FIXED BROADBAND WIRELESS
SYSTEM DESIGN

HARRY R. ANDERSON, Ph.D., P.E.

CONSULTING ENGINEER
USA

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Preface

The growing demand for high-speed data connections to serve a variety of business and personal uses has driven an explosive growth in telecommunications technologies of all sorts including optical fiber, coaxial cable, twisted-pair telephone cables, and wireless. Nations have recognized that telecommunications infrastructure is as significant as roads, water systems, and electrical distribution in supporting economic growth. In developing countries it is not particularly unusual to see cell phone service in a town or village that does not yet have a water or sewer system. In the United States, recent government initiatives have recognized the importance of broadband telecommunications to economic growth.

This book focuses on fixed broadband wireless communications – a particular sector of the communication industry that holds great promise for delivering high-speed data to homes and businesses in a flexible and efficient way. The concept of ‘broadband’ communications is a relative one. Compared to the 1200-baud modems commonly used 20 years ago, today’s dial-up phone connections with 56-kbps modems are ‘broadband’. The demands and ambitions of the communication applications and their users have expanded, and will continue to expand, on what is meant by ‘broadband’. The term is evolving, as is the technology that is classified as broadband. Nevertheless, for the purposes of this book I will use the somewhat arbitrary definition that broadband wireless systems are those designed for, and capable of handling baseband information data rates of 1 Mbps or higher, knowing that future developments may well move this threshold to 5 or 10 Mbps and beyond. The term ‘broadband’ also has an engineering significance that will be discussed in some detail in this book. Broadband wireless channels, as distinguished from narrowband channels, are those whose transfer characteristics must be dealt with in a particular way, depending on the information transmission speed and the physical characteristics of the environment where the service is deployed.

The term ‘fixed’ has also become somewhat nebulous with the technological developments of the past few years. Whereas fixed and mobile were previously well-understood differentiators for system types, we now have intermediate types of network terminals including fixed, portable, nomadic, and mobile, among others. Recent system standards such as those for 3G UMTS W-CDMA define different service levels and data rates depending on whether the user is in a fixed location, walking, or moving at high speed. This trend portends a convergence of fixed and mobile system types whose operation and availability are largely transparent to the application users. As will be shown, whether the system user is at a fixed location or in motion affects several decisions about the system design, the most appropriate technology, and the quality and performance that can be expected from a wireless application.

Although there have been a few books recently written on broadband, and specifically wireless broadband, in general they have been intended for non-technical audiences.

This book is intended for engineers who are faced with designing and deploying fixed broadband wireless systems, and who must also have sufficient understanding of the theory and principles on which the designs are based to formulate creative solutions to special engineering problems that they will eventually face. Along with generally accepted design assumptions and simplifications, the underlying theory and requisite mathematics are included where necessary to provide this foundation knowledge.

In addition to design engineers who deal with fixed broadband wireless systems on a daily basis, this book is also well suited to graduate and post-graduate level courses that are focused on wireless communications engineering. Wireless communication system design and planning is an increasingly important area that warrants serious academic treatment.

This book also covers some areas that have not classically fallen in the domain of wireless RF engineers; in particular, traffic modeling, environment databases, and mapping. Wireless system design is driven by the commercial requirements of the system operators who ultimately build viable businesses by successfully serving the traffic demands of the customers in their service areas. Detailed statistical modeling of packet-based traffic for a variety of applications (e-mail, web-browsing, voice, video streaming) is an essential consideration in fixed broadband system design if the operator's capacity and quality of service objectives are to be achieved.

The chapters in this book are organized with the fundamentals of electromagnetic propagation, channel and fading models, antenna systems, modulation, equalizers and coding treated first since they are the building blocks on which all wireless system designs are based. Chapters on multiple access methods and traffic modeling follow. The remaining chapters set forth the specific details of many types of line-of-sight (LOS) and non-line-of-sight (NLOS) systems, including elemental point-to-point links as well as point-to-multipoint, consecutive point, and mesh networks. Because of their importance, a separate chapter is devoted to designing both LOS and NLOS point-to-multipoint networks. The final chapter deals with the important subject of channel assignment strategies where the capacity and service quality of the wireless network is ultimately established.

Fixed wireless design relies on a number of published sources for data and algorithms. For convenience, the essential data, such as rain rate tables and maps, is included in the Appendices. In general, the referenced publications chosen throughout are currently available books or journal papers which are readily accessible in academic libraries or on-line. For the most recent or unique work, technical conference papers are also utilized.

A book of this type is clearly not a solo effort. I would like to thank several people who offered valuable comments, including Tim Wilkinson for reviewing Chapters 7 and 8, George Tsoulos for reviewing Chapter 6, and Jody Kirtner for reviewing Chapter 5, and for her efforts in proofreading the entire manuscript. Creating and refining a technical work such as this book is an evolutionary process where comments, suggestions, and corrections from those using it are most welcome and encouraged. I hope and anticipate that this book will prove to be a worthwhile addition to the engineering libraries of those who design, deploy, and manage fixed broadband wireless systems.

Harry R. Anderson
Eugene, Oregon, USA
January, 2003.

1

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.

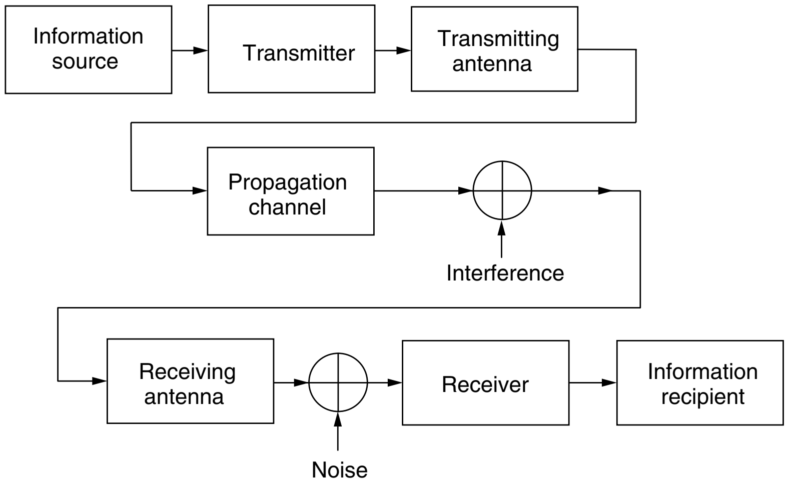

Figure 1.1 Block diagram of a basic wireless communications system.

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.