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Fixed broadband wireless systems

1.1 INTRODUCTION

The theoretical origin of communications between two points using electromagnetic (EM) waves propagating through space can be traced to James Maxwell's treatise on electromagnetism, published in 1873, and later to the experimental laboratory work of Heinrich Hertz, who in 1888 produced the first radio wave communication. Following Hertz's developments at the end of the nineteenth century, several researchers in various countries were experimenting with controlled excitation and propagation of such waves. The first transmitters were of the 'spark-gap' type. A spark-gap transmitter essentially worked by producing a large energy impulse into a resonant antenna by way of a voltage spark across a gap. The resulting wave at the resonant frequency of the antenna would propagate in all directions with the intention that a corresponding signal current would be induced in the antenna apparatus of the desired receiving stations for detection there. Early researchers include Marconi, who while working in England in 1896 demonstrated communication across 16 km using a spark-gap transmitter, and Reginald Fassenden, who while working in the United States achieved the first modulated continuous wave transmission. The invention of the 'audion' by Lee DeForest in 1906 led to the development of the more robust and reliable vacuum tube. Vacuum tubes made possible the creation of powerful and efficient carrier wave oscillators that could be modulated to transmit with voice and music over wide areas. In the 1910s, transmitters and receivers using vacuum tubes ultimately replaced spark and arc transmitters that were difficult to modulate. Modulated carrier wave transmissions opened the door to the vast frequency-partitioned EM spectrum that is used today for wireless communications.

Radio communications differed from the predominate means of electrical communication, which at the time was the telegraph and fledgling telephone services. Because the new radio communications did not require a wire connection from the transmitter to the receiver as the telegraph and telephone services did, they were initially called *wireless communications*, a term that would continue in use in various parts of the world for several

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decades. The universal use of the term *wireless* rather than *radio* has now seen a marked resurgence to describe a wide variety of services in which communication technology using EM energy propagating through space is replacing traditional wired technologies.

1.2 EVOLUTION OF WIRELESS SYSTEMS

As the demand for new and different communication services increased, more radio spectrum space at higher frequencies was required. New services in the Very High Frequency (VHF) (30–300 MHz), Ultra High Frequency (UHF) (300–3,000 MHz), and Super High Frequency (SHF) (3–30 GHz) bands emerged. Table 1.1 shows the common international naming conventions for frequency bands. Propagation at these higher frequencies is dominated by different mechanisms as compared to propagation at lower frequencies. At low frequency (LF) and Mediumwave Frequency (MF), reliable communication is achieved via EM waves propagating along the earth–atmosphere boundary – the so-called *groundwaves*. At VHF and higher frequencies, groundwaves emanating from the transmitter still exist, of course, but their attenuation is so rapid that communication at useful distances is not possible. The dominant propagation mechanism at these frequencies is by space waves, or waves propagating through the atmosphere. One of the challenges to designing successful and reliable communication systems is accurately modeling this space-wave propagation and its effects on the performance of the system.

The systems that were developed through the twentieth century were designed to serve a variety of commercial and military uses. Wireless communication to ships at sea was one of the first applications as there was no other ‘wired’ way to accomplish this important task. World War I also saw the increasing use of the wireless for military communication. The 1920s saw wireless communications used for the general public with the establishment of the first licensed mediumwave broadcast station KDKA in East Pittsburgh, Pennsylvania, in the United States using amplitude modulation (AM) transmissions. The 1920s also saw the first use of land-based mobile communications by the police and fire departments where the urgent dispatch of personnel was required.

From that point the growth in commercial wireless communication was relentless. Mediumwave AM broadcasting was supplemented (and now largely supplanted) by

Table 1.1 Wireless frequency bands

Frequency band	Frequency range	Wavelength range
Extremely low frequency (ELF)	<3 kHz	>100, 000 m
Very low frequency (VLF)	3–30 kHz	100,000–10,000 m
Low frequency (LF)	30–300 kHz	10,000–1,000 m
Mediumwave frequency (MF)	300–3,000 kHz	1,000–100 m
High frequency (HF)	3–30 MHz	100–10 m
Very high frequency (VHF)	30–300 MHz	10–1.0 m
Ultra high frequency (UHF)	300–3,000 MHz	1.0–0.1 m
Super high frequency (SHF)	3–30 GHz	10–1.0 cm
Extra high frequency (EHF)	30–300 GHz	1.0–0.1 cm

frequency modulation (FM) broadcasting in the VHF band (88–108 MHz). Television appeared on the scene in demonstration form at the 1936 World Fair in New York and began widespread commercial deployment after World War II. Satellite communication began with the launch of the first Russian and American satellites in the late 1950s, ultimately followed by the extensive deployment of geostationary Earth orbit satellites that provide worldwide relay of wireless communications including voice, video, and data.

Perhaps the most apparent and ubiquitous form of wireless communication today are cellular telephones, which in the year 2002 are used by an estimated one billion people worldwide. The cellular phone concept was invented at Bell Labs in the United States in the late 1960s, with the first deployments of cell systems occurring in the late 1970s and early 1980s. The so-called third generation (3G) systems that can support both voice and data communications are now on the verge of being deployed.

Fixed wireless systems were originally designed to provide communication from one fixed-point terminal to another, often for the purpose of high reliability or secure communication. Such systems are commonly referred to as 'point-to-point (PTP)' systems. As technology improved over the decades, higher frequency bands could be successfully employed for fixed communications. Simple PTP telemetry systems to monitor electrical power and water distribution systems, for example, still use frequencies in the 150- and 450-MHz bands. Even early radio broadcast systems were fixed systems, with one terminal being the transmitting station using one or more large towers and the other terminal the receiver in the listener's home. Such a system could be regarded as a 'Point-to-Multipoint (PMP)' system. Similarly, modern-day television is a PMP system with a fixed transmitting station (by regulatory requirement) and fixed receive locations (in general). Television can also be regarded as 'broadband' using a 6-MHz channel bandwidth in the United States (and as much as 8 MHz in other parts of the world), which can support transmitted data rates of 20 Mbps or more.

The invention of the magnetron in the 1920s, the 'acorn' tube in the 1930s, the klystron in 1937, and the traveling wave tube (TWT) in 1943 made possible efficient ground and airborne radar, which saw widespread deployment during World War II. These devices made practical and accessible a vast new range of higher frequencies and greater bandwidths in the UHF and SHF bands. These frequencies were generically grouped together and called *microwaves* because of the short EM wavelength. The common band designations are shown in Table 1.2. Telephone engineers took advantage of the fact that

Table 1.2 Microwave frequency bands

Microwave band name	Frequency range (GHz)
L-band	1–2
S-band	2–4
C-band	4–8
X-band	8–12
Ku band	12–18
K-band	18–27
Ka band	27–40

PTP microwave links used in consecutive fashion could provide much lower signal loss and consequently higher quality communication than coaxial cables when spanning long distances. Although buried coaxial cables had been widely deployed for long-range transmission, the fixed microwave link proved to be less expensive and much easier to deploy. In 1951, AT&T completed the first transcontinental microwave system from New York to San Francisco using 107 hops of an average length of about 48 km [1]. The TD-2 equipment used in this system were multichannel radios manufactured by Western Electric operating on carrier frequencies of around 4 GHz. Multihop microwave systems for long-distance telephone systems soon connected the entire country and for many years represented the primary mechanism for long-distance telecommunication for both telephone voice and video. The higher frequencies meant that greater signal bandwidths were possible – microwave radio links carrying up to 1800 three-kilohertz voice channels and six-megahertz video channels were commonplace.

On the regulatory front, the Federal Communications Commission (FCC) recognized the value of microwave frequencies and accordingly established frequency bands and licensing procedures for fixed broadband wireless systems at 2, 4, and 11 GHz for common carrier operations. Allocations for other services such as private industrial radio, broadcast studio-transmitter links (STLs), utilities, transportation companies, and so on were also made in other microwave bands.

Today, these long-distance multihop microwave routes have largely been replaced by optical fiber, which provides much lower loss and much higher communication traffic capacity. Satellite communication also plays a role, although for two-way voice and video communication, optical fiber is a preferred routing since it does not suffer from the roughly 1/4 s round-trip time delay when relayed through a satellite in a geostationary orbit 35,700 km above the Earth's equator.

Today, frequencies up to 42 GHz are accessible using commonly available technology, with active and increasingly successful research being carried out at higher frequencies. The fixed broadband wireless systems discussed in this book operate at frequencies in this range. However, it is apparent from the foregoing discussion of wireless system evolution that new semiconductor and other microwave technology continues to expand the range at which commercially viable wireless communication hardware can be built and deployed. Frequencies up to 350 GHz are the subject of focused research and, to some extent, are being used for limited military and commercial deployments.

The term *wireless* has generally applied only to those systems using radio EM wavelengths below the infrared and visible light wavelengths that are several orders of magnitude shorter (frequencies several orders of magnitude higher). However, free space optic (FSO) systems using laser beams operating at wavelengths of 900 and 1100 nanometers have taken on a growing importance in the mix of technologies used for fixed broadband wireless communications. Accordingly, FSO systems will be covered in some detail in this book.

1.3 MODELS FOR WIRELESS SYSTEM DESIGN

The process of designing a fixed broadband wireless communications system inherently makes use of many, sometimes complex, calculations to predict how the system will perform before it is actually built. These models may be based on highly accurate measurements, as in the case of the directional radiation patterns for the antennas used in the system, or on the sometimes imprecise prediction of the levels and other characteristics of the wireless signals as they arrive at a receiver. All numerical or mathematical models are intended to predict or simulate the system operation before the system is actually built. If the modeling process shows that the system performance is inadequate, then the design can be adjusted until the predicted performance meets the service objects (if possible). This design and modeling sequence make take several iterations and may continue after some or all of the system is built and deployed in an effort to further refine the system performance and respond to new and more widespread service requirements.

The ability to communicate from one point to another using EM waves propagating in a physical environment is fundamentally dependent on the transmission properties of that environment. How far a wireless signal travels before it becomes too weak to be useful is directly a function of the environment and the nature of the signal. Attempts to model these environmental properties are essential to being able to design reliable communication systems and adequate transmitting and receiving apparatus that will meet the service objectives of the system operator. Early radio communication used the LF portion of the radio spectrum, or the so-called long waves, in which the wavelength was several hundred meters and the propagation mechanism was primarily via groundwaves as mentioned earlier. Through theoretical investigation starting as early as 1907 [2], an understanding and a model of the propagation effects at these low frequencies was developed. The early propagation models simply predicted the electric field strength as a function of frequency, distance from the transmitter, and the physical characteristics (conductivity and permittivity) of the Earth along the path between the transmitter and receiver. The models themselves were embodied in equations or on graphs and charts showing attenuation of electric field strength versus distance. Such graphs are still used today to predict propagation at mediumwave frequencies (up to 3000 kHz), although computerized versions of the graphs and the associated calculation methods were developed some years ago [3].

All wireless communication systems can be modeled using a few basic blocks as shown in Figure 1.1. Communication starts with an information source that can be audio, video, e-mail, image files, or data in many forms. The transmitter converts the information into a signaling format (coding and modulation) and amplifies it to a power level that is needed to achieve successful reception at the receiver. The transmitting antenna converts the transmitter's power to EM waves that propagate in the directions determined by the design and orientation of the antenna. The propagation channel shown in Figure 1.1 is not a physical device but rather represents the attenuation, variations, and any other distortions that affect the EM waves as they propagate from the transmitting antenna to the receiving antenna.

By using EM waves in space as the transmission medium, the system is necessarily exposed to sources of interference and noise, which are often beyond the control of the system operator. Interference generally refers to identifiable man-made transmissions. Some systems such as cellular phone systems reuse frequencies in such a way that interference transmitters are within the same system and therefore can be controlled. Cellular system design is largely a process of balancing the ratio of signal and interference levels to achieve the best overall system performance.

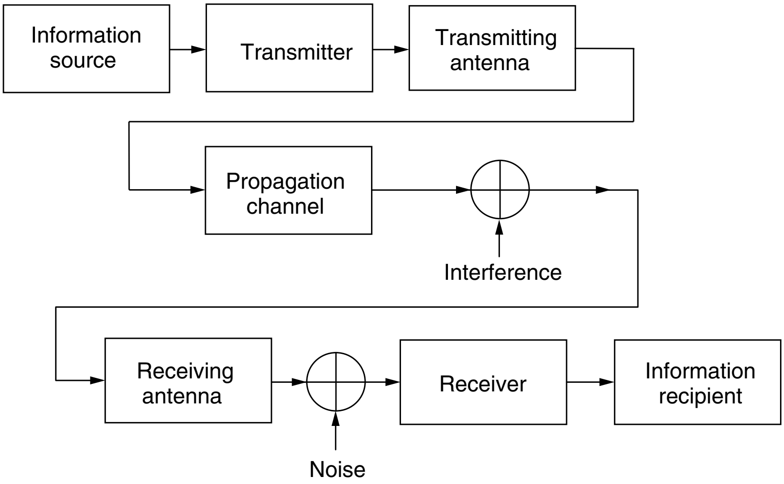

Figure 1.1 Block diagram of a basic wireless communications system.

External noise sources may be artificial or natural, but are usually differentiated from interference in that they may not be identifiable to a given source and do not carry any useful information. Artificial noise sources include ignition noise from automobiles, noise from all sorts of electrical appliances, and electrical noise from industrial machinery among others. Natural external noise includes atmospheric noise from the sun's heating of the atmosphere and background cosmic noise. The noise power from these various sources is very much a function of frequency, so depending on the frequency band in use, these noise sources may be important or irrelevant to the system design.

At the receiver, the receiving antenna is immersed in the EM field created by the transmitting antenna. The receiving antenna converts the EM fields into power at the terminals of the receiving antenna. The design and orientation of the receiving antenna compared to the characteristics of the transmitted field in which it is immersed, determine the amount of power that is present at the receiving antenna terminals. Besides the transmitted field, the EM fields from the interference and noise sources are also converted to power at the receiving antenna terminals, again depending on the design and orientation of the receiving antenna. The so-called smart or adaptive antennas, to be discussed later in this book, can actually change their characteristics over time to optimize signal reception and interference rejection. The power at the receiving antenna terminals is coupled to the receiver that processes the power in an effort to recover exactly the source information that was originally transmitting. For some systems this process can be quite complex, with methods for decoding signals, correcting data errors, mitigating or exploiting signal variations, and rejecting interference being part of modern fixed broadband receiving systems. Ultimately after processing, the received information is presented to the system user in the form of audio, video, images, or data. The accuracy and fidelity of the received signal when compared to originally transmitted source information is a broad general measure of the quality of the communication system and the success of the system design.

1.4 DEMAND FOR COMMUNICATION SERVICES

The creation of any wireless communication system is driven by a need for services by individuals, businesses, governments, or other entities. Government and military demand for services is an ongoing requirement that is largely accommodated first when spectrum resources are allotted. The remaining spectrum is divided into blocks or bands that generally are intended to be best suited to particular service objectives. Within these bands, regulatory authorities over the years have in many cases established rigid technical standards so that equipment manufacturers, system operators, and the buyers (consumers) of telecommunications equipment could rely on the equipment being compatible and working correctly together. Over the past two decades there has been a trend by the FCC to simply assign frequency bands for various services and let the wireless industry choose the appropriate technology through marketplace competition or standards-setting processes conducted by private organizations. The debate between government-mandated standards and marketplace forces setting standards continues today with valid arguments for both regulatory and marketplace approaches.

Ultimately standards are intended to achieve reliable service to the target market. The type and nature of the services that wireless communication systems must provide is constantly changing, which perhaps has become the greatest stress on the standards-setting process. Whereas 5 decades ago nationwide standards for AM, FM, and TV broadcasting could be established and work effectively for several decades, the rapidly changing services that must be delivered have lead to standards being revised and replaced every 10 years. The cellular telephone industry is a perfect example. The early, so-called 1G, standards established in the 1980s were quickly recognized as inadequate because the demand for capacity was much greater than expected. The 2G standards established in the late 1980s and early 1990s are now being replaced by 3G standards, with 4G standards in the planning stages. The need to replace standards in such a short time has been entirely driven by the demand for services and the type of services demanded. A ubiquitous mobile cell phone service that offered simple voice calls was a significant achievement in the 1980s, but now demand for a wide range of data services at increasing data rates is considered essential to having a competitive wireless service offering.

For the fixed broadband wireless system, the digital service demand can be broken down into two basic classes – Internet access for the public and businesses and general private high-speed data communications for small, medium, and large businesses. The explosive growth in Internet usage over the past decade has made it the new community connection that everyone feels compelled to have available – as were telephones 50 years ago. Some of the services or applications that are most commonly used on the Internet are

- E-mail
- Web-browsing
- File and image download and general file transfer via file transfer protocol (FTP)
- Streaming audio files for ‘real-time’ audio connections
- Streaming video files for ‘real-time’ video connections
- Voice over Internet protocol (VoIP), also a ‘real-time’ service.

As discussed in some detail later in this book, each of these applications has particular characteristics in terms of data rate, the statistical distribution of the data flow, and user expectations that affect the way a fixed wireless system must be designed to successfully support them. From a simple inspection, it is clear that some of these services are much more demanding on the communication system than others. Whether the system operator considers the additional cost of deploying a system that can support some or all of these applications a worthwhile expenditure in light of anticipated revenue is a business decision that may be difficult to make. The cost of deployment in turn is controlled by the technology utilized and the efficiency of the system design. The savings in deployment costs that can be achieved through intelligent and accurate system design often far outweigh the cost savings achieved by choosing one technology over another.

The other major service requirement for fixed broadband wireless systems is private high-speed data connections for business, military, and government. This type of service can be regarded as the ‘traditional’ domain of PTP fixed wireless networks such as the transcontinental microwave systems carrying telephone and video traffic described earlier. Besides telephone companies, many organizations used fixed microwave for internal business communication, among them

- Utilities that used such links to connect dams, power generating stations, substations, pumping stations, and so on.
- FM and TV broadcasters who need to connect studio facilities with often remote mountaintop transmitting facilities, and to relay signals to remote auxiliary repeater or translator transmitting stations, or remote electronic news gathering (ENG).
- Businesses that need to connect various offices, plants or other facilities with broadband services including data and internal computer networks such as local area networks (LAN) or wide area networks (WAN).
- Educational institutions that must connect various campus facilities or remote campuses for high-speed data and video transmissions including teleconferencing.
- Backhaul links that connect cellular base transmitting stations (BTS) to mobile switching centers (MSCs) carrying all the voice and data traffic to the public switched telephone network (PSTN).

As with Internet services, the types and carriage requirements of such services continues to expand, thus placing growing demands on the technology, the system design techniques, and on spectrum regulators to provide adequate spectrum to accommodate these requirements. As discussed in the next section, the current international spectrum allocations have a significant impact on how fixed broadband wireless systems can be built to meet the described service requirements.

1.5 LICENSED FREQUENCY BANDS

The use of radio spectrum worldwide is regulated by the International Telecommunications Union (ITU), which operates with the participation of all member nations under the auspices of the United Nations. The ITU serves to address the needs of all countries during the World radio communications Conference (WRC, formerly WARC) held every three years; the next WRC will be held in Geneva, Switzerland in 2003. At the WRC, the delegations must juggle and resolve the often conflicting demands of member nations and of different service operators that require spectrum allocations for mobile, fixed, and satellite technologies. Within the bands set by the WRC, the Radio Regulation Board (RRB, formerly International Frequency Registration Board or IFRB) established rules for how actual assignments and sharing are to be handled in the band assignments made at the WRC.

The spectrum available for the construction of fixed broadband wireless systems can be divided into licensed and license-exempt frequency bands. In general, licensed spectrum provides for some degree of interference protection because each new licensee must demonstrate compliance with certain standards for limiting interference to other existing nearby licensed systems. There are also radiated transmitter power level and other parameter limitations that each licensee must observe. License-exempt bands do not require individual transmitters to be licensed in order to operate, but there are still radiated power restrictions that usually keep power at low levels as a *de facto* way of limiting interference. There may also be a rudimentary channelization scheme and modulation standard; again, to make possible as many successful operations as possible without destructive interference. Some cooperation and coordination may sometimes be necessary to make the most of these measures. Cordless telephones, remote control toys, and IEEE802.11b/802.11a wireless LAN devices (to be discussed in this book) are examples of license-exempt systems.

There are a number of frequency bands that have been allocated throughout the world for use by licensed fixed broadband services. Within the general ITU band designations, individual countries may elect to implement or not implement polices that allow those frequencies to be licensed and used within their country boundaries. This is especially true for fixed broadband wireless services. Because of these country-specific differences, it is not useful in the context of this book to present a comprehensive tabulation of all these frequency bands. However, Tables 1.3 and 1.4 provide a convenient summary for the United States and most European countries, respectively. The frequency bands listed are intended as examples of the variety of services that have access to the microwave spectrum for fixed services. The tables include the major bands used for newer PTP and PMP broadband services such as Local Multipoint Distribution Service (LMDS). The information in Table 1.3 was extracted from [4,5] while the information in Table 1.4 was extracted from [6,7].

In addition to requirements to obtain a license for systems operating in these bands, each band also has a number of technical criteria that each system must satisfy. In general, these criteria are established to reduce or minimize interference among systems that share the same spectrum, and to ensure that the spectrum efficiency (information transmitted) is sufficiently high to justify occupying the spectrum. In a given band, there may be requirements for minimum and maximum radiated power levels, particular efficient modulation types, and even standards for the radiation patterns of directional antennas to reduce interference to other operators in the band. These technical standards can be detailed and complex, and may vary from country to country. Designing and deploying

Table 1.3 Examples of US licensed fixed wireless bands

Frequency band (GHz)	Service name	Notes
2.150–2.156	MDS1	Single 6-MHz channel for MMDS services
2.156–2.162	MDS2	Single 6-MHz channel for MMDS services
2.156–2.160	MDS2A	Narrow 4-MHz MMDS channel
2.500–2.690	MMDS/ITFS	Thirty-one 6-MHz channels that are shared between ITFS and MMDS operators
3.8–4.2	—	Common carrier band for PTP link systems
5.9–7.1	—	Common carrier band for PTP link systems
10.7–11.7	—	Common carrier band for PTP link systems
12.7–13.25	—	CARS band for cable television relay services
17.7–18.820	—	Shared use for broadcast auxiliary, common carrier, CARS, private operational fixed PTP systems
24.25–25.25	DEMS	DEMS = digital electronic messaging service. The band includes 5 × 40-MHz FDD channels with 800-MHz spacing
28	LMDS	LMDS = local multipoint distribution service. Block A is 1,150 MHz in three parts: 27.5–28.35 GHz, 29.10–20.25 GHz, and 31.075–31.225 GHz, Block B is 150 MHz in two parts: 31.0–31.075 and 31.225–31.3 GHz
38	—	50-MHz FDD channels 38.6–38.95 GHz with channel pairs at 39.3–39.65 GHz

Note: MMDS = Multipoint Multi-channel Distribution Service.
ITFS = Instructional Television Fixed Service.
CARS = Cable Television Relay Service.

a fixed wireless system in any particular country requires a careful review and functional understanding of the administrative rules that govern the use of the intended licensed spectrum space.

1.6 LICENSE-EXEMPT BANDS

As mentioned above, there is a growing interest in using the so-called license-exempt bands. One of the primary reasons is that it allows users of the wireless service to purchase off-the-shelf wireless modems for connecting to a system. In the United States, the 11-Mbps IEEE 802.11b standard that specifies Direct Sequence Spread Spectrum (DSSS) technology operating in the 2.4-GHz band is the best current example of self-deployed license-exempt technology. However, license-exempt bands offer no regulatory

Table 1.4 Examples of European licensed fixed wireless bands

Frequency band (GHz)	Service name	Notes
3.4–3.6	—	Duplex spacings of 50 or 100 MHz are employed. 3.7 GHz is the upper limit of this band is in some countries
3.8–4.2	—	High capacity public operator band for PTP link systems
5.9–7.1	—	High capacity public operator band for PTP link systems
7.1–8.5	—	Medium and high capacity public operator band for long haul PTP systems
10.15–10.65	—	5 × 30-MHz channels with duplex spacings of 350 MHz
10.7–11.7	—	High capacity public operator band for PTP link systems
12.7–13.3	—	Low and medium capacity public operator band
14.4–15.4	—	Fixed link operations of various types
17.7–19.7	—	Public operator band for low and medium capacities
21.2–23.6	—	Public operator band for PTP link systems of various types
24.5–26.5	—	ETSI 26-GHz band. 3.5- to 112-MHz FDD channels with 1008-MHz duplex spacing. Channel widths vary from country to country
37–39.5	—	Common carrier band for PTP link systems

interference protection except that afforded by the interference immunity designed into the technology itself. With relatively modest penetration of these systems to date, the robustness of the design for providing the expected quality of service in the presence of widespread interference and many contending users has yet to be fully tested. As the number of people using license-exempt equipment increases in a given area, the ultimate viability of having a multitude of people using a limited set of frequencies will be tested. Table 1.5 shows the license-exempt bands currently used in the United States for fixed broadband communications.

The license-exempt spectrum has been designated in Europe, though the uptake of the technology has been slower than in the United States. As discussed in the next section, several long-running standard-setting efforts designed for this purpose did not bear fruit in a timely fashion, resulting in many of these efforts being suspended or abandoned in favor US standards already in place. Table 1.6 shows the license-exempt bands currently available for use in Europe. At the time of this being written, the IEEE 802.11a high-speed network standard has not been certified for use in Europe, although this is expected to happen in the year 2002.

Table 1.5 US license-exempt fixed wireless bands

Frequency band (GHz)	Service name	Notes
2.4–2.483	ISM	ISM = industrial, scientific, and medical. This band is where IEEE 802.11b DSSS networks operate
5.15–5.35	U-NII	U-NII = unlicensed national information infrastructure. This band is where IEEE 802.11a orthogonal frequency division multiplexing (OFDM) systems operate among several other proprietary standards. Channel widths are 20 MHz. Particular power limits apply for segments of this band intended for indoor and outdoor applications
5.725–5.825	U-NII	Same as 5.15–5.35-GHz U-NII band except this band is intended only for outdoor applications with radiated power levels up to 4 W

Table 1.6 European license-exempt fixed wireless bands

Frequency band (GHz)	Service name	Notes
2.4–2.483	ISM	ISM = industrial, scientific, and medical. This is the same band where IEEE 802.11b DSSS networks operate in the United States
5.15–5.35	HiperLAN	HiperLAN is the fast wireless network standard for Europe, which uses an OFDM transmission standard similar to IEEE 802.11a. This band is intended for indoor operations with radiated powers limited to 200 mW
5.470–5.725 GHz	HiperLAN/2	Proposed frequency band for outdoor operations with radiated power levels limited to 1 W

1.7 TECHNICAL STANDARDS

Many fixed broadband wireless systems, especially private PTP microwave systems, use technology and engineering methods and technology that comply with a minimum regulatory framework but otherwise are proprietary methods that have been developed to achieve an advantage over their commercial competition. Since communication is intended only among nodes or terminals within of the same network, there is no need for public standards that would facilitate a manufacturer developing and marketing equipment. Over the years, this approach has lead to considerable innovation in fixed-link equipment with new power devices, receivers, coding and decoding schemes, and very spectrum-efficient high-level modulation types being successfully developed and deployed.

As noted above, there has been a trend in regulatory agencies, especially the FCC, to set the minimum technical standards necessary to control interference among different system operators, with the details of the transmission methods left to individual operators. This is the case with the LMDS bands in the United States, for example, where operators with licenses to use these bands in different cities can chose any technology they wish to employ. The pivotal question here is ‘Is the system intended to serve a large customer base that needs low-cost terminal devices or is the system intended to serve a narrow set of customers who sufficiently value the service to pay higher prices for terminal equipment capable of greater performance?’

Even in this context there is still considerable motivation to establish standards, especially for systems that expect to provide service to vast numbers of users in businesses and residences randomly dispersed throughout a service area. With detailed transmission standards, two particular benefits may be achieved

- Competing companies will manufacture large quantities of standards-compliant devices, thus drastically reducing the price of individual devices.
- Operators will more willingly deploy systems that comply with standards because they can expect a large quantity of inexpensive terminal devices available for use by their customers, thus enlarging their customer base.

Included here is a brief summary of the standard-settings efforts and organizations that are focused on the fixed broadband wireless systems for widespread deployment. The actual details of the standards are not discussed here since they are extremely detailed, usually requiring several hundred pages to document. Interested readers can consult the references for more specific information on these standards. Moreover, except in limited ways, the details of standards, especially many aspects of the medium access control (MAC) layer, are not germane to the wireless network design process.

1.7.1 IEEE 802.11 standards

The IEEE 802.11 Working Group is part of the IEEE 802 LAN/MAN Standards Committee (LMSC), which operates under the auspices of the IEEE, the largest professional organization in the world. The committee participants representing equipment manufactures, operators, academics, and consultants from around the world are responsible for establishing these standards.

The original IEEE 802.11 standard provided for wireless networks in the ISM band that provide data rates of only 1–2 Mbps. These rates were substantially less than inexpensive wired Ethernets that routinely ran at 10 or 100 Mbps speeds and could be readily deployed with inexpensive equipment. To improve the capability of these wireless networks, two additional projects were started.

The IEEE 802.11b project was actually started in late 1997 after 802.11a project (hence, a ‘b’ suffix instead of an ‘a’). The standard was completed and published in 1999 to provide for wireless networks operating at speeds up to 11 Mbps using the unlicensed 2.4-GHz ISM band in the United States and other parts of the world. With this standard, the 2.4-MHz band is divided into six channels, each 15 MHz wide. Power levels of

802.11b devices are limited to mW, and use of spread spectrum transmission technology is required to reduce the potential of harmful interference to other users. To manage access by multiple users, it provides for the collision sense multiple access (CSMA) approach for sharing the channels.

The IEEE 802.11a standard was also completed and published in 1999. It provides for operation of the 5-GHz U-NII bands (see Table 1.5) using OFDM modulation. Using 20-MHz channels, it provides for data rates up to 54 Mbps. IEEE 802.11a also specifies CSMA as the multiple access technology.

The most recent standard from this committee is 802.11g, which is intended to provide better data rates than 802.11b but still use the 2.4-GHz band. As of this writing, this standard is not well defined although it likely will use OFDM of some sort.

Further information can be found at the 802.11 Working Group web site [8], or through IEEE.

1.7.2 IEEE 802.16 standards

The IEEE 802.16 Working Group on Broadband Wireless Access is also part of IEEE 802 LMSC. It was originally organized to establish standards for fixed broadband systems operating above 11 GHz, especially the 24-GHz DEMS, 28-GHz LMDS, and 38-GHz bands. The purpose was to speed deployment of systems through the benefits of mass marketing of standard terminal devices. Since then, the committee work has expanded to include systems operating on frequencies from 2 to 11 GHz; this standards effort is now designated IEEE 802.16a.

The 802.16 WirelessMAN™ Standard ('Air Interface for Fixed Wireless Access Systems') covering 10 to 66 GHz was approved for publication in December 2001. This followed the publication in September 2001, of IEEE Standard 802.16.2, a Recommended Practice document entitled 'Coexistence of Fixed Broadband Wireless Access Systems', also covering 10 to 66 GHz. The corresponding standard for 2 to 11 GHz will be designated IEEE 802.16.2.a.

The 802.16a standard for the 2- to 11-GHz standard uses the same MAC layer as 802.16, but necessarily has different components in the physical layer. Balloting on the 802.16a air interface standard is expected to be completed and the 802.16a standard approved and published in mid to late 2002.

Further information can be found at the 802.16 Working Group web site [9], or through IEEE.

1.7.3 ETSI BRAN standards

The European Telecommunications Standards Institute (ETSI) and its committee for Broadband Radio Access Networks (BRAN) has worked on several standards for wireless networking for a number of years. These include

- *HIPERLAN/2*: This is a standard that has a PHY (Physical) layer essentially the same as 802.11a but a different MAC layer using time division multiple access (TDMA) rather than CSMA. Like 802.11a, it is intended to operate in the 5-GHz band and provide data rates up to 54 Mbps. The first release of the HIPERLAN/2 standard was published in April 2000. There is also ongoing work to develop bridge standards to IEEE networks and IMT-2000 3G cell phone systems.

- *HIPERACCESS*: This is intended as a long-range variant of HIPERLAN/2 intended for PMP operation at data rates up to 25 Mbps in various kinds of networks. HIPERACCESS is intended to operate in the 40.5- to 43.5-GHz band, although these spectrum allocations have not yet been made.
- *HIPERMAN*: This standard is design for interoperable fixed broadband wireless access in the 2- to 11-GHz frequency range, with the air interface designed primarily for PMP. According to [10], the HIPERMAN standard uses the 802.16a standard as a baseline starting point.
- *HIPERLINK*: This standards effort is designed for short range (<150 meters), high-speed (up to 155 Mbps) links that would connect HIPERMAN and HIPERACCESS networks. Work on this standard has not yet started.

At this time there is some contention between the IEEE 802.11a and HIPERLAN/2 standards for high-speed wireless access in the 5-GHz spectrum. Attempts are currently being made to bridge the differences and provide certification for the IEEE 802.11a standard in Europe, along with coexistence rules for neighboring systems.

1.8 FIXED, PORTABLE, AND MOBILE TERMINALS

As mentioned in the Preface, the differences that distinguish fixed and mobile systems have become somewhat blurred. The term *fixed* is clear – the transmitting and receiving terminals of the wireless transmission circuit are physically fixed in place. A microwave link system with the transmitting and receiving antennas mounted on towers attached to the ground, a rooftop or some other structure is a reference example of a fixed system. In fact, any system that incorporates a high-gain fixed pattern antenna such as a parabolic dish or horn antenna is necessarily a fixed system since precise alignment of the antennas so that they point in the proper directions is required for the system to work properly. MMDS–type antennas mounted on the outside wall or roof of a residence to receive signals from a transmitter toward which the antenna is pointed is also a good example of a fixed system, even though the antennas may have less directionality than those used in PTP microwave link systems. Even television broadcast systems are fixed systems in this sense. The transmitting and receiving antennas are fixed, as is the TV itself while it is being watched. An exception to this are high-gain antennas receiving satellite signals on board ships where sophisticated gimbaling systems are required to keep the antenna pointed in the correct orientation regardless of the movements of the ship.

The IEEE 802.11 standards are primarily designed for fixed and ‘portable’ terminal devices. Also referred to as *nomadic* in ITU and other European documents, a portable terminal is one that stays in one place while it is being used, but can readily be picked up and moved to another location. A notebook computer with an 802.11b wireless access

PC card is a good example of such a portable device. Another portable device would be a desktop wireless modem that is connected to a computer via a USB port, but while operating, the modem is expected to be in more or less one place – on a desktop, for example. Moving it across the desk or to another room makes it portable, but while in use, it is stationary. The concept of such an indoor portable wireless modem with a data rate capability of 5 to 10 Mbps currently dominates much of the leading system design and manufacturer developments in fixed broadband wireless access in licensed bands below 11 GHz.

The classification of fixed systems can be further refined by recognizing that for some networks, one terminal of the transmission link is at an *ad hoc* location rather than an 'engineered' location; that is, no engineering knowledge or effort has been used to determine a good location for the terminal device. Instead, the terminal location has been chosen by the user to be the place that is most convenient. A notebook computer with a wireless modem of some sort placed on an arbitrarily located desk is an example of such a system. This contrasts to a system in which an antenna is mounted on the outside or roof of a structure and carefully pointed by a technician to achieve a certain performance level. *Ad hoc* fixed systems present new challenges to system design since the problem of analyzing coverage and interference, and ultimately performance, is quite similar to that of mobile radio or cellular systems in which the design must provide for terminals located essentially anywhere in the system service area.

The differences between engineered and *ad hoc* fixed wireless systems have a dramatic impact on the commercial success of the system. An engineered system requires the expensive step of sending a trained technician to every terminal location at least once to complete a successful installation. The value to the operator of this customer's business must be significant enough to justify the cost of this 'truck roll'. Certainly for some customers such as large businesses that require microwave links carrying hundreds of megabits of data, this may very well be the case. However, for systems designed to serve thousands of more casual communication users such as homes, home offices, and small businesses, a system design that can work effectively with *ad hoc* 'self-installed' terminals without the necessity of truck roll is needed for that system to be commercially viable.

Finally, the term *mobile* can be distinguished as applying to those systems designed to support terminals that are in motion when being used. The recent 3G UMTS standards even differentiate the level of service that should be provided on the basis of the speed of the mobile terminal. The 3G specification identifies three levels of mobile speed

- 0 km/hr, where data rates up to 2.048 Mbps can be provided.
- 3 km/hr (pedestrian), where data rates up to 384 kbps can be provided.
- 30 km/hr (vehicular), where data rates up to 144 kbps can be provided.
- 150 km/hr (fast train), where data rates up to 64 kbps can be provided.

While 2.5G and 3G cellular systems of all types (GPRS, EDGE, UMTS W-CDMA and CDMA2000) will be important mechanisms for providing voice and data communication worldwide, they are not fixed systems as defined here. However, the engineering methods they employ and the data rates that are possible make the extension of these technologies to fixed broadband wireless scenario a logical step. Several system hardware developers are currently pursuing exactly this course in an effort to provide the high-speed, *ad hoc* wireless broadband service described earlier. A good example is the TDMA TDD (time division duplex) version of the UMTS W-CDMA standard. Although primarily designed for mobile services, these technologies will be treated in this book to the extent that they are applicable to the fixed broadband network deployment.

1.9 TYPES OF FIXED WIRELESS NETWORKS

The types of fixed wireless network topologies that will be treated in this book fall into four broad categories. Each is briefly introduced in the following sections with more detailed technical design and analysis to follow in later chapters.

1.9.1 Point-to-point (PTP) networks

Point-to-point (PTP) networks consist of one or more fixed PTP links, usually employing highly directional transmitting and receiving antennas, as illustrated in Figure 1.2. Networks of such links connected end to end can span great distances as in the case of the original AT&T 4-GHz link network that crossed the United States in 1951. Links connected end to end are often referred to as tandem systems, and the analysis for the end-to-end reliability or availability of the whole network must be calculated separately from the availability of individual links.

1.9.2 Consecutive point and mesh networks

Consecutive point networks (CPN) are similar to PTP networks in that they consist of a number of links connected end to end. However, as illustrated in Figure 1.3, CPN

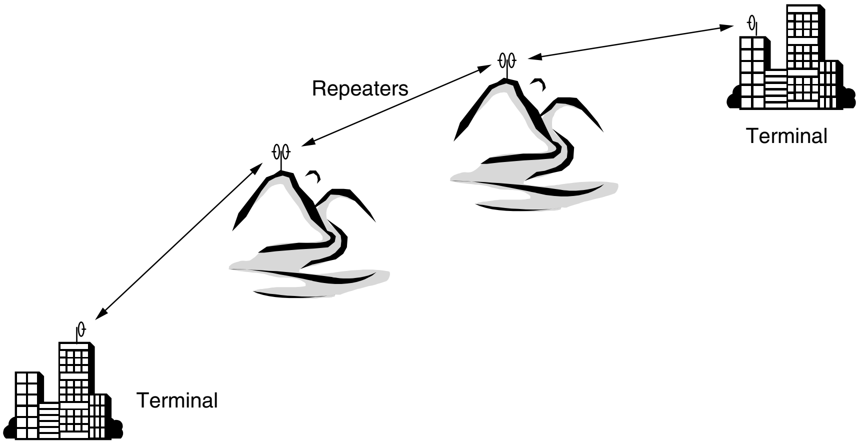

Figure 1.2 Point-to-point (PTP) network connecting two cities through mountaintop repeaters.

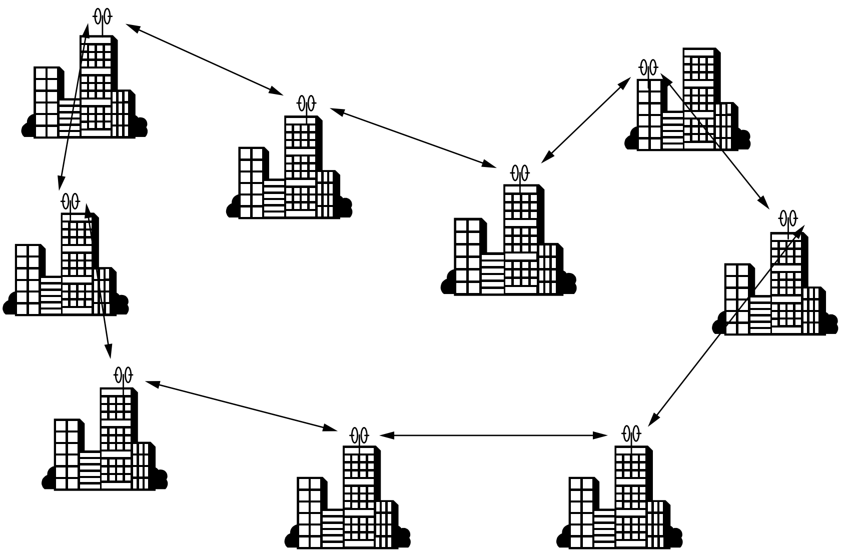

Figure 1.3 Consecutive point network (CPN) connecting buildings within a city.

are configured as rings usually attached to an optical fiber node at some point along the ring that ultimately connects into worldwide optical fiber networks. The data traffic travels in both directions around the ring. The main advantage of such a ring system is that if a problem develops at some point along the ring such that the traffic flow is interrupted, the traffic can be automatically rerouted in the other direction around the ring. The disadvantage is that the traffic originated by and destined for customers on the ring must share the same radio link data transmission capacity. Depending on the capacity of the CPN and the number of customers on the ring (and their data rate requirements), this can be an important limitation that must be considered in link dimensioning.

Mesh networks are a variation of CPNs that are generally configured as links connected in both rings and branching structures. The main advantage is that mesh networks provide alternate paths for connected customers who might otherwise lack line-of-sight (LOS) visibility to the network, increasing the potential number of connected customers. However, like CPNs, the traffic for any given customer must sometimes be routed through several nodes, possibly straining the data capacity of the links connecting those nodes and possibly introducing data delivery delays (latency) that can affect the quality of service for services that require real-time response (such as VoIP). The additional nodes involved in achieving an end-to-end connection can result in lower reliability than multipoint networks in which only one wireless link is needed to connect to the network.

1.9.3 Point-to-multipoint (PMP) networks

PMP networks used a ‘hub and spoke’ approach to deliver data services as illustrated in Figure 1.4. The hub is analogous to the base station in a cellular system. It consists of

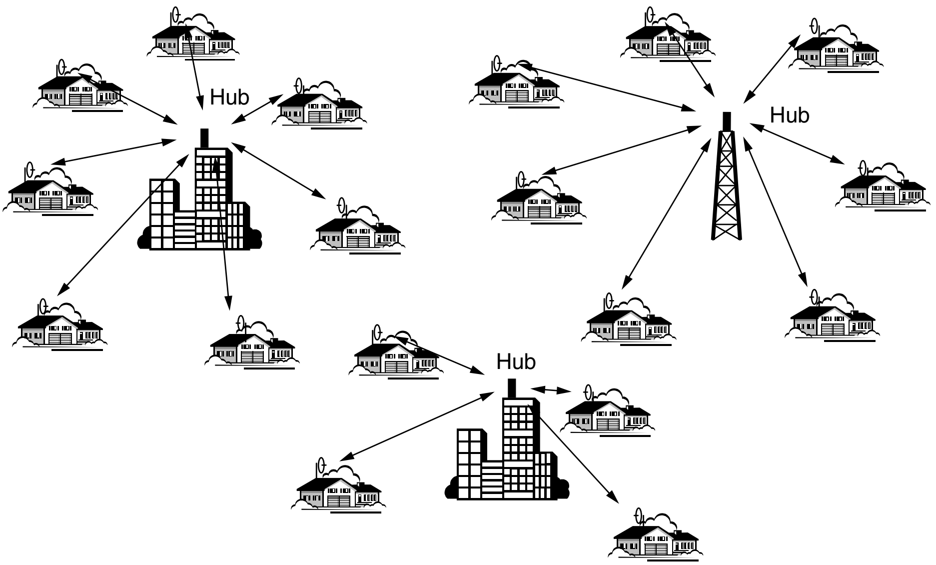

Figure 1.4 Point-to-multipoint (PMP) network.

one or more broad-beam antennas that are designed to radiate toward multiple end-user terminals. Depending on the frequency band employed, and the data rates to be provided to end users, normally several hubs are needed to achieve ubiquitous service to a city. The remote end-user terminals are engineered installations in which directional antennas have been installed in locations that are in the LOS to the hub and oriented by a technician to point at the hub location. In some cases this may require extensive work at each terminal location.

PMP network architecture is by far the most popular approach to fixed broadband wireless construction. It mimics the network topology successfully used for decades in wired telephone networks, cable television networks, and even electrical, gas, and water utilities of all sorts. For wireless, the major drawback is the cost of the infrastructure to construct the hubs needed to achieve comprehensive LOS visibility to a large percentage of the service.

1.9.4 NLOS point-to-multipoint networks

Non-line-of-sight (NLOS) PMP networks are identical in topology to the PMP networks described above. The difference lies in the nature of the remote terminals. Instead of the remote terminals being engineered and professionally installed to achieve successful performance using an outside antenna, the terminals are arbitrarily positioned at the convenience of the end user inside a house or office. In most cases, the location of these terminals will be places that do not have a clear, obstruction-free view of a network hub and are thus called non-line-of-sight. The signal attenuation and amplitude variability that occurs along the wireless signal path from the network hub to NLOS location present new challenges to system designers in their efforts to provide a reliable high-speed data service to every terminal. The engineering problem is similar to the problem of providing service to mobile phones; however, as explained in later chapters, the fixed wireless engineer can exploit some advanced techniques in the terminal and network that are not yet practical for cellular system engineers.

1.10 ORGANIZATION OF THIS BOOK

This book is organized into several chapters that provide detailed discussions of the engineering principles on which the design of fixed broadband wireless systems are based, followed by several chapters that discuss on a more pragmatic level methods and techniques that can be utilized in designing real fixed wireless systems. The methods described are intended to be applied to generic system types rather than any particular manufacturer's equipment or approach to network construction. While different manufacturers may tout their products as being uniquely better than those of their competitors, in reality all are based on the same engineering principles described in this book.

Chapters 2 through 6 provide an engineering foundation for the physical mechanisms and current technology for fixed broadband wireless systems. Chapter 2 deals with the theoretical fundamentals of EM wave and wave propagation and, in particular, the impact that the physical environment has on EM wave propagation. This discussion includes both effects from the natural environment such as terrain, rain scattering, atmospheric refraction, fog, and so on, and effects from the artificial environment including shadowing, reflection, diffraction, and scattering from buildings and other structures.

Chapter 3 uses the theoretical propagation mechanisms described in Chapter 2 to construct propagation or channel models. As the word implies, a 'model' is a close representation for the real thing; it is not the real thing. Since the models will be used to design fixed wireless systems, the closer the model is to the 'real thing', the better. Over the decades, considerable effort has been made into making the models better. Distinctive classifications and subclassifications of models have emerged that fall into three general areas: theoretical, empirical, and physical models. Propagation models themselves traditionally have been used to describe the median EM field strength at distance from the transmitter. A more comprehensive approach is a channel model that attempts to describe not only the field strength at some point away from the transmitter but also the variations in the field as a function of time, frequency, and location. The performance of many modern fixed broadband wireless systems, especially NLOS PMP systems, depends on information provided by a channel model.

Chapter 4 deals with models of signal fading. Signal fading occurs due to changes in atmospheric conditions, the presence of rain and other precipitation, and changes in the locations of objects in the propagation environment. Fading phenomena are described in statistical terms. For high reliability digital links, these fading model statistical descriptions have a primary impact on the impact of predicted availability and reliability of the link.

Chapter 5 also discusses the important topic of terrain, clutter, and building (structure) models that are used in conjunction with propagation and channel models. As discussed in this chapter, the accuracy of the propagation model is often limited by the accuracy of the physical databases rather than the engineering methods in the model itself.

Chapter 6 discusses the important subject of antennas for fixed wireless systems. This chapter includes descriptions of traditional PTP fixed antennas such as parabolic dishes and horns, as well as 'smart' or adaptive and MIMO (multiple input, multiple output) antenna systems that are emerging as important techniques for achieving high capacity NLOS links.

Chapter 7 discusses the basic principles of digital modulation, equalizers, and coding. Every fixed wireless system uses a modulation method of some sort, whether it is a multiplex analog FM as in the original telephone carrier systems, or digital modulation that ranges from simple lower efficiency methods such as BPSK (binary phase shift keying) and QPSK (quadrature phase shift keying) to more elaborate and efficient methods such as 64QAM or 256QAM (quadrature amplitude modulation). Even simple OOK (on–off keying like a telegraph) is used in FSO systems.

Chapter 8 also deals with the important subject of multiple access and duplexing techniques such as

- FDMA (frequency division multiple access)
- TDMA (time division multiple access)
- CDMA (code division multiple access)
- SDMA (space division multiple access)
- OFDMA (orthogonal frequency division multiple access)
- FDD (frequency division duplexing)
- TDD (time division duplexing).

All multiple-access techniques are fundamentally trying to increase the number of users that can simultaneously access the network while maintaining a certain level of service quality (data rate, throughput, delay, and so on). The ability of a multiple-access scheme to achieve this objective can have the largest impact on the network's commercial success.

Chapter 9 lays the groundwork for the fixed wireless system design by discussing traffic and service models, the physical distribution of traffic and various traffic types, and service application models. This chapter also includes new traffic simulation results that provide a convenient approach for dimensioning the capacity of a wireless network hub to achieve a given service quality to a projected population of end users.

Chapter 10 describes traditional PTP fixed link design methods that have been in use for many years, with a focus on developing and using link budgets to assess performance and availability. This process includes choosing tower locations and heights, path clearance analysis, rain and fade outage analysis, and ultimately link availability. Link budgets and fading criteria for NLOS links are also discussed. The link design methods and analyses presented in this chapter are basic building blocks that are also used to design consecutive point and mesh networks, as well as PMP networks.

Chapter 11 provides the steps to designing both LOS and NLOS PMP networks, including identifying traffic sources and choosing hub locations that provide adequate coverage based on the link budgets developed in Chapter 10. Dimensioning the hub cell service areas, the multiple-access channel data rates and the hub sector capacities to meet the projected traffic load is also discussed. The use of Monte Carlo simulations to evaluate the quality of a design is also dealt with in this chapter. The objective of a design is to produce a system plan that can be subject to the iterative process of refining and updating the network plan as needed.

Chapter 12 deals with the important subject of channel planning. The efficient assignment of frequencies, time slot, and codes to meet traffic demands that vary with time and location is critical to realizing the highest capacity and commercial benefit of the available spectrum. The channel assignment techniques discussed include static and dynamic methods, including dynamic packet assignment (DPA). The integration of newer technologies that enhance network capacity is also discussed. Chapter 12 also discusses some ideas that generalized the concept of spectrum space as a Euclidean space, with path loss, time, and frequency as the dimensions of space rather than the traditional three physical dimensions as well as time and frequency. This approach to viewing the wireless spectrum offers some insights into efficient system planning that would not otherwise be as apparent.

1.11 FUTURE DIRECTIONS IN FIXED BROADBAND WIRELESS

Fixed broadband wireless has a history that spans several decades. The progress in the technology, especially hardware innovations for transmitters and receivers, has opened the door to effectively exploiting higher and higher frequency bands. Even more dramatic developments in high density very large scale integration (VLSI) has led to highly efficient signal processing, coding, and multiple-access techniques that were not feasible in mass-produced devices even a few years ago.

The upward innovation ramp will continue with access to frequencies above 60 GHz, which is now imminent. The administrative process to allow commercial deployment in these frequencies has already begun. Developments in higher power transmitting devices and lower noise receiving devices, along with adaptive spatial signal processing, will also permit more extensive use of existing bands beyond their currently perceived limitations. Employing 28-GHz frequencies for NLOS networks, currently considered infeasible, will probably become possible with upcoming hardware improvements.

New approaches to utilizing spectrum will also assume a more prominent role. Ultra wideband (UWB) technology is one example that has recently gained FCC approval in the United States. UWB uses very narrow pulse technology that spreads the signal power over a very wide bandwidth resulting in average power levels that are intended to be sufficiently low to preclude interference to other spectrum occupants. A similar innovation is MIMO technology that can potentially increase the data rate capacity between link terminals by as much as an order of magnitude over conventional approaches.

The availability of low-cost, accessible license-exempt technologies led by IEEE 802.11b (Wi-Fi) in the 2.4-GHz band has captured the imagination of millions worldwide by unveiling the exciting possibilities of high-speed wireless data connections to the Internet. The energy in the enterprises pursuing business opportunities using these networks will also flow into more sophisticated and capable fixed broadband wireless technologies discussed in this book. The rapidly growing number of wireless Internet service providers (WISPs) is a harbinger of the business opportunities that will abound for service providers, equipment vendors, and application developers.

Worldwide, fixed wireless networks offer the best opportunity for bringing electronic communication to the majority of the Earth's population still lacking even basic telephone service. Wireless networks can rapidly extend service into remote areas at much lower cost when compared to installing poles or digging trenches to accommodate wired networks.

The technical innovations and potential applications have moved wireless closer to the mythical concept of a secure, private, high capacity, dimensionless, low-cost, tetherless communications connection that is available everywhere at low cost and minimal environmental impact. The current progress in fixed broadband wireless technology is an incremental step in this human evolutionary pursuit.

1.12 CONCLUSIONS

This chapter has presented a brief history of wireless technology and in particular fixed wireless technology as it originally saw wide-scale deployment with multilink networks for cross-continent telephone traffic. The growing demand for various types of high-rate data services were also discussed along with the frequency bands for licensed and license-exempt fixed broadband networks that regulators have allotted to meet the recognized demand for data services. Several network topologies include PTP, consecutive point (CPN), PMP, and NLOS PMP, which are presented in schematic form. The chapters that follow provide the substance and the details required to build on this framework, and extend these concepts to creating successful, high-performance fixed broadband wireless systems.

Compared to wired alternatives, wireless technologies offer substantially more flexibility in choosing how and where services are deployed and the types of applications that can be supported. The ability to more readily modify, reconfigure and enhance wireless networks compared to wired networks ensures a significant and growing future for fixed broadband wireless communications technology.

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