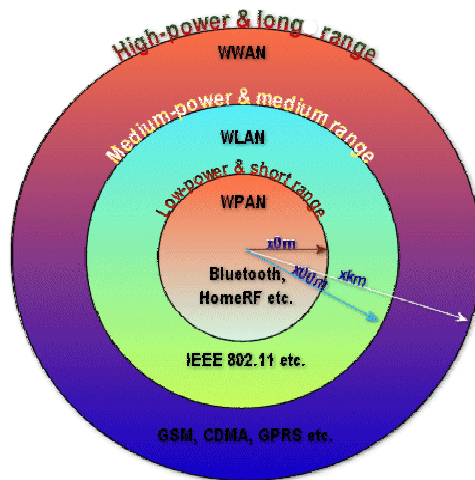


Figure 20 – Wireless technologies

8. Conclusions and Future Directions

The speed of change in digital communications is most prominently represented by broadband wireless access and home networking technologies. In this chapter, we have thoroughly investigated current high-speed broadband wireless communication systems, data distribution, and wireless local and personal area networking proposals for homes and offices. The technologies we have covered are the major players in the world of last mile broadband wireless access given the rapid growth in demand for high-speed Internet and Web access.

Important future directions of BWA could be: evolving BWA from mostly business applications to residential applications; bandwidth on demand and high spectrum utilization; more reconfigurable systems and adaptivity to support multiband, multiple standards, and multiple carriers; and convergence of broadband wireless access and broadband wireless mobile [45]. With the spectrum allocated by the ITU for future fourth-generation mobile communications (4Gmobile), we expect the convergence of BWA and 4Gmobile to be a major focus of activity in the wireless communications field.

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References

- [1] Infrared Data Association. "IrDA Standards," <http://www.irda.org/standards/standards.asp>, April 2000.
- [2] V. Erceg *et al.*, "An Empirically Based Path Loss Model for Wireless Channels in Suburban Environments," *IEEE JSAC*, Vol. 17, No. 7, July 1999, pp. 1205–11.
- [3] V. Erceg *et al.*, "A Model for the Multipath Delay Profile of Fixed Wireless Channels," *IEEE Journal on Selected Areas in Communications*, Vol. 17, No. 3, Mar. 1999, pp. 399–410.
- [4] L. J. Greenstein *et al.*, "A New Path-Gain/Delay-Spread Propagation Model for Digital Cellular Channels," *IEEE Transactions on Vehicular Technology*, vol. 46, no. 2, May 1997, pp. 477–85.
- [5] L. J. Greenstein *et al.*, "Ricean K-factors in Narrowband Fixed Wireless Channels," *WPMC '99 Conf. Proc.*, Amsterdam, The Netherlands, Sept. 1999.
- [6] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-Time Codes for High Data Rate Wireless Communication: Performance Criterion and Code Construction," *IEEE Trans. Info. Theory*, vol. 44, Mar. 1998, pp. 744–65.
- [7] A. J. Paulraj and T. Kailath, "Increasing Capacity in Wireless Broadcast Systems Using Distributed Transmission/Directional Reception," U.S. Patent, no. 5,345,599, 1994.
- [8] G. J. Foschini, "Layered Space-Time Architecture for Wireless Communication in a Fading Environment When Using Multi-Element Antennas," *Bell Labs. Tech. J.*, Autumn 1996, pp. 41–59.
- [9] G. D. Golden *et al.*, "Detection Algorithm and Initial Laboratory Results using the V-BLAST Space-Time Communication Architecture," *Elect. Lett.*, vol. 35, no. 1, Jan. 1999, pp. 14–15.
- [10] K. Sheikh *et al.*, "Smart Antennas for Broadband Wireless Access Networks," *IEEE Commun. Mag.*, Nov. 1999, pp. 100–105.
- [11] S. R. Bullock, "Broadband Communications and Home Networking," *Noble Publishing*, ISBN 1-8844932-19-3, 2001.
- [12] L. Wirbel, "LMDS, MMDS Race for Low-Cost Implementation," *Electronic Engineering Times*, November 1999.

- [13] V. Tipparaje, "Local Multipoint Distribution Service (LMDS)," Ohio State University, December 2000.
- [14] C. Mason, "LMDS: Fixed Wireless Wave of the Future?," *America's Network*, June 1998.
- [15] D. P. Agrawal and Q-A. Zeng, "Introduction to Wireless and Mobile Systems," *Brooks/Cole Publishing*, 438 pages, ISBN 0534-40851-6, 2003.
- [16] ITU, "Satellite Communications Handbook, Fixed Satellite Service." *International Telecommunications Union, International Radio Consulting Committee*, Geneva 1988.
- [17] IEEE 802.16-2001, "IEEE Standard for Local and Metropolitan Area Networks — Part 16: Air Interface for Fixed Broadband Wireless Access Systems," Apr. 8, 2002.
- [18] IEEE P802.16a/D3-2001: "Draft Amendment to IEEE Standard for Local and Metropolitan Area Networks — Part 16: Air Interface for Fixed Wireless Access Systems — Medium Access Control Modifications and Additional Physical Layers Specifications for 2–11 GHz," Mar. 25, 2002.
- [19] B. Bossard, "Low Power Multi-Function Cellular Television System," U.S. patent No. 4 747 160, 1988.
- [20] ITU-R Draft Rec. 3/47, rev. 1, "Propagation Data and Prediction Methods Required for the Design of Terrestrial Broadband Millimeter Radio Access Systems Operating in a Frequency Range of about 20–50 GHz," Geneva, Switzerland, 1999.
- [21] N. Scevak, "Can 802.11 Become a Viable Last Mile Alternative?," <http://australia.internet.com/r/article/jsp/sid/11942>, May 2002.
- [22] IEEE Std. 802.11. "IEEE Standard for Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification," June 1997.
- [23] IEEE Std 802.11a/D7.0-1999, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High Speed Physical Layer in the 5GHz Band.
- [24] ETSI, "Broadband Radio Access Networks (BRAN); HIPERLAN type 2 technical specification; Physical (PHY) layer," August 1999.
- [25] R. Van Nee *et al.*, "New High-Rate Wireless LAN Standards", *IEEE Commun. Mag.*, vol. 37, no.12, Dec. 1999, pp. 82–88.
- [26] A. Doufexi *et al.*, "Throughput Performance of WLANs Operating at 5GHz Based on Link Simulations with Real and Statistical Channels," *IEEE VTC '01 Spring*.
- [27] G. Anastasi, L. Lenzini, and E. Mingozzi "MAC Protocols for Wideband Wireless Local Access: Evolution Toward Wireless ATM", *IEEE Pers. Commun.*, Oct. 1998, pp. 53–64.
- [28] A. Hettich and M. Schrother, "IEEE 802.11a or ETSI BRAN HIPERLAN/2: Who Will Win the Race for a High-Speed Wireless LAN Standard," *Euro. WL Conf.*, Germany, Oct. 1999, pp. 169–74.
- [29] J. Khun-Jush *et al.*, "Structure and Performance of HIPERLAN/2 Physical Layer," *IEEE VTC '99 Fall*, pp. 2667–71.
- [30] ETSI, "Broadband Radio Access Networks (BRAN); HIPERLAN Type 2; Data Link Control (DLC) Layer; Part 1: Basic Transport Functions," Dec.1999.
- [31] A. Doufexi *et al.*, "A Study of the Performance of HIPERLAN/2 and IEEE 802.11a Physical Layers," *IEEE VTC*, Spring 2001.

- [32] Bluetooth SIG, <http://www.bluetooth.com/>.
- [33] Spike, <http://www.spikebroadband.net/>.
- [34] K.J. Negus, A.P. Stephens, and J.Lansford, "HomeRF: Wireless networking for the connected home", in *the IEEE Personal Communications*, February 2000.
- [35] B.P. Crow, I. Wadjaja, J.G. Kim, and P.T. Sakai, "IEEE 802.11 Wireless Local Area Networks," In *IEEE Communications Magazine*, September 1997, 116-126.
- [36] IEEE 802.15 Working Group for WPANs, <http://grouper.ieee.org/groups/802/15/>.
- [37] Bluetooth Special Interest Group, "Bluetooth FAQ," <http://www.bluetooth.com/bluetoothguide/faq/1.asp>, April 2000.
- [38] A. S. Tanenbaum, "Computer Networks," *Prentice Hall*, ISBN 0-13-349945-6, 1996.
- [39] HomeRF Group Working Group, "About HomeRF Working Group," <http://www.homerf.org/about.html>, April 2000.
- [40] HomeRF Technical Committee, "Shared Wireless Access Protocol, Cordless Access (SWAP-CA) Specification," Revision 1.2, October 1999.
- [41] G. Ungerboeck, "Trellis Coded Modulation with Redundant Signal Sets Part 1: Introduction," in *IEEE Communications Magazine*, Vol. 25, No. 2, February 1987.
- [42] C. M. Cordeiro and D. P. Agrawal, "Mobile Ad Hoc Networking," *Tutorial/Short Course in 20th Brazilian Symposium on Computer Networks*, pp. 125-186, May 2002, <http://www.eecs.uc.edu/~cordeicm/>.
- [43] 802.16 Working Group, <http://www.ieee802.org/16>.
- [44] ITU Wireless Access System (WAS), <http://www.itu.int/was>.
- [45] W. W. Lu, "Compact Multi-Dimensional Broadband Wireless - Convergence of Wireless Mobile and Access," *IEEE Commun. Mag.*, Nov. 2000, pp. 119-23.
- [46] J. Cai and D. Goodman, "General Packet Radio Service in GSM," in *IEEE Communication Magazine*, October 1997.
- [47] D. L. Waring, J. W. Lechleider, and T. R. Hsing, "Digital subscriber line technology facilitates a graceful transition from copper to fiber," in *IEEE Communications Magazine*, March 1991.
- [48] G. T. Hawley, "Systems considerations for the use of xDSL technology for data access," in *IEEE Communications Magazine*, March 1997.
- [49] D. Raychaudhuri, and K. Joseph, "Channel access protocols for Ku-band VSAT networks: a comparative evaluation," in *IEEE Communications Magazine*, May 1988.
- [50] T. S. Rappaport, "Wireless Communications," *Prentice Hall*, ISBN: 013375536, January 1996.
- [51] S. Middleton, "IEEE 802.15 WPAN Low Rate Study Group PAR," doc. number IEEE P802.15-00/248r3, submitted September 2000; http://grouper.ieee.org/groups/802/15/pub/2000/Sep00/00248r4P802-15_LRSG-PAR.doc.
- [52] D. Lal, R. Toshniwal, R. Radhakrishnan, D. P. Agrawal, and J. Caffery, "A Novel MAC Layer Protocol for Space Division Multiple Access in Wireless Ad Hoc Networks," in *Proceedings of IC3N*, Miami, Florida, 2002.
- [53] Zigbee Alliance, <http://www.zigbee.com>.