message dimensions (i.e., subchannels by OFDM symbols), and a DL frame prefix checksum. As illustrated by Figure 11–24, downlink bursts can be of various different sizes. A downlink burst consists of a certain number of subchannels that are used for an integer multiple of three OFDMA symbols. A downlink burst's modulation, coding scheme, and dimensions are defined in the DL-MAP message. The MAC layer defines the downlink transmission frame size and the length of the different transmission sections. The uplink burst also consists of a number of subchannels transmitted over a number of OFDMA symbols. The number of OFDMA symbols is equal to $1 + 3N$ where N is a positive integer. The first OFDMA uplink symbol transmitted by an SS contains a preamble on all allocated subchannels (refer back to Figure 11–24). The smallest uplink allocation is one subchannel and four OFDMA symbols. Larger allocations, known as extended allocations, are possible and depicted, along with a minimal size allocation, by Figure 11–25. The MAC layer also sets the length of the uplink frame and the uplink mapping.

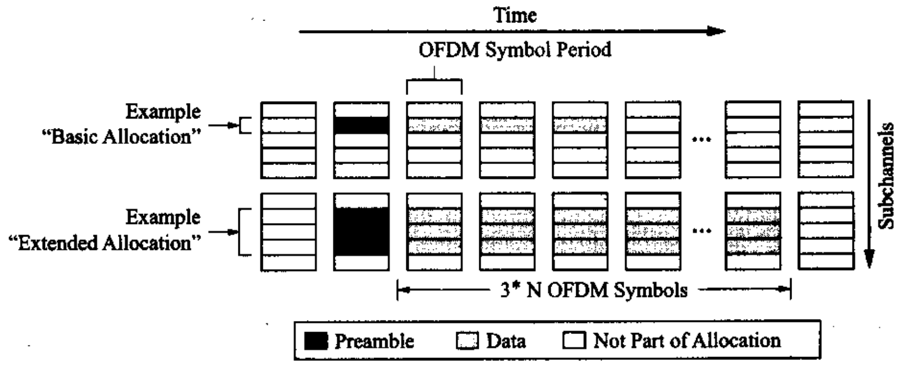


Figure 11–25 OFDMA uplink symbol burst allocations (Courtesy of IEEE).

OFDMA Carrier and Pilot Allocations

The allocation of carriers for pilot and data functions is performed slightly differently for downlink and uplink transmissions. For downlink, the pilot tones are allocated first and the remaining carriers are then allocated for data. For the uplink, all the available carriers are first partitioned into subchannels and then the pilot carriers are allocated within each subchannel. This provides a common set of pilots for downlink broadcast transmissions that go from the base station to all SSs. For uplink transmissions, since each subchannel may be allocated to a different SS, they each have their own pilots. Figure 11–26 depicts the allocation of the fixed and variable pilot carriers for the downlink direction whereas Figure 11–27 depicts the carrier allocations for a particular subchannel (one of thirty-two) in the uplink direction. Notice that there are only four different pilot location scenarios within the downlink OFDMA symbols that are repeated every four symbols. For the uplink, each subchannel consists of a total of fifty-three carriers of which four carriers are variable location pilots and one carrier is a fixed location pilot. Each subchannel pilot position permutation leaves forty-eight carriers for data and is repeated every twelve OFDMA symbols.

OFDMA Ranging, Bandwidth Requests, and Channel Coding

For WirelessMAN-OFDMA operation the MAC defines a single ranging channel (refer back to Figure 11–25). This OFDMA ranging channel consists of an even number of adjacent subchannels and the index of the lowest-number subchannel is even. Details of the channel are contained in the UL-MAP message. An initial ranging transmission is used by an SS that wants to synchronize itself to the system for the first time. The SS randomly chooses a ranging code from a list of pseudorandom binary sequences. The code is then transmitted via an OFDMA symbol (1 code bit per carrier using BPSK modulation). The same code is transmitted on two consecutive OFDM symbols. Once the SS has synchronized to the system, periodic

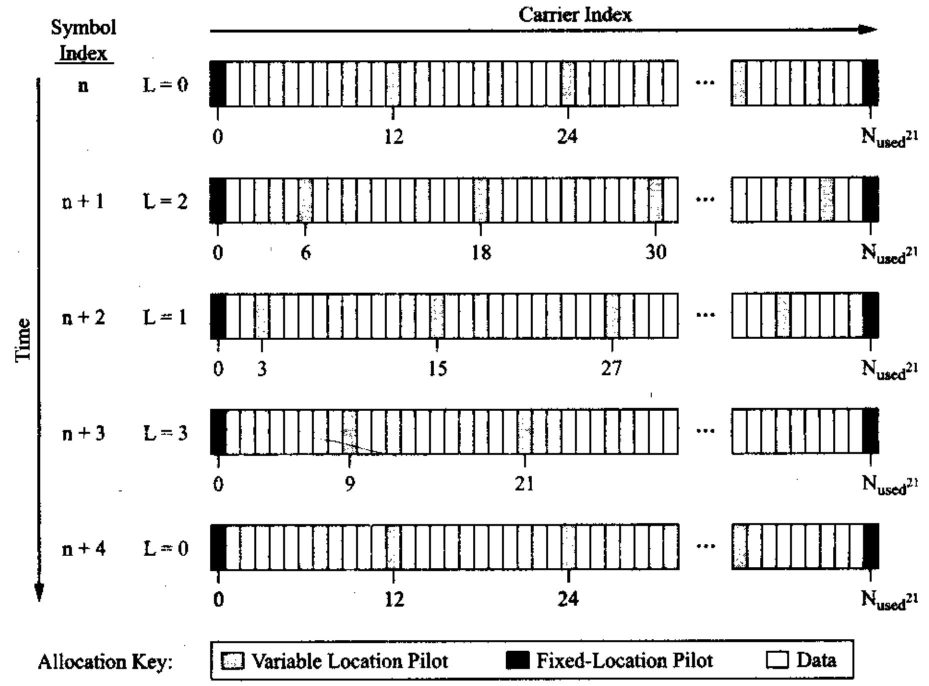


Figure 11–26 OFDM carrier and pilot channel allocations in the downlink direction (Courtesy of IEEE).

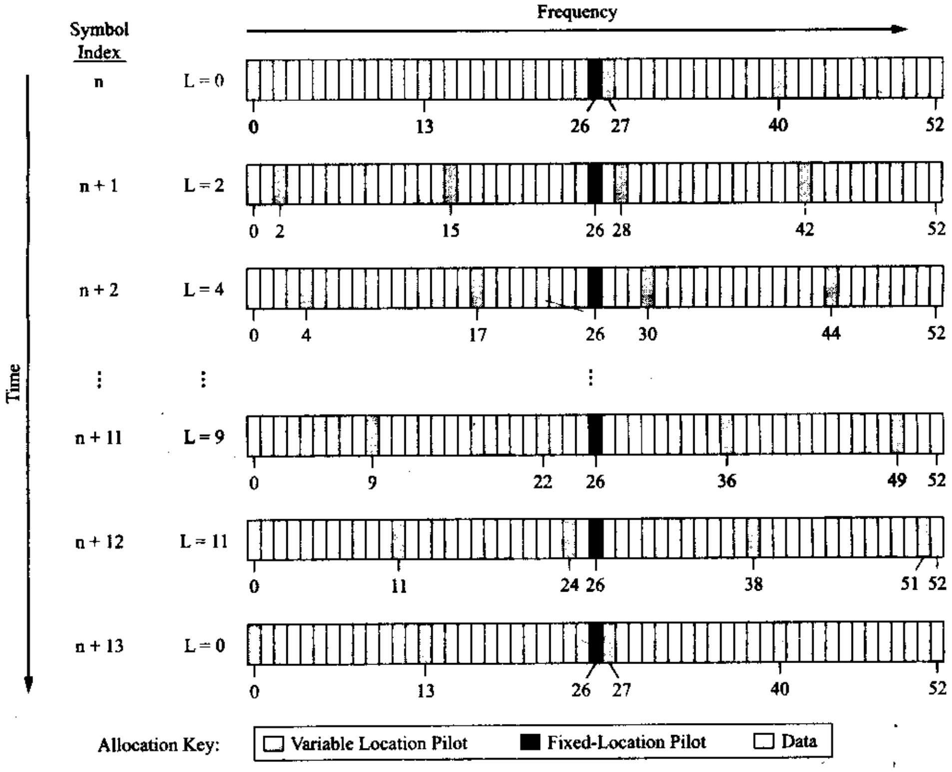


Figure 11–27 OFDM carrier and pilot channel allocations in the uplink direction (Courtesy of IEEE).

ranging transmissions are sent by the SS. In this case, the SS transmits one ranging code on the ranging channel for a single OFDMA symbol. SS uplink bandwidth requests also use the same technique just described.

There are forty-eight possible pseudorandom codes that are used for the three different operations just described. These codes are subdivided into three groups: initial ranging, periodic ranging, and bandwidth requests. Through the use of these various codes the base station of an OFDMA system is able to extract both timing (ranging) and power information. The base station obtains a great deal of information about the characteristics of the user channel during the signal processing performed in the process of code detection. The timing and power measurements allow the system to adjust to the propagation conditions and propagation delay caused by the distance between the BS and the SS.

Channel coding for the WirelessMAN-OFDMA system consists of procedures that randomize the data to be transmitted and provide FEC encoding, interleaving, and modulation. These processes are very similar to what has already been discussed earlier in this chapter and any variations in the process do not alter the basic purpose or objective of the process—to provide the correct mapping to the OFDMA symbols and to lower the transmission bit error rates. Data modulation on both the downlink and uplink is restricted to QPSK, 16-QAM, and optional 64-QAM, with various levels of encoding and interleaving functions available. As might be expected, adaptive modulation and coding is supported on the downlink and the uplink supports different modulation schemes for each SS based on MAC messages coming from the BS. The pilot carriers of the OFDMA symbols are modulated by a pseudorandom binary sequence determined by their location within the OFDMA symbol.

OFDMA Diversity, Control, and Channel Quality Measurements

The WirelessMAN-OFDMA specification supports space time coding diversity as previously discussed within this chapter. The reader is referred back to Figure 11–17 for a system diagram of this operation. The system control functions of network synchronization, ranging, and power control are also identical to those already discussed for the other IEEE 802.16a physical layer specifications. Furthermore, channel quality measurements of RSSI and CINR are also supported within this wireless OFDMA system.

OFDMA Transmitter and Receiver Specifications

For this physical layer specification the transmitter must support a power level control of 45 dB for licensed bands and 30 dB for license-exempt bands. The receive bit error rate must be less than 10^{-6} for the received power levels shown in dBm in Table 11–2 and a noise figure of 7 dB. The fractions under the modulation forms indicate the coding rate used by the system.

WirelessHUMAN Option

The WirelessHUMAN option for IEEE 802.16a is to be used in the 2–11 GHz license-exempt bands. It basically calls for the use of dynamic frequency selection protocols that are used to limit interference between other wireless systems operating in these unlicensed bands. Each of the previously discussed IEEE 802.16a physical layers may be used in this manner provided that they also adhere to the channelization specifications to be described here.

Within the 5–6 GHz frequency range, the channel center frequency is given by:

$$\text{Channel center frequency (MHz)} = 5000 + 5 \times n_{ch} \tag{11-1}$$

where $n_{ch} = 0, 1, \ldots, 199$. Table 11–3 indicates the set of allowed channel sets for the United States and Europe as per this writing and Figure 11–28 shows the United States' channel sets in the frequency domain.

Table 11–2 IEEE 802.16 receiver specifications (Courtesy of IEEE).

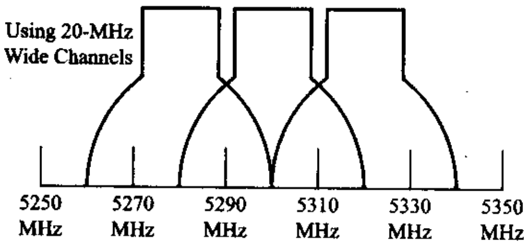
Bandwidth (MHz)	*QPSK*		*16-QAM*		*32-QAM*	
	1/2	*3/4*	*1/2*	*3/4*	*1/2*	*3/4*
1.5	–91	–89	–84	–82	–78	–76
1.75	–90	–87	–83	–81	–77	–75
3	–88	–86	–81	–79	–75	–73
3.5	–87	–85	–80	–78	–74	–72
5	–86	–84	–79	–77	–72	–71
6	–85	–83	–78	–76	–72	–70
7	–84	–82	–77	–75	–71	–69
10	–83	–81	–76	–74	–69	–68
12	–82	–80	–75	–73	–69	–67
14	–81	–79	–74	–72	–68	–66
20	–80	–78	–73	–71	–66	–65

Table 11–3 IEEE 802.16 allowed channel sets for the United States and Europe (Courtesy of IEEE).

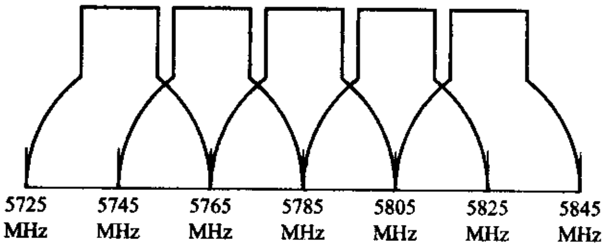
Regulatory Domain	*Band (GHz)*	*Channelization (MHz)*	
		20	*10*
United States	U-NII middle 5.25–5.35	56, 60, 64	55, 57, 59, 61, 63, 65, 67
	U-NII upper 5.725–5.825	149, 153, 157, 161, 165	148, 150, 152, 154, 156, 158, 160, 162, 164, 166
Europe	CEPT band B 5.47–5.725	100, 104, 108, 112, 116, 120, 124, 128, 132, 136	99, 101, 103, 105, 107, 109, 111, 113, 115, 117, 119, 121, 123, 125, 127, 129, 131, 133, 135, 137
	CEPT band C 5.725–5.875	148, 152, 156, 160, 164, 168	147, 149, 151, 153, 155, 157, 159, 161, 163, 165, 167, 169

11.6 IEEE 802.16 COMMON SYSTEM OPERATIONS

This section is provided in an effort to wrap up any loose ends about the operation of IEEE 802.16-compliant wireless MANs. The actual IEEE 802.16/16a standard is many hundreds of pages in length and therefore omissions about various details of system operation are bound to happen. The goal of this chapter



U-NII Middle Band



U-NII Upper Band

Figure 11–28 USA IEEE 802.16 Wireless-HUMAN channel sets (Courtesy of IEEE).

is not to provide every detail of system operation but to provide a general sense of how the system works and an overview of the technologies used to implement the system. The next few sections are meant to fill in some gaps of system operation that have yet to be discussed. These brief overviews will not answer all the questions one might have about these aspects of system operation but will provide some insight into how things work.

Network Entry and Initialization Procedures

The MAC protocol includes a network entry and initialization procedure that essentially eliminates the need for the manual configuration of a new SS within an IEEE 802.16 system (see Figure 11–29). When a new SS is first powered up, it will search for an active operating channel by scanning through its list of acceptable operating channels. It may also listen for the broadcast of a particular base station ID. Upon deciding on which channel to attempt communications, the SS will try to synchronize with the downlink transmissions by decoding the periodic frame preamble bursts. Once the SS is synchronized, it will listen to UDC MAC management messages in an attempt to learn the uplink channel characteristics (modulation and FEC schemes) being used on possible uplink channels. If an SS has been attached to a system and a loss of signal has occurred, the SS will attempt to reacquire the lost downlink channel using stored channel parameters to aid in this process.

The next step in the initialization process is ranging. Upon deciphering the appropriate parameters to use for an initial ranging transmission, the SS will scan the UL-MAP message to find an initial maintenance interval (IMI). This interval is made large enough to accommodate the maximum round-trip propagation delay and other system delays. The SS sends an RNG-REQ message during an IMI time period. This first ranging burst is sent at a minimum power setting. If no ranging response is received by the SS, increasingly higher transmitting powers are used until a ranging response is received. The BS provides timing advance, power adjustment values, and frequency offset adjustments addressed to the individual SS in the ranging response message. These values are based upon the arrival time of the initial ranging request and signal-strength and frequency measurements. The ranging process adjusts each SS's timing offset in such a fashion that the SS appears to be colocated with the BS (i.e., the internal clocks of the SS and the BS are offset by the propagation delay between them). In the RNG-RSP message, the BS also provides CIDs for the basic

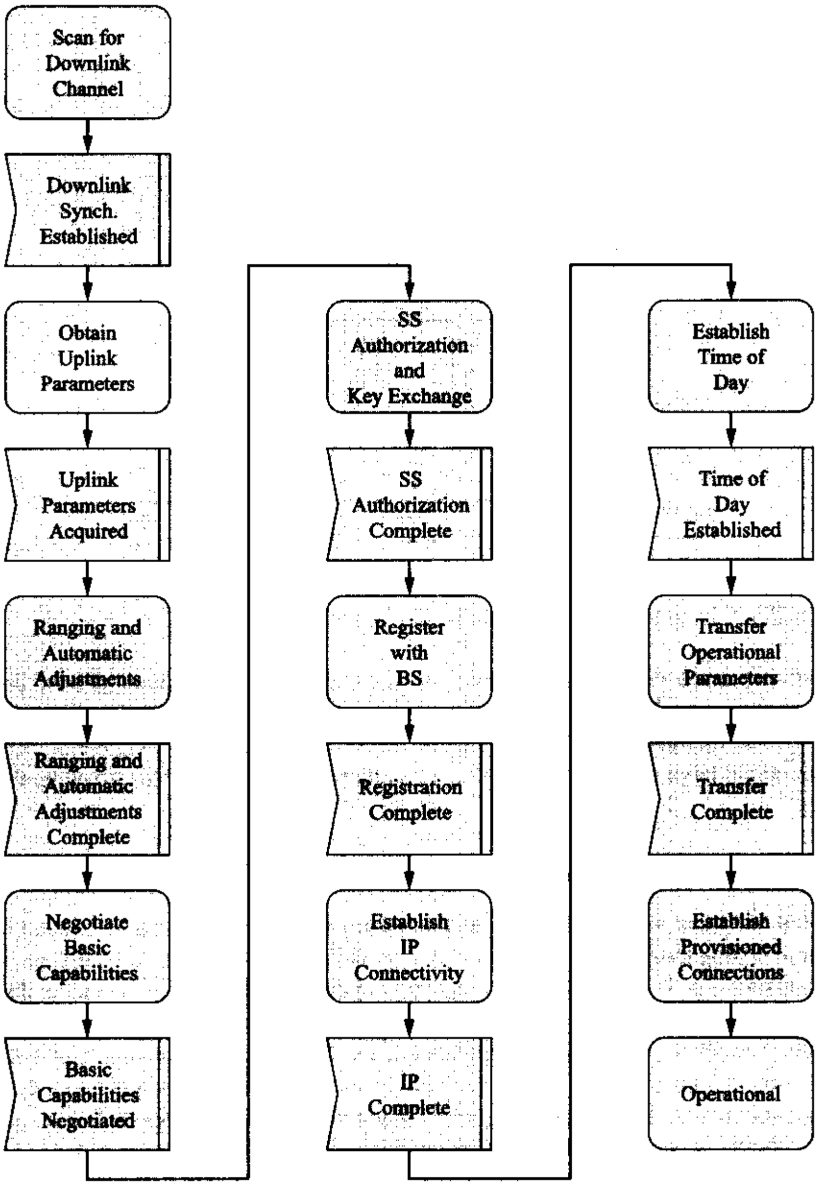


Figure 11–29 Flowchart for IEEE 802.16 subscriber station automatic network entry and initialization operations (Courtesy of IEEE).

and primary MAC connections. Now the SS will wait for an individual station maintenance interval assigned to its basic CID and transmit another RNG-REQ message using the basic CID MAC connection. The BS returns another RNG-RSP message with fine-tuning adjustment parameters. This last process repeats itself until the SS is within tolerances allowed by the BS. At this point, the SS may commence the transmission of normal data traffic on the uplink.

The next step in the initialization process is a negotiation of basic capabilities. Right after the ranging process has been completed the SS transmits an SBC-REQ message that allows the SS to inform the BS of its basic capabilities. Next, the SS authentication and registration process takes place. Each SS comes with a 48-bit MAC address and a manufacturer-issued, factory-installed X.509 digital certificate. These values are sent to the BS by the SS in the authorization request and authentication information messages. The network checks the SS's identity and level of authorization. If the SS is authorized to join the network, the BS will respond to the SS's request with an authorization reply message containing an authorization key that is encrypted with the SS's public key. If the authorization process is successful, the SS will register with the network. This registration process will provide the SS with its secondary management CID (the third MAC management connection) and determine capabilities related to connection setup and MAC operation. During the registration process, the SS will indicate the IP version to use over the secondary connection. The next steps in the overall process establish IP connectivity (i.e., the SS invokes dynamic host configuration protocol [DHCP] to obtain an IP address), establish the time of day via the Internet time protocol, transfer operational parameters by downloading the SS configuration file from the TFTP configuration file server, and finally, establish provisioned connections. This last operation is facilitated by the BS sending a DSA-REQ message to the SS to set up connections for provisioned service flows from the SS to the BS. The SS responds with the DSA-RSP message. As has already been discussed, service flows may be dynamically established by the SS or BS, and dynamic service changes, during which service flows are renegotiated, are supported by the IEEE 802.16 standard.

Uplink Scheduling Service

To increase system efficiency, a set of basic services (see Table 11–4) have been defined for use over the IEEE 802.16 air interface. These services are based on those defined for cable modems by the DOCSIS standard. These services are unsolicited grant service, real-time polling service, non-real-time polling service, and best effort service. Each one of these services has been specifically tailored to a particular type of data flow. Unsolicited grant service (UGS) is designed for the support of real-time applications that generate fixed-size packets of data on a periodic basis. Some typical applications that could use this type of service are T1/E1, voice, Voice over IP (VoIP), and constant-bit-rate ATM. The BS schedules regular periodic grants (the grant size is negotiated at setup) to the SS. This service eliminates the overhead and latency of SS bandwidth requests. Provisions are built into this service to recover from system problems like clock rate mismatches (i.e., the BS can allocate additional bandwidth if needed), and the SS is restricted from using any contention request opportunities.

Table 11–4 Matrix of IEEE 802.16 basic services (Courtesy of IEEE).

Scheduling Type	*PiggyBack Request*	*Bandwidth stealing*	*Polling*
UGS	Not Allowed	Not Allowed	PM bit is used to request a unicast poll for bandwidth needs of non-UGS connections
rtPS	Allowed	Allowed for GPSS	Scheduling only allows unicast polling
nrtPS	Allowed	Allowed for GPSS	Scheduling may restrict a service flow to unicast polling via the transmission/request policy; otherwise all forms of polling are allowed
BE	Allowed	Allowed for GPSS	All forms of polling allowed

Real-time polling service (rtPS) is designed to support real-time service flows that are dynamic in nature. In this case, the service offers periodic dedicated request opportunities to meet real-time data transfer needs. The SS issues requests that specify the size of the desired grant. This service increases overhead and latency but increases optimum data transport efficiency by supporting variable grant sizes. This service is well suited for carrying VoIP or MPEG video. Non-real-time polling service (nrtPS) is designed to support services that require variable-size grants on a regular basis. This service is similar to real-time polling service except that the SS may use random access transmit opportunities for sending bandwidth requests. This service is suitable for applications that can tolerate longer delays and are not significantly affected by delay jitter. Services such as Internet access, certain ATM connections, and high-bandwidth FTP are well suited to this service. Best effort (BE) service gives neither throughput nor delay guarantees. For this service the SS sends requests for bandwidth during random access slots or dedicated transmission opportunities. Since the network load is unpredictable, best effort service can result in time delays that are intolerable for most types of data traffic except that offered on a best effort basis.

Bandwidth Requests and Grants

The IEEE 802.16 MAC layer supports two classes of SSs. These two classes are distinguished by their ability to accept bandwidth grants on only a per connection basis or on the basis of the total SS operation. Both of these SS classes request bandwidth on a per connection basis, which allows the BS uplink scheduling program to take into account QoS when allocating bandwidth. The grant per connection (GPC) class of SSs uses the bandwidth grant only for the connection that it was allotted to. The grant per SS (GPSS) class of SSs are granted bandwidth that is provided to the SS on a collective basis. A GPSS type of SS will typically be able to exploit this functionality to its benefit. Typically, for the GPSS type of SS the bandwidth request for a particular connection will be used by that connection. However, if need be, the SS may reapportion the bandwidth to react to either QoS changes or changing environmental conditions (rain or snow fades, etc.). In this case, the bandwidth explicitly allocated to MAC management messages could be increased to allow the system to respond more rapidly to the changing conditions. Therefore, GPSS systems tend to be more efficient and scalable than GPC SSs and they are the only class of stations allowed in the 10–66 GHz bands. Bandwidth requests may be either incremental or aggregate in nature. A BS that receives a bandwidth request will check the TYPE field in the bandwidth request header and either add the new bandwidth request to the former allocated value or replace the value entirely depending upon the type of request. So-called piggybacked bandwidth requests that do not have a TYPE field are always treated as incremental. The self-correcting nature of the request/grant protocol (i.e., no acknowledgement is returned) requires that, periodically, the aggregate bandwidth response is used to correct for possible missed requests.

The SS has numerous ways in which it can request bandwidth from the BS. A combination of methods is typically employed to make the system more efficient and to provide the bandwidth needed for the underlying system management functions and the services being supplied to the end user. Unsolicited bandwidth grants, contention-based requests, and polling are all possible means to provide bandwidth to the SS. A bandwidth request may come as a stand-alone bandwidth request or as a piggyback request. The bandwidth requests are made in terms of the number of bytes needed to carry both the MAC header and payload during either a request IE or an any data grant burst type IE interval. Bandwidth is always requested on a CID basis and allocated on a connection or SS basis. Polling is the process by which the BS allocates bandwidth to the SSs for the specific purpose of making bandwidth requests. Polling of individual SSs (unicast mode) is done by allocating in the uplink map sufficient bandwidth for the SS to respond with a bandwidth request if desired. SSs with active UGS connections are not polled unless they set the "Poll Me" bit in the header of a UGS packet. Groups of SSs may be polled in multicast groups or a broadcast poll may be issued by the BS. Certain CIDs are reserved for these purposes. Again, bandwidth is allocated in the uplink map for requests from groups of SSs. Only SSs requesting bandwidth reply over the uplink.

Radio Link Control

Radio link control (RLC) is used to support the transition from one burst profile to another, as well as the more traditional functions of power, frequency, and timing (ranging) control. As described previously, during initialization, measurements of both downlink and uplink channel quality have been made and are continuously made during system operation. The BS begins the broadcast of burst profiles appropriate for the conditions, the equipment, and other factors such as the region's rain profile. Burst profiles for the downlink are each tagged with a downlink interval usage code (DIUC) and bursts used on the uplink are similarly tagged with an uplink interval usage code (UIUC). During the initial system access, the SS uses its measurements of the downlink channel to request a particular burst profile from the BS by transmitting its choice of DIUC to the BS. The BS may or may not honor the SS's request. On the uplink side the BS commands the SS to use a certain uplink burst profile by simply sending a UIUC with the SS's grants in the UL-MAP messages. The RLC continues to monitor and control burst profiles. Environmental conditions (weather) may cause the RLC to modify the burst profiles for either more or less robustness. The RLC will continue to adapt the SS's current downlink and uplink burst profiles in an attempt to provide the most efficient system operation. The protocol for changing the uplink burst profile is simple: the BS sends a new UIUC whenever granting the SS bandwidth. For the downlink burst profiles it is necessary for the BS to periodically allocate a station maintenance interval to a GPC SS. The SS may then use the RNG-REQ message to request a change in the downlink burst profile. The preferred method to affect a change is for either a GPC or GPSS SS to transmit a downlink burst profile change request (DBPC-REQ) message. The BS may reply back with a DBPC-RES message either confirming or denying the requested change.

Certainly, many details of WMAN operation have been glossed over in these explanations. However, it is hoped that the reader has gotten a feel for the basic procedures involved in the setup and continuing operation of a wireless MAN.

QUESTIONS AND PROBLEMS

1. Describe the application space for the IEEE 802.16 standard.
2. What frequency range did the original IEEE 802.16 standard address?
3. Describe the basic wireless MAN.
4. Contrast a wireless MAN with a wireless LAN.
5. How is system capacity typically increased for a wireless MAN?
6. What is meant by LOS operation?
7. Contrast downlink and uplink operation for a wireless MAN.
8. Describe the IEEE 802.16 DL-MAP message.
9. Describe the IEEE 802.16 UL-MAP message.
10. What are the function/purpose of IEEE 802.16 MAC management messages?
11. Contrast wireless MAN frequency division duplex operation with time division duplex operation.
12. How does the IEEE 802.16 standard support the dynamic allocation of system bandwidth?
13. What modulation schemes are typically supported by an IEEE 802.16-compliant base station?
14. Describe IEEE 802.16 wireless MAN power control.
15. What is the required subscriber station output power called for by the IEEE 802.16 standard?
16. What is different about the type of EM wave propagation that might occur within the 2–11 GHz range and EM wave propagation in the 10–66 GHz range?
17. Discuss the function/purpose of wireless mesh networks.
18. What advantage does the use of OFDM modulation provide when used to implement a wireless MAN?
19. What is the function/purpose of dynamic frequency selection in the context of WirelessHUMAN operation?
20. Describe the basic procedure for IEEE 802.16 network entry.
21. Why is ranging necessary for the successful operation of an IEEE 802.16 system?
22. What is the basic function/purpose of IEEE 802.16 radio link control?
23. How is an IEEE 802.16 subscriber station uniquely identified?
24. The basic services available over an IEEE 802.16 system are based on what standard?
25. What is the function/purpose of IEEE 802.16 real-time polling service?

CHAPTER

12

Broadband Satellite and Microwave Systems

Upon completion of this chapter, the student should be able to:

- Discuss the rationale for broadband satellite systems.
- Explain why line-of-sight propagation is used to model satellite system operation.
- Explain the concept of a link budget.
- Discuss the different types of satellite systems and their advantages and disadvantages.
- Discuss broadband satellite system architectures.
- Discuss the technical design challenges posed by broadband satellite systems.
- Discuss the rationale behind the increased use of digital microwave radio.

This chapter provides a high-level overview of the field of communications satellites and broadband digital microwave transmission. After an introduction to broadband satellite and microwave radio applications, the topic of line-of-sight propagation is reviewed. Using several link budget examples, practical satellite and microwave systems are introduced to the reader. Emphasis then shifts to explanations of the fundamental concepts of satellite system architectures with detailed discussions of GEO, HEO, LEO, and MEO satellite systems provided. With the basics of satellite systems covered, the general theory and projected operation of broadband satellite systems is now introduced. Since the implementation of these systems is still pending, a survey of the technical challenges encountered in the design of these systems is presented next. Several examples of proposed and operational nongeosynchronous satellite systems are given. The chapter concludes with an overview of broadband digital microwave radio systems and their increasing role in the delivery of broadband connectivity to the core network.

12.1 INTRODUCTION TO BROADBAND SATELLITE AND MICROWAVE SYSTEMS

As we move toward the 4G wireless era, satellite delivery of broadband multimedia services will likely become an integral part of the telecommunications infrastructure. Satellite systems will deliver high-speed data and provide Internet access to various geographically diverse users of the evolving network. Additionally, broadband digital microwave systems will be called upon to provide alternative delivery methods to the legacy T-carrier telephone system transport technologies. These point-to-point systems will find use in the extension of both wired and wireless LANs, the delivery of Internet connectivity, and as part of the core delivery network for cellular systems in the 3G and beyond era, as well as many other uses.

These two topics are grouped together in this chapter because they share a common characteristic: they both use wireless line-of-sight (LOS) propagation. There are, however, some noteworthy differences in the entirety of propagation conditions each experiences and their fundamental applications that give rise to differences between the two technologies. At the present time, terrestrial microwave systems are a fairly mature, highly reliable technology as pointed out in Chapter 1 whereas broadband mobile satellite technology is still in its infancy. Also, despite optimistic predictions, there have been numerous delays in the deployment of several of the most highly publicized, proposed broadband Internet satellite systems. In addition, financial difficulties have arisen for some of the more recently deployed satellite systems using new architectures and technologies to support mobile satellite applications. More will be said about this issue in Chapter 13. This chapter is meant to provide an overview of these wireless technologies; it is not by any means an exhaustive coverage of all their technical details or the economics of their operation.

Broadband Satellite Applications

The early geosynchronous communications satellites, primarily used for network video delivery and long-haul telephone service, have been in existence for many years. These satellite systems have basically served as repeaters in the sky, retransmitting signals to large sections of the earth's surface. Numerous other satellite systems using geosynchronous and other, different nongeosynchronous orbital schemes have served various specialized purposes from weather forecasting, to military communications and reconnaissance, to exotic remote sensing missions, and serving as navigational aids, to name but a few applications. Like most new technologies, the first generations of these satellite systems were limited in their functionality by the available technology of the day. Satellite systems that provided data transmission capability typically operated at lower frequencies and with limited data rates whereas the systems that provided broadband video transmission used microwave frequencies that provided an adequate amount of bandwidth. Typically, the amount of available satellite transmitting power was limited and therefore necessitated large receiving earth terminals (i.e., using antennas that were a number of meters in diameter).

The succeeding generations of satellite systems have been able to use newer technology that can provide higher data rates, higher transmitting power levels, and operation at higher frequencies. Today in the United States, DIRECTV and the DISH Network supply fairly low-cost satellite service with hundreds of TV channels, new high-definition television (HDTV) picture formats, and numerous additional music channels through a subscriber-mounted eighteen-inch receiving antenna. Other new consumer-oriented systems like XM and SIRIUS satellite radio are becoming mainstream customer services. Still other location-based services like General Motors' OnStar vehicle safety system make use of the Global Positioning System (GPS) navigational satellite system. Furthermore, new, innovative, dedicated-application satellite systems designed for a variety of purposes have been deployed over time while some of the original systems have been upgraded with replacement satellites or entirely new systems. Some of these relatively newer satellite systems like Iridium and Globalstar offer global mobile telephone service, short message service, and limited data service (approximately 9.6 kbps maximum) whereas other systems provide connectivity specifically to maritime industries, for instance. In most cases, these new mobile satellite systems provide this connectivity through small, handheld mobile subscriber earth terminals (see Figure 12–1).

Presently, the deployment of a new generation of broadband mobile satellite systems that can offer multimedia services with higher data transfer rates on a global scale is pending. Using new architectures that allow the satellite system to be part of the core network, these systems will be the first to provide high-speed bidirectional satellite service to consumers. Several of these systems are scheduled to become operational during 2005. Once deployed, they will usher in a new era in broadband satellite communications.

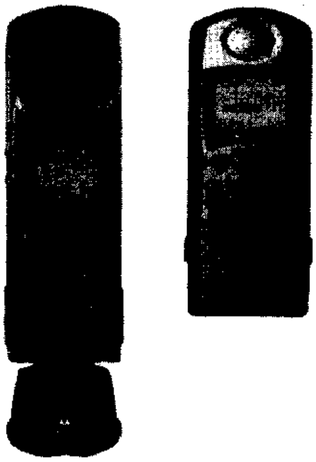


Figure 12–1 Typical subscriber handheld earth terminals—Iridium telephones (Courtesy of Motorola).

Broadband Microwave Applications

Using licensed frequency bands, broadband fixed terrestrial microwave technology has been in existence for over fifty years (refer back to Chapter 1 for more details). Typically deployed between population centers, these microwave relay systems usually provided broadband transport of long-distance telephone calls or network video feeds for affiliated television stations. Reaching their height of popularity during the 1970s and 1980s, broadband terrestrial microwave quickly went into decline in many of the heavily populated areas of the United States as fiber-optic cable and geosynchronous satellite systems were quickly deployed during this era. Today, network video programming is almost exclusively distributed via global satellite systems. However, for less densely populated areas and for areas of rugged or inaccessible terrain (very often one and the same), digital microwave transmission was and still is very often the transmission system of choice for long-distance telephone or broadband data services.

As mentioned previously, broadband digital microwave has been enjoying a resurgence in popularity recently for the delivery of both data and voice service. This is especially true for the cellular industry that has been increasingly employing microwave links mounted on the cellular tower as an economic alternative to legacy copper wire pairs or fiber- optic cable connections (see Figure 12–2). Also, these microwave

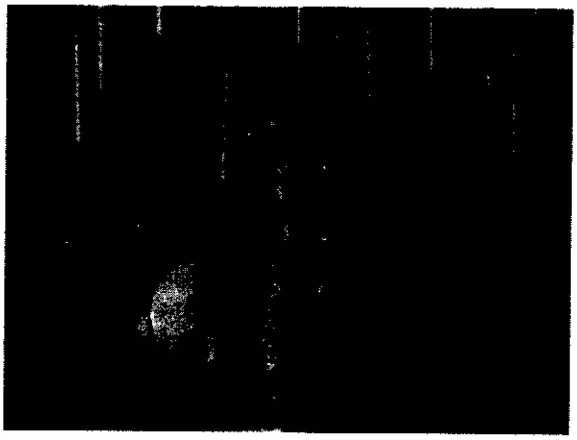


Figure 12–2 Microwave backhaul links mounted on a cellular tower.

links have been used more and more to provide access to remote or inaccessible cell site locations that are without traditional telecommunications infrastructure.

Another expanding area of use is related to the emerging IEEE 802.XX wireless technologies. With the advent of the unlicensed national information infrastructure (U-NII) bands in the microwave frequency range, there has been a proliferation of new equipment designed to supply both point-to-point and point-to-multipoint high-speed data for services like wired and wireless LANs and wireless MANs (i.e., IEEE 802.11x and 802.16x, respectively). Additionally, Enterprise adopters of these technologies have used fixed microwave links to bridge together or extend the reach of these new technologies. One might also recall that the original IEEE wireless MAN standard called for the use of the licensed microwave and millimeter wave bands above 10 GHz for the delivery of this service. Other users of broadband microwave systems include wireless Internet service providers (WISPs) and numerous other services that depend upon line-of-sight transmission schemes for the delivery of these services.

12.2 LINE-OF-SIGHT PROPAGATION

In Section 2 of Chapter 8, the Friis equation for line-of-sight radio wave propagation was discussed. This equation may be used to predict radio wave propagation in free space and also for fixed terrestrial line-of-sight systems if the transmitting and receiving antennas are high enough above the ground and there are no obstructions between them. The Friis equation, repeated here for convenience, predicts the power that will be received from a transmitter at a distance, *d*.

$$P_R = P_T G_T G_R \left(\frac{\lambda}{4\pi d} \right)^2 \qquad \textbf{12-1}$$

In general, if the link is stationary or fixed, there is even more predictability to the relative received signal strength and the reliability of the link. As pointed out previously in Chapter 8, there are many other propagation effects that can come into play and affect the transmission link. For terrestrial systems, some of these factors include atmospheric attenuation, precipitation, shadowing, and reflected and scattered signal propagation paths. For satellite systems, one adds the effects of transionospheric propagation (i.e., the Faraday effect), signal frequency shift due to the Doppler effect, and signal blocking to the list. The net result in both cases is the possibility of reduced RSS and severe signal-strength fades.

Design of these types of transmission links is usually performed by using software design tools that are optimized for the particular application. For terrestrial links, propagation models based on the line-of-sight Friis equation are combined with terrain data available from geographic information systems (GIS) to provide detailed analysis of point-to-point and point-to-multipoint systems. These sophisticated software programs incorporate transmission component and antenna characteristics, frequency of operation, rainfall rate predictions, the curvature of the earth, clutter height and type, and Fresnel zone and path obstruction diffraction effects. These and other factors are used to design and predict link reliability with a fairly high degree of accuracy. Other design software features usually include signal interference analysis, colorized signal-strength contour maps, diversity schemes, and the ability to generate sophisticated reports of the transmission network, its characteristics, and an inventory of the digital microwave network equipment.

The mathematical prediction of the received signal level from a geosynchronous satellite system is fairly straightforward since the signal propagation path approximates a fixed line-of-sight, obstruction-free link. To deal with the various propagation effects that tend to degrade the received power, a link margin is typically assumed. The link margin is usually specified in dBs and increases with increasing frequency of operation. For these types of calculations one may rearrange and evaluate the Friis equation using dB as shown here:

$$P_R(\text{dBm}) = P_T(\text{dBm}) + G_T(\text{dB}) + G_R(\text{dB}) - 20\log\left(\frac{4\pi d}{\lambda}\right) \qquad \textbf{12-2}$$

The average received power level in dBm from a geosynchronous satellite can be calculated from Equation 12-2. For the worst-case scenario, one would subtract the link margin to determine the average received power level during the worst possible propagation conditions when the highest signal attenuation occurs.

For recently deployed or yet-to-be-deployed broadband satellite systems used to provide data connectivity to mobile subscribers, determining the average received signal power is not an easy task. Typically, these systems are nongeosynchronous in nature and as a consequence are subject to all the adverse propagation conditions previously cited. In this sense, these systems are similar to cellular telephone systems since they are subject to the same extreme real-time fluctuations in received signal strength that are typically experienced by mobile cellular telephones.

Therefore, the use of Equation 12-2 is but a starting point to the design of mobile satellite systems. More will be said about the design of these systems later in this chapter.

Link Budget Calculations

As already mentioned in other chapters, for a wireless system to operate properly, there is a minimal nominal power level that must be delivered to a receiver to provide a certain level of performance. What this needed received signal level is depends upon several factors including the quality of the receiver (i.e., the amount of noise and distortion generated internally by the receiver) and the transmission link's maximum tolerated average bit error rate. In general, the higher the received signal strength and the more noise free the receiver, the lower the bit error rate or the higher the possible data transmission rate. The next several sections will provide several sample link power budget calculations.

Direct Broadcast Satellite Link

Services like DIRECTV are provided by more recently deployed geosynchronous satellites located at an altitude of 35,786 km above the earth's surface. These direct broadcast satellites (DBSs) are typically equipped with traveling wave tube (TWT) amplifiers that are capable of producing output powers of several hundreds of watts. The earth terminal receivers are the familiar eighteen-inch dish antennas with a low noise block (i.e., a combination low noise amplifier [LNA] and downconverter) located at the dish focal point (see Figure 12–3). Today's conventional low noise block will have a noise figure of approximately 1.0 dB or less or an equivalent noise temperature of about 75°K. These DBS systems provide downlink transmission in the 12.2- to 12.7-GHz frequency range (i.e., Ku band).

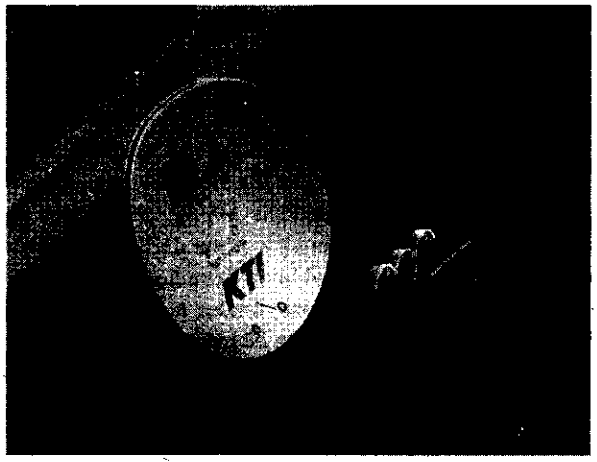


Figure 12–3 Direct broadcast satellite dish system.

Example 12–1

If the nominal transmitter output power is 120 watts for a DIRECTV DBS and the transmitting antenna gain is 34 dB, determine the received signal power if the eighteen-inch receiving dish has a nominal gain of 33 dB. Assume that the operating frequency is 12.45 GHz and the receiving antenna is directly below the satellite.

Solution: First calculate the wavelength, λ, in meters. Since,

$$\lambda = \frac{300}{f\ (\text{MHz})}, \qquad \lambda = \frac{300}{12{,}450} = 0.0241\ \text{m}$$

Next, convert 120 watts to dBm; this can be done by using the formula,

$$P_T(\text{dBm}) = 10 \log\left(\frac{120\text{W}}{1\text{mW}}\right) = 50.8\ \text{dBm}$$

Now, using Equation 12-2 one calculates:

$$P_R = 50.8\text{dBm} + 34\text{dB} + 33\text{dB} - 20 \log\left(\frac{4\pi \times 35{,}786{,}000}{0.0241}\right) =$$
$$P_R = 117.8\text{dBm} - 205.4\text{dB} =$$
$$P_R = -87.6\text{dBm}$$

Thus the received signal level is approximately –87.6 dBm. With a receiver noise temperature of about 75°K, combined with the forward error correction coding scheme used by the transmitter, this is a sufficient signal level to provide fairly good-quality video reception.

Digital Microwave Link

Fixed terrestrial broadband microwave systems may operate in either licensed bands or the new unlicensed U-NII bands. The assigned licensed bands differ from region to region, but in any case, frequency allocations are available worldwide from approximately 4 GHz to 38 GHz. Presently, the U-NII bands in the United States are at 2.4 GHz and also in the 5-GHz band (note that the 3.5-GHz band is also available for the rest of the world). Typically, the microwave radio system consists of an RF outdoor unit (ODU) and a rack-mountable indoor unit (IDU) (see Figure 12–4).

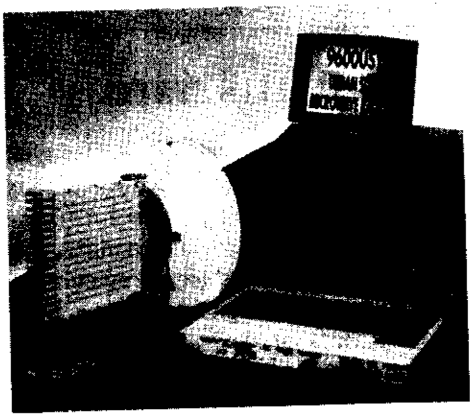


Figure 12–4 Typical digital microwave backhaul equipment (Courtesy of Alcatel).

The ODU is usually a combination RF transmitter/receiver unit and an integrated antenna. The IDU usually consists of interchangeable or reconfigurable interface sections and the digital modulation/demodulation signal processing subsystems. The IDU feeds the ODU through a coaxial cable connection and the interface sections provide female connectors for standard cabling jacks. Depending upon the final bandwidth of the transmitted signal (5, 10, 20, 25, or 30-MHz bandwidths are standard) the user often has the ability to mix or partition the type of transmitted data signals. Today's equipment commonly uses QPSK, 8-PSK, 16-QAM, 32-QAM, or higher-order QAM modulation techniques and allows transmission of a mix of nxDSn (i.e., various combinations of multiple DS1s or DS3s or a mix of both) and Ethernet at various bit rates. Typical transmitter output powers are in the +16 to +25 dBm range with receiver sensitivities in the –70 to –90 dBm range depending upon the frequency of operation, the type of modulation, transmitted signal bandwidth, and the final mix of data transmission streams.

Example 12–2

A digital microwave link is set up to transmit 24 DS1s using 16-QAM with a 20-MHz bandwidth at 38 GHz. Both the transmitting and receiving antennas have diameters of 30 cm and a nominal gain of 38.5 dB. If the transmitter output power is +16 dBm and the receiver sensitivity is –74 dBm for a bit error rate of 10^{-7}, determine the maximum system range assuming unobstructed LOS propagation and a 15-dB link margin.

Solution: Using Equation 12-2, one may calculate:

$$P_R(\text{dBm}) = +16\text{dBm} + 38.5\text{dB} + 38.5\text{dBm} - 20\log\left(\frac{4\pi d}{\lambda}\right)$$

With a link margin of 15 dB, the received signal power must be at least –74 dBm +15 dB = –59 dBm for perfect conditions. Therefore,

$$-59\text{dBm} = 93\text{dBm} - 20\log\left(\frac{4\pi d}{\lambda}\right)$$

The wavelength of a 38-GHz signal is given by,

$$\lambda = \frac{300}{38000} = 0.00789\text{ m}$$

And substitution into the prior expression yields $d = 25.0$ km

Therefore, the maximum predicted useful range possible for this digital microwave link is approximately 25 km using this overly simplified mathematical model.

12.3 FUNDAMENTALS OF SATELLITE SYSTEMS

As indicated before, the earliest operational communications satellite systems used **geosynchronous earth orbits** (GEOs) that provided large signal-illumination footprints (approximately one-third of the earth's surface) to facilitate broadcasting applications and to provide for fixed receiving antenna positions that approximate line-of-sight propagation from satellite to earth terminal. For these types of satellite systems, the transmission quality tends to be fairly constant and legacy modulation techniques (e.g., wideband FM) could be employed for the delivery of television signals. Satellite systems designed for the delivery of broadband multimedia applications have different design criteria. The newer operational systems or proposed future systems targeting this application space tend to be of the **low earth orbit** (LEO), **medium earth orbit** (MEO), or **highly elliptical orbit** (HEO) design or some hybrid combination of these and the GEO category. Due to their lower orbital altitudes, LEO and MEO satellite systems have smaller footprints than GEO systems. In all cases, for a fairly complete coverage of the entire earth's surface, a constellation of orbiting satellites is needed. This portion of the system is also known as the **space segment**. Additionally, a network of gateways, user terminals, and network operations and control systems (collectively known as the **ground segment**) is required. In general, LEO, MEO, and HEO systems consist of constellations of satellites routinely circling the earth in predictable orbital patterns.

A primary characteristic of a satellite constellation is the altitude of the constellation above the earth's surface. The satellite altitude is selected based on several design criteria including signal propagation delay time, available satellite signal power, duration of satellite visibility, desired extent of coverage area, and avoidance of the Van Allen radiation belts. Another important design characteristic is the inclination angle of the satellite's orbit since the inclination of a satellite's orbit is closely related to the coverage area the satellite provides. The orbit inclination angle has a large influence on signal propagation. GEO satellites have an inclination of 0 degrees whereas polar orbits are at inclinations of 90 degrees. The combination of the inclination angle and the latitude of the earth terminal's location determines the required receiving antenna elevation angle. In the Northern Hemisphere, at medium latitudes, to receive the signal from a GEO satellite, it is necessary to aim the receiving antenna toward the southern horizon (i.e., a low elevation angle). Also, to have line-of-sight reception it is necessary to have an unobstructed view of the southern sky. For the geosynchronous case, the antenna elevation angle becomes greater the closer the receiver is to the equator and less the farther north one goes. At latitudes greater than 81 degrees, a GEO satellite appears to the receiving antenna to be below the horizon! Low receiving antenna elevation angles give rise to an increased probability of signal shadowing and blockage effects that increase the probability of signal fades, additional noise, or bit or frame errors during the reception of the desired satellite signal.

The more polar inclination angles that are typical of LEO and MEO satellite constellations in combination with the use of multiple orbital planes allows for coverage of the earth's temperate zones where the vast majority of the earth's population resides. If fact, a constellation in polar orbit (90 degrees inclination) permits complete global coverage with the least number of satellites. If these types of constellations consist of a reasonable number of satellites, they also allow for more than one satellite to be visible from a given point at any time.

Categories of Satellite Systems

As mentioned already, there are many different types of satellite systems already deployed that are used for a myriad of different applications. Although many systems are used to extend our global telecommunications capabilities, others are used for remote sensing and data gathering on a global scale. In general, satellite systems can be categorized according to the altitude of the constellation. The next few sections will provide details of the four basic categories: GEO, LEO, MEO, and HEO.

GEO *Satellite Systems*

Geosynchronous satellite systems are distinctive in that the satellite's revolution around the earth is synchronized with the earth's rotation. Placed in orbit above the equator at an altitude of 35,786 km, the geosynchronous satellite remains essentially stationary over the earth's surface (see Figure 12–5). For the earthbound observer, the satellite appears fixed over the equator. However, periodic station-keeping activities using onboard thrusters are necessary to keep the satellite from drifting out of its parking spot. Three geosynchronous satellites are usually sufficient to provide complete coverage of the populated areas of the earth (excluding high-latitude areas).

The disadvantages of geosynchronous systems are mostly related to their inherent lack of adaptability that restricts their usefulness for applications other than global broadcasting. In particular, geosynchronous satellites have had high deployment costs due to the expensive launch vehicle needed to place them in orbit. In the past, the relatively high orbital altitude has resulted in the need for large transmitting powers and large antennas for both the satellite and the earth stations. Then again, with the use of higher-frequency bands and the development of improved high-power amplifiers these problems have been reduced in scope.

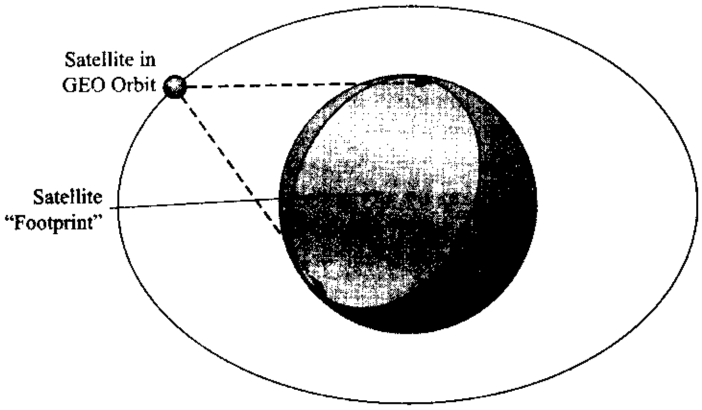


Figure 12–5 Geosynchronous satellite orbit.

However, the one problem that has not changed for geosynchronous satellites is the large signal-propagation delay time. Typical values of round-trip time (RTT) are 500 to 560 ms. This amount of delay is totally unacceptable for real-time Internet applications like Voice over IP (VoIP) since the transport protocol TCP/IP depends upon a positive feedback mechanism to achieve rate control and the reliable delivery of data. More will be said about this topic in a later section of this chapter.

Applications for geosynchronous satellite systems are for global broadcasting and a modified form of broadband multimedia delivery (i.e., unidirectional in the downlink) that will be discussed in more detail later. Actually, today's GEO systems support voice, data, and video services, with numerous nationally owned systems usually providing fixed services to a particular region of the earth's surface. For the United States, GEO systems have long provided voice backup capacity for the majority of the long-distance carriers. Early on, a primary function for GEO systems was to carry national television network feeds from a central location to affiliate stations around the country. Presently, new consumer services (video, music, broadband access, navigation, etc.) are being offered through GEO systems like DIRECTV, DirecWay, and others. Today direct satellite broadcast systems are highly competitive with terrestrial-based legacy cable TV networks. Furthermore, new higher-power GEO systems with spot-beam antennas can operate with smaller terrestrial terminals than ever before and therefore can support some limited mobile applications.

In summary, GEO systems have a proven track record and an orbital predictability that has yet to be achieved long term by the more complex systems presently being designed and deployed. With their fixed location in the sky, GEO systems tend to have fewer maintenance issues, longer lifetimes, and their high bandwidth capacity might yet prove to be an economic advantage over newer designs. GEO systems still have unacceptable transmission delay and due to the large coverage area per satellite an obviously more dramatic effect on the entire system should there be a failure of a single satellite in the GEO constellation. Also, due to their fixed location and low angle of inclination, GEO systems present limited opportunities for mobile applications in urban areas where tall buildings and other structures (collectively known as clutter) may block line-of-sight signals for handheld mobile terminals.

LEO Satellite Systems

LEO satellite systems use orbits located roughly 500 to 1500 km above the earth's surface with the maximum orbital height just below the first Van Allen radiation belt. For LEO satellite systems the most important attribute is the signal round-trip time that is in the order of 10 to 20 ms for an orbit of 1000 km. This delay time is extremely comparable to that of a terrestrial-based broadband telecommunications link. Other LEO satellite system details include: the orbital time period is in the order of 100 minutes, the LEO satellite is visible for only approximately 10 minutes during a typical orbital pass, and the maximum satellite coverage area has a typical radius of 3000 to 4000 km.

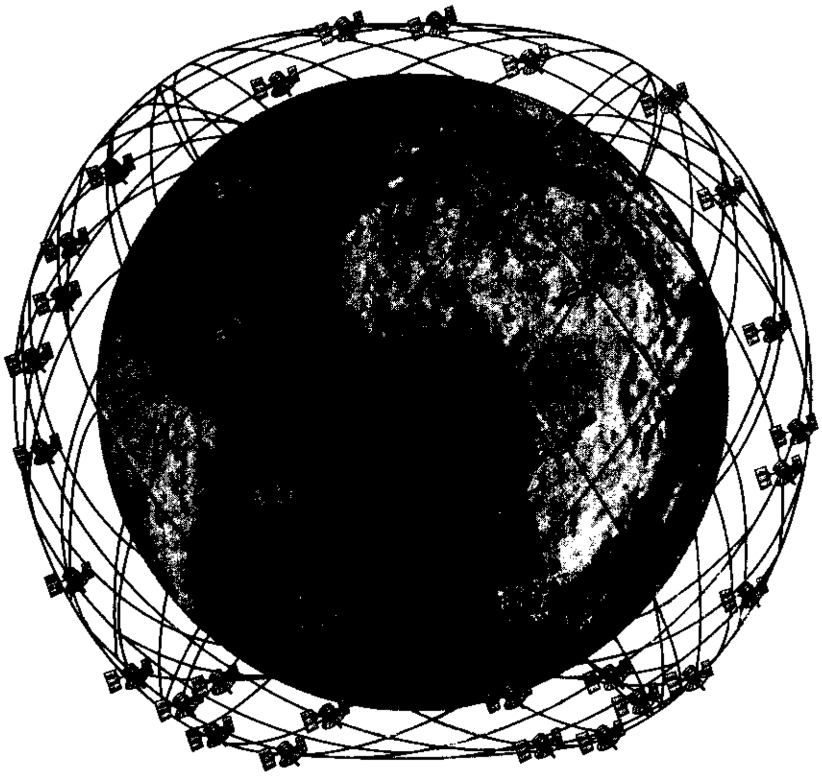


Figure 12–6 LEO constellation of satellites.

To provide coverage that ensures that more than one satellite is visible from a spot on the earth's surface at all times requires that the satellite constellation consist of numerous satellites (see Figure 12–6). Furthermore, due to the short visibility time of any one satellite, the system must be capable of frequent satellite-to-satellite handovers. This need for frequent handoffs also implies that there is a need for the constant relaying of signals from ground stations to satellites or between the satellites themselves over what are known as intersatellite links or ISLs.

As can be appreciated, the desire to provide constant coverage on a global scale with a constellation of fast-moving LEO satellites has just increased the complexity of the required system considerably. The ground segment of the system must provide more sophisticated tracking and switching equipment and the space segment must be able to provide intersatellite communication links and switching functions. These last two requirements imply that the satellites themselves must possess sufficient onboard processing power and switching capability to perform these functions.

In summary, the biggest advantages to LEO-based satellite systems are the much lower round-trip delay time coupled with the less demanding RF equipment requirements (smaller antenna size, lower transmitting power, etc.) and the larger orbit inclination angle used by the satellite constellation. What this last fact implies is that a larger elevation angle may be used by the antenna of a subscriber's fixed earth terminal or that the satellite in contact with a handheld mobile will tend to be more directly overhead. For each scenario, this fact can help overcome the difficulties caused by ground-based obstructions or surface clutter. A potential weak point for LEO systems is the limited satellite life span compared to MEO and GEO satellites. Besides the life span reduction due to drag from the earth's atmosphere, battery requirements are much more rigorous for LEO systems due to the numerous charge and discharge cycles that occur due to the frequent eclipses that occur for a satellite in low earth orbit. This fact will require spare satellites either in orbit or on the ground ready for launch.

Little, Big, and Mega LEO Satellite Systems There are several varieties of LEO satellite systems: so-called Little LEO, Big LEO, and Mega LEO systems. Little LEO satellites tend to be physically small, consist of a small number of satellites, and use very little bandwidth for the satellite-to-earth communications links. Of course, this last fact limits the amount of traffic that can be carried by a Little LEO system unless various bandwidth efficiency schemes are employed (frequency reuse, multilevel digital modulation schemes, etc.). Little LEO satellite systems support services and applications that are low bandwidth in nature. Some typical applications include paging; short message service; fleet tracking; the remote monitoring of cell sites, weather monitoring sites, vending machines, ocean buoys, and so on; and other similar tasks.

These low-bandwidth, occasional-use applications make Little LEO systems economically attractive. Presently, operational systems include Orbcomm and other special-purpose systems used by the scientific community for various applications like remote sensing. Plans for several newer commercial systems have recently been scraped.

Big Leo systems with many satellites are designed to carry voice traffic as well as data. They are used for applications such as satellite phones or global mobile personal communications systems. Most Big LEO systems offer mobile data service, and some system operators offer semifixed voice and data service to areas that have little or no existing terrestrial telephony infrastructure. Smaller Big LEO systems are also planned to serve limited regions of the globe. Examples of operating Big LEO systems are Iridium and Globalstar. Mega LEO systems, which consist of hundreds of satellites, have been proposed that will handle broadband data when they become operational. The most high profile of these proposed systems is Teledesic, Bill Gates' Internet in the sky. These types of systems are being optimized for packet-switched data rather than voice. Key to these systems is the ability to act as both an access and core system (i.e., ISLs are used extensively). More will be said about this in the next section. As already discussed, the disadvantages to these systems certainly revolve around the more complex systems required for control, handoff, and switching of large constellations consisting of hundreds of satellites and of course the sheer expense of the systems themselves. As of this writing, Teledesic has been folded into New ICO and appears to no longer be a viable plan.

MEO Satellite Systems

The typical MEO satellite system will be located between the first and second Van Allen radiation belts and have an orbital altitude of 5000 to 15,000 km. This gives a round-trip signal delay time for an MEO system in the range of 110 to 130 ms. Since the orbital period for the typical MEO satellite is six to eight hours, the time of visibility from a fixed location on the earth's surface is over an hour. The battery requirements for a MEO satellite are less than those of a LEO satellite but more than those of a GEO satellite. This is because the MEO satellite will undergo fewer eclipse cycles than LEO satellites but certainly more than GEO satellites. Typical MEO systems can operate with approximately ten to twenty satellites distributed over two or three orbital planes (see Figure 12–7).

Since MEO systems require far fewer satellites to make up the system constellation compared with LEO systems, the tracking and switching requirements are not as severe. Also, since MEO systems typically employ satellites with larger bandwidth and power capacity than LEO systems, they may be more adaptable to changes in shifting market demand compared to LEO systems. Applications for MEO systems include mobile phone service like that offered by Big LEO satellite systems. However, since MEO satellite life spans are not as long GEO satellites, they might not be as economically attractive as terrestrial-based cellular systems. Presently proposed systems include Orblink from Orbital Sciences and a new system from New ICO (formerly Teledesic, ICO Global Communications, and Ellipso (an HEO architecture proposal)).

HEO Satellite Systems

HEO satellite systems operate differently than LEO, MEO, or GEO systems. HEO satellites orbit the earth in an elliptical path that takes them close to the earth for a short period and then away from the earth for a much longer period (see Figure 12–8).

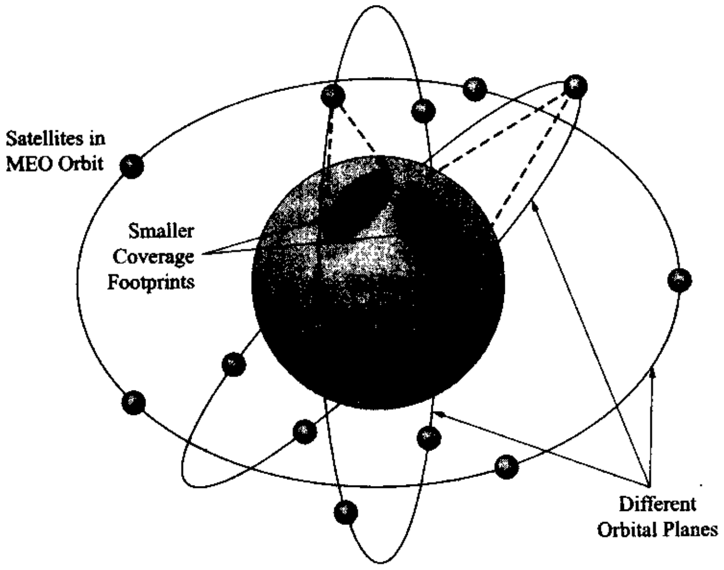


Figure 12–7 MEO satellite system.

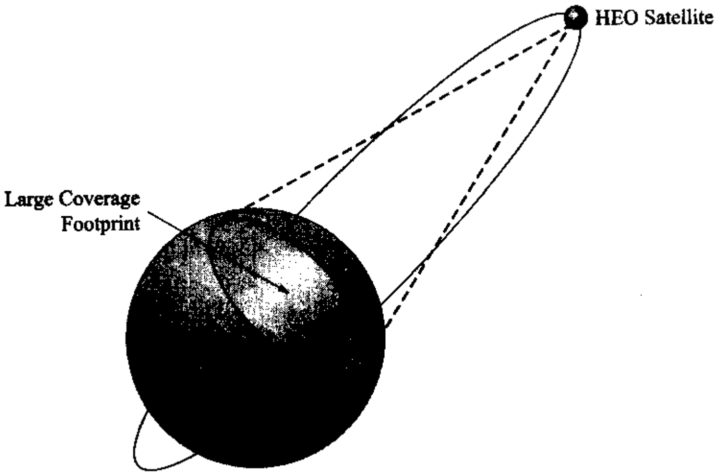


Figure 12–8 HEO satellite system.

This different orbital configuration is what makes HEO satellite systems attractive. During the time that the HEO satellite is farthest from earth, it can illuminate a much larger footprint or area of coverage on the earth's surface. At the same time that the HEO satellite is providing this increased coverage area its rate of travel slows down. Since the time spent at the farthest point from earth is a fairly large proportion of the total orbital period, the HEO satellite mimics the behavior of a GEO satellite once per orbit. HEO satellite systems are designed so that their orbits maximize the amount of time spent over populated areas. This type of design ensures that fewer constellation satellites are required compared to LEO and MEO systems. At the same time, unfortunately, HEO system coverage is not as complete as with the other systems already discussed. Therefore, most HEO satellite system designs are in fact a hybrid combination of MEO, GEO, and HEO satellites if global coverage is desired. Proposed HEO satellite systems include Ellipso and Pentriad. However, at this time no further details are available about the future deployment of these systems and in fact, as just mentioned, Ellipso has been folded into New ICO.

Frequency of Operation

There are frequencies in the VHF and UHF bands and the microwave and millimeter wave bands that have been assigned to satellite services on a global basis during the last several World Radiocommunication Conferences. However, the frequencies allotted between 137 and 401 MHz certainly do not provide the necessary bandwidth required for multimedia applications. Instead, these lower bands are used by various Little LEO systems to provide low-bit-rate data transmission services. Other frequency allocations at L band (1610 to 1626.5 MHz) and S band (2483.5 to 2500 MHz) are not suitable for multimedia service either. These frequencies are used by the Big LEO systems for standard telephone and short message service as well as for satellite positioning. Recent FCC frequency allocation changes in nearby frequency ranges for mobile satellite service (MSS) will be addressed in Chapter 13. Frequencies in the C band range (4 to 8 GHz) have traditionally been used for GEO system uplink and downlink transmissions. The Ku band between 10 and 18 GHz is presently being used for satellite broadcasting applications as well as for high-speed Internet connections from a variety of satellite systems. Several of the proposed new satellite systems plan on utilizing Ku band for both downlink and uplink connectivity for the delivery of multimedia services to the subscriber. Alternatively, others propose using Ku band for downlink and Ka band (18 to 31 GHz) for uplink. Still others are proposing using the approximately 1.5-GHz range from 19.7 to 21.2 GHz for downlink and the 500 MHz of bandwidth from 29.5 to 31 GHz for uplink in the Ka band. The availability and cost of the appropriate RF components will probably be the deciding factor for determining what frequency bands are used when all is said and done. Since Ka band undergoes considerable weather-related attenuation, earth terminals must be able to compensate for signal fades of greater than 20 dB when using this band. Finally, for future systems there are plans to use even higher frequencies that will offer larger amounts of bandwidth. Some of the frequency bands being explored include V band (40–75 GHz), Q band (33–50 GHz), U band (40–60 GHz), E band (60–90 GHz), and W band (75–115 GHz). At the present time, components for these frequencies are not as reliable, readily available, or as inexpensive as lower-frequency devices. Therefore, satellite systems that will eventually operate at these frequencies are off in the future. The reader should note that the FCC has already opened up several of these bands for terrestrial wireless Internet applications (refer back to the chapters on the IEEE wireless standards). This fact will probably help to drive the development and eventual mass production of components for these higher-frequency regimes.

12.4 BROADBAND SATELLITE NETWORKS

Some of the challenges faced by the designers of broadband satellite systems have already been outlined. The need to either physically reduce the round-trip delay time experienced by satellite links or to develop new protocols or architectural schemes to work around this problem is necessary. Furthermore, many technical stumbling blocks exist at the physical, MAC, and network and transport layers that must be resolved before these systems will be able to offer transparent high-speed network access. Until the consumer is satisfied with the quality of the experience and the cost of that experience is comparable to other delivery methods, using a satellite network for Internet access will just be a promised technology whose time has not yet come. Already, as of this writing, many of the satellite companies formed to construct these "Internet in the sky" systems have ceased operations or merged together. It will be interesting to see what the future will bring.

Broadband Satellite System Architectures

A broadband satellite system can act either as an access network or as an access/core network. To this point in time, most operational broadband satellite systems are simply access networks. By definition, the satellite **access network** does not interpret user signaling. The signal sent by the subscriber's terminal is

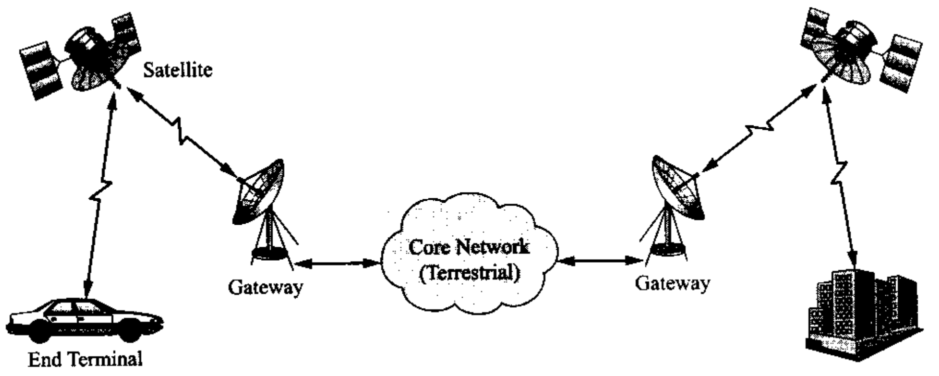


Figure 12–9 Satellite access network.

received by a satellite that retransmits it to a ground segment gateway, which in turn connects to the terrestrial core network (see Figure 12–9). At this point, the subscriber's message is forwarded to the intended recipient's terminal through either the terrestrial network or a satellite access network.

A satellite access/core network works in the following manner (see Figure 12–10). A signal sent from the subscriber's terminal and received by the satellite system is transmitted to the recipient either through the satellite system via **intersatellite links** between satellites (using onboard processing and switching systems) to connect to the correct satellite or through a ground-based gateway to the terrestrial core network that serves the recipient.

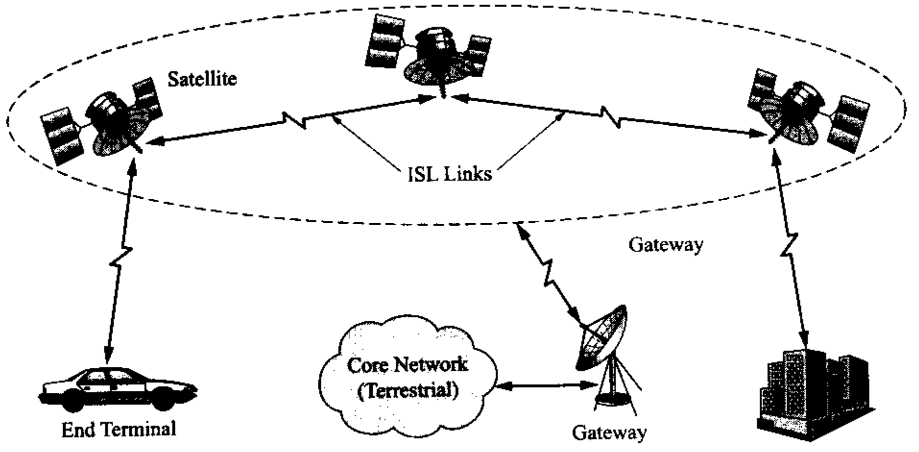


Figure 12–10 Satellite access/core network.

Depending upon the architecture of the satellite constellation, the ISLs may be between satellites in the same orbit, satellites in other orbital planes, or satellites in other orbits entirely. However, these last two types of intersatellite transmission may have a negative effect on signal propagation delay time.

The ability of a satellite system to take on either the limited function of an access network or the more complex function of a core network is dependent upon the capability of the onboard equipment (also known as the satellite payload). For years, the vast majority of communications satellites have acted as simple retransmission stations or so-called **bent-pipes.** A familiar example would be the early GEO satellites used extensively for network video distribution. They received uplink signals in the 6-GHz frequency band and retransmitted the downlink signals in the 4-GHz band (see Figure 12–11), thus acting simply as transponders.

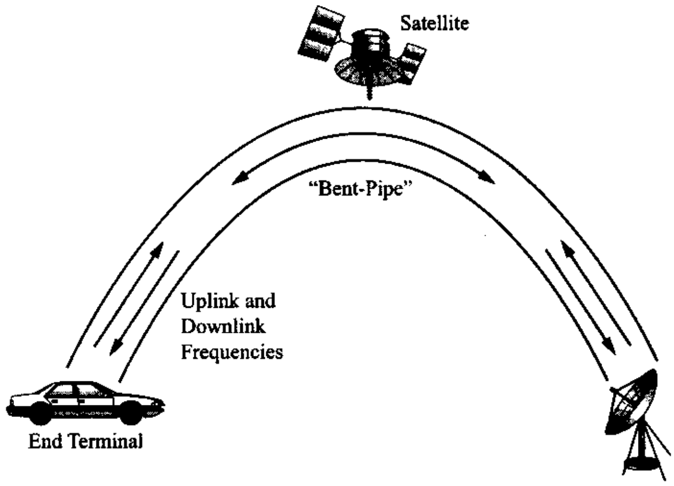


Figure 12–11 Bent-pipe satellite system.

An advantage to this type of operation is that the signal is retransmitted transparently. When considering broadband data transmission via a bent-pipe, it is possible to use new types of transmission protocols without any problems since the system never makes use of the transmission protocol during the retransmission process.

With today's technology, the processing and switching functions required of a core network are possible to implement and include in the satellite payload. Therefore, it is presently theoretically possible to construct in outer space a channel or packet-switched transmission network using a satellite constellation that possesses the functionality of steerable beam antennas; in other words, a satellite system that serves as an Internet backbone in orbit (see Figure 12–12).

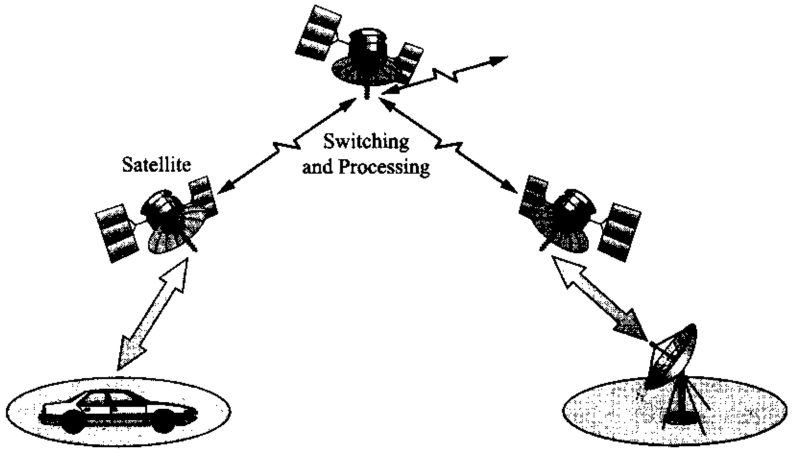


Figure 12–12 Satellite- based Internet network.

A beneficial consequence of the satellite system being both an access and core network is that the required terminal antennas or the transmitted power can be made smaller. This is due to the fact that now the signal undergoes regeneration aboard the satellite thus taking advantage of the use of error correcting techniques before the signal is retransmitted. This situation is similar to how the T-carrier system operates. As long as the signal-to-noise ratio is above a certain threshold level for each transmission link, almost error-free transmission is possible. The benefit this process provides is not trivial since it allows for the reduction in the size of a mobile terminal. However, since the satellite system now provides onboard switching, the link is no longer transparent and as a consequence the system must use a specific type of transmission protocol. This means that the system must be highly reliable and possibly reconfigurable to be able to adapt to future protocol modifications since onboard repairs or adjustments in outer space are not very feasible for these satellite systems (although it should be noted that it has been done in the past).

Hybrid Broadband Satellite Architectures

Several presently operating satellite systems make use of direct broadcasting satellite (DBS) systems primarily used for video signal delivery to provide Internet access to subscribers. One such system is DirecWay. However, presently these systems are hybrids (being unidirectional in nature) since they only use the DBS satellites for downlink connectivity. Due to the asymmetrical nature of Internet traffic, these systems are able to use a lower-speed terrestrial link (see Figure 12–13) for the uplink connectivity to the Internet and the satellite feed for the higher-speed downlink connection. These systems use the DVB-S transport standard that will be described in more detail shortly.

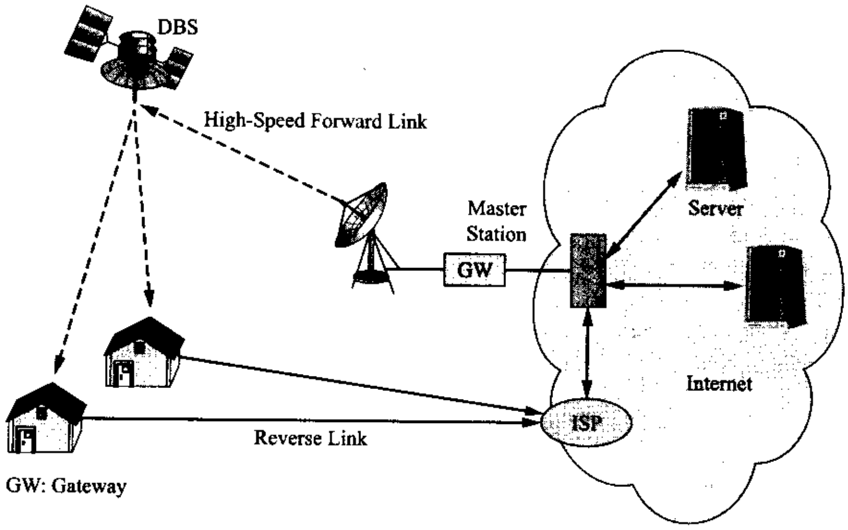


Figure 12–13 Hybrid broadband satellite system (Courtesy of IEEE).

Technical Challenges for Broadband Satellite Systems

It should be pointed out again that many technical challenges must be overcome before it is possible to construct operational and efficient broadband satellite networks capable of delivering multimedia services on a global basis. These challenges are not just at the physical layer, they extend across the lower layers of the OSI model. The next several sections will discuss some of these issues and possible solutions to them. At the physical layer, it is suspected that the reader will note the many similarities of satellite systems to cellular systems in terms of the access technologies, propagation difficulties, and the technologies used to increase transmission reliability.

Satellite Physical Layer Challenges

At the physical layer, many technical difficulties still exist for broadband satellite systems. Some of the major issues include weather-related attenuation, LOS obstruction, shadowing and multipath fading effects, and nonlinear distortions caused by the onboard high-power amplifier (HPA). The next several sections will examine these problems in more detail.

Satellite Propagation Problems The basic detrimental effects for satellite propagation that can be identified include precipitation (rainfall, hail, snow, etc.), multipath fading, shadowing effects, and blocking (the extreme limiting case of shadowing). Also, as with cellular systems, the physical movement of satellites and mobile terminals has the net effect of introducing a random and time-varying behavior into the radio channel. Simple models that combine all these effects together have been proposed but need a great deal of refinement to be of any value for predicting satellite propagation conditions. The need for a good model is driven by the desire that the mobile satellite system must be fully integrated with other terrestrial telecommunications networks in order to enable global seamless and ubiquitous communications. For this to be the case, an acceptable satellite channel model should satisfy the following criteria: be accurate, combine the many effects already mentioned, account for different channel states (i.e., transitions from shadowing to nonshadowing and vice versa), and should also be able to play a role in system optimization.

One of the most difficult propagation problems for LEO systems is the path obstruction due to low elevation angles of the satellite as it moves in its orbit. A proposed solution is to use diversity reception by using the signals from other satellites in view of the subscriber (see Figure 12–14) as the inputs to a RAKE receiver (refer back to Chapter 8). Recall that diversity reception also helps with the slow fade problem.

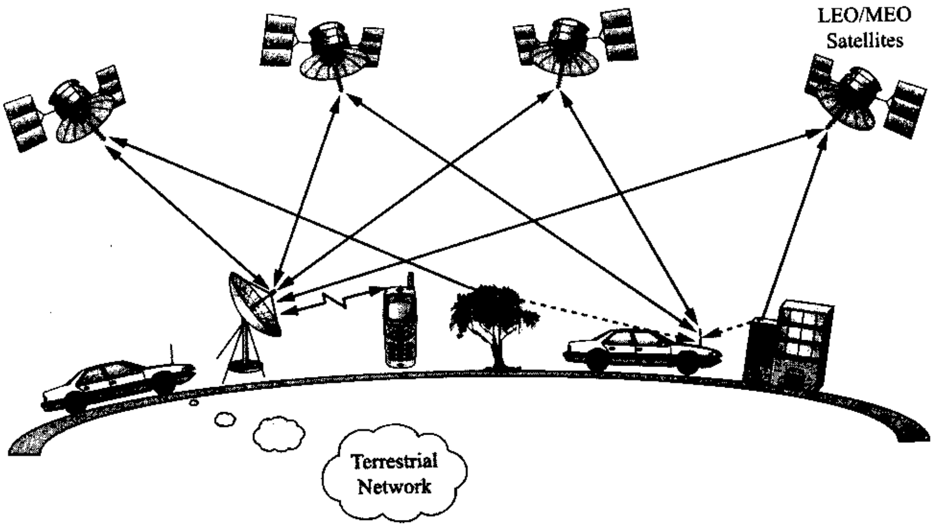


Figure 12–14 Satellite diversity reception (Courtesy of IEEE).

Satellite High-Power Amplifier Problems Today's satellites are equipped with HPAs like traveling wave tube (TWT) amplifiers or solid-state power (SSP) amplifiers. When operated at or near maximum efficiency, these devices exhibit heavy nonlinear distortion. Due to this fact, earlier satellite systems used relatively inefficient digital modulation schemes such as BPSK and QPSK that are less sensitive to nonlinear amplification. A great deal of research and experimentation is presently under way to develop adaptive modulation techniques that modify the modulation scheme to the current channel conditions. These techniques would then permit the use of more spectrally efficient modulation schemes like higher-order n-QAM. The ability to use these more efficient modulation techniques will result in a higher system data transmission capacity.

Satellite Modulation and Coding Schemes As just stated, for increased data rates, mobile satellite systems will have to use bandwidth-efficient modulation schemes such as n-QAM, OFDM, and combinations of both. At the same time, to mitigate the poor performance of the radio channel and the nonlinearity of the satellite's HPAs, various coding schemes will have to be employed to reduce the bit error rate. Many of these coding techniques have already been touched upon in the other chapters of this text—Reed-Solomon, convolutional, trellis, and turbo codes are but a few of the major ones used in practical wireless systems. Since the propagation impairments for satellites are similar to cellular it is commonly believed that the solutions employed by satellite systems will be similar as well.

Satellite MAC Layer Challenges

MAC protocols are necessary to determine how users gain access to a shared channel. Furthermore, the construction of a MAC protocol can play a significant role in the ability of a network to provide QoS and efficiently interface with higher-level protocols. For broadband and mobile satellite systems, a MAC protocol is necessary to deal with the large number of potential users that are scattered over the satellite footprint. Furthermore, the users are most likely not uniformly distributed across the served area nor are they likely to contend over time for the uplink channel in an evenly distributed fashion. Typically, the performance of a MAC protocol depends upon the characteristics of the shared channel and the type of traffic it carries. Internet traffic, by its nature, is bursty. Also, various real-time multimedia applications such as streaming video or VoIP require QoS guarantees. For satellite-based systems, the long round-trip time, inherent power constraints, and the amount of onboard computational and switching capacity available must be taken into account when considering the type of MAC protocol to implement. Also, an efficient satellite system MAC protocol should be easy to implement, fairly simple, and somewhat flexible so as to accommodate network reconfiguration (a constantly reoccurring phenomena for LEO systems). The vast majority of presently proposed satellite MAC protocols fall into one of three basic schemes: fixed assignment, random access, and demand/dynamic assignment.

Fixed Assignment Satellite MAC Protocols Efficient fixed assignment schemes are borrowed from terrestrial cellular telephone technology or the popular IEEE 802.XX standards:

- Frequency division multiple access (FDMA)
- Time division multiple access (TDMA)
- Code division multiple access (CDMA) and wideband CDMA (W-CDMA)
- Orthogonal frequency division multiplex (OFDM)
- Combinations of the previous technologies (OFDM/TDMA, multicarrier CDMA [MC-CDMA], multicarrier direct sequence CDMA [MC-DS-CDMA], etc.)

Since these access techniques have been discussed extensively in other chapters throughout this text, no further comments about their theory of operation will be made at this time.

It is felt that simple legacy FDMA and TDMA techniques are too inefficient for use with multimedia broadband satellite systems. On the other hand, CDMA (particularly W-CDMA) is more flexible and a good candidate for use in mobile satellite systems as is OFDM/TDMA technology. Combinations or hybrids of OFDM and CDMA techniques are also good candidates for fixed access broadband satellite systems.

Random Access Satellite MAC Protocols These types of MAC protocols allow a random access scheme where each user's terminal transmits regardless of the transmission status of others. Retransmission after collision will increase the average packet delay and frequent collisions may lower the overall throughput greatly. Random access schemes are best suited for "best effort" services and as such are not well suited for applications requiring tight QoS guarantees for delivery of multimedia services. Therefore, these types of MAC protocols are probably not good candidates for satellite systems with large numbers of users and large values of round-trip delay time.

Demand/Dynamic Assignment Satellite MAC Protocols Demand/ dynamic assignment MAC protocols attempt to solve the QoS problem by dynamically allocating system bandwidth in response to user requests. For these schemes, when a connection no longer needs a slot allocation, the satellite may assign it to another user. Hybrid fixed assignment schemes that allow dynamic adjustment within a slot time (refer back to Chapter 11 for more details of IEEE 802.16x operation) are also of interest to satellite system designers. Recent interest has been shown in the distributed coordination function (DCF) and point coordination function (PCF) and their extended versions outlined in the IEEE 802.11x wireless LAN standards for possible implementation by satellite networks. Therefore, it is possible that some of the same techniques implemented by the IEEE 802.XX wireless technologies may be adapted for use by satellite systems.

Satellite Link Layer Technologies Although IP protocol dominates the end systems attached to broadband satellite systems, early broadband satellite design has embraced ATM as the link layer technology for interconnecting the satellite terminals. The transmission of data packets would be completed with IP over ATM. As the implementation of proposed broadband satellite systems is delayed, newer technology like IP switching using multiprotocol label switching (MPLS) might become more attractive to the satellite system designers.

Satellite Network and Transport Layers

As already stated, a constellation of rapidly moving satellites located at some distance from the earth's surface presents some interesting design challenges. In terms of routing issues, the constantly changing topology of a LEO satellite network gives rise to a host of concerns. Furthermore, a satellite-based Internet backbone will experience problems with TCP performance due to the relatively long round-trip time. These two areas of concern will be explored further in the next two sections.

Broadband Satellite Routing Issues Satellite systems with ISLs have complex routing issues due to the continuous satellite movement. Satellite networks implemented with LEO architectures exhibit a dynamic network topology and the ISLs form a type of mesh network. Complicating the matter is that these mesh networks can be intraplane or interplane in nature, with the latter type of mesh network requiring the additional capability to connect and disconnect itself in response to the dynamically changing positions of the satellites in the system and the inability of the ISL links to be maintained at extremely rapid relative velocities between satellites approaching one another in different orbital planes. Furthermore, short satellite visibility time and the desire to provide twenty-four-hour continuous coverage gives rise to constant intersatellite handoff requirements. Also, additional interbeam handoff requirements become necessary due to the use of numerous spot antenna beams for each satellite.

Within the satellite system, routing may be implemented on the ground or onboard the satellite. In either case, existing real-time information about the space segment of the system and the ground segment is required for the routing to function properly. In any case, the routing scheme should be able to handle network topographical variations. Presently, some routing mechanisms used in the Internet cannot be used for satellite systems due to the constant topographical changes. Recently, several new routing concepts have been introduced in an attempt to resolve these difficulties. There are also several routing issues involving border gateways external to the satellite network that need to be resolved before these systems can be effectively integrated into the core network.

Broadband Satellite Transport Issues TCP/IP and UDP/IP with their tremendous legacy will most likely be continued to be used for quite some time into the future. Therefore, a satellite-based Internet will most likely continue to serve applications based on TCP and UDP. As mentioned earlier, TCP performance when used with satellite systems is problematic since TCP relies on a positive feedback mechanism to achieve rate control and reliable delivery. Network performance is compromised by the long round-trip time for satellite systems (especially GEO systems) that results in less timely feedback further resulting in less efficient network operation. Additionally, satellite transmission over the air interface is inherently more error prone than wireline connections. However, TCP does not distinguish between packets received in error or those discarded due to congestion. The net result of this situation is a reduction in network data throughput. In an effort to correct some of these problems, the Internet Engineering Task Force's (IETF) TCP over satellite working group is developing TCP extensions that will provide performance enhancements. Also, "workarounds" that deal with some of the more difficult TCP shortfalls are also being devised and specific satellite transport protocols (STPs) are presently under development by various groups.

Use of DVB-S Transport for Broadband Satellite Systems As discussed previously, DBS systems are presently being used for hybrid broadband Internet connectivity in the downlink direction only. The transport mechanism used for this service is the **digital video broadcasting satellite** (DVB-S) standard that is used exclusively for the transmission of video and multimedia data services. DVB-S uses either a 188- or 204-byte container as the basic transmission unit. Reed-Solomon and other coding techniques are used to provide forward error correction to the transmitted data. Transmission typically employs QPSK (8-PSK and 16-QAM are optional) modulation to achieve a overall data stream rate of 38 mbps or higher depending upon the final signal bandwidth. Using MPEG-2 data compression, this data stream can contain from four to eight TV broadcasts, 150 radio channels, or 550 ISDN connections. The impending implementation of the Spaceway system proposed by Hughes will be a two-way geosynchronous system using DVB-Sn for both uplink and downlink transmissions. A more advanced standard for direct satellite transmission, DBB-S2, is in its final stages of ratification. It allows four modulation schemes (QPSK, 8-PSK, 16-QAM, and 32-QAM) with advanced forward error correction schemes that will improve transmission efficiency. Compatible with MPEG-4 compression techniques, DVB-S2 will provide enhanced transmission of high-definition TV signals.

Cross-Layer Design for Satellite Systems

The challenge for future broadband satellite systems is to design them in such a way that the satellite networks integrate seamlessly into the existing terrestrial infrastructure and at the same time efficiently use the satellite resources. Methods to achieve these goals have been centered on what is known as cross-layer design. The idea behind cross-layer design is to provide the higher layers with the physical and MAC layer knowledge of the wireless medium in order to allow the efficient allocation of system resources. In this scenario, information is shared between layers to facilitate the optimization of overall network performance. This technique has already started to be employed in the design of cellular systems and most likely will be carried over into the broadband satellite space.

Proposed and Operational Broadband Satellite Systems

An example of a proposed but on-hold Big LEO broadband satellite system is the Skybridge system designed by Alcatel. The Skybrige space segment consists of a constellation of eighty satellites (plus spares) located at an altitude of 1469 km with an orbital inclination of 53 degrees (refer back to Figure 12–6). The eighty satellites are organized as two identical subconstellations of forty satellites each. There are a total of twenty orbital planes with four satellites per plane.

The Skybridge LEO satellites use frequencies in the Ku band for signal transmission with a reported maximum data transmission rate of up to 60 mbps in both the downlink (10.7 to 12.75 GHz) and uplink (12.75 to 14.5 GHz) directions. Each satellite is capable of generating eighteen steerable spot beams for downlink and uplink use. Using transparent (bent-pipe) transmission (i.e., no onboard signal processing), with a total capacity of 215 Gbps, it is predicted that the system can accommodate more than 20 million equivalent users. Furthermore, with a short 30-ms propagation time, the system can support interactive multimedia services, Internet access, and other high-data-rate applications. The ground segment consists of a planned 140 gateways world-wide. Each gateway will serve a circular area with a radius of 350 km. The gateway stations will connect to the terrestrial network through ATM switches. User earth terminals that cost approximately $500 will be supplied to residential subscribers whereas ground terminals for professional users will be more expensive. This sounds like a great plan but at this point the odds are against it happening in the near future.

Examples of operational Big LEO systems include Globalstar and Iridium. These two mobile satellite system competitors have experienced financial difficulties ever since their startup. Iridium consists of a constellation of sixty-six satellites plus spares in orbit at 780 km. There are six orbital planes with an orbital inclination of 86.4 degrees and each satellite is capable of producing forty-eight spot beams. Mobile telephone service is provided at L band and intersatellite links are at Ka band. At one time the system was slated for a planned deorbiting. However, it was resurrected by the U.S. Department of Defense for national security reasons. The Globalstar system consists of a constellation of forty-eight satellites plus spares in orbit at 1414 km. Globalstar differs from Iridium in that there is no intersatellite relay capability. The reader can find more details about these systems and others that have been previously mentioned by going to the Web sites of the respective satellite systems.

12.5 BROADBAND MICROWAVE AND MILLIMETER WAVE SYSTEMS

As already discussed, broadband microwave systems have been deployed and operational for a long time providing a variety of services as licensed systems. Recently, as the cost of these systems has decreased, and in conjunction with the rapid growth of the cellular industry and the introduction of the IEEE wireless technologies (Wi-Fi and Wi-Max), the use of direct point-to-point digital microwave systems has taken on a more prominent role in the delivery of high-speed data and providing connectivity to the core network. Additionally, with the release of the U-NII bands, digital microwave systems using these unlicensed bands have started to flood the market. Many legacy microwave systems exist that provide E- and T-carrier transport speeds, as well as the delivery of Ethernet, ATM, and SONET speed data streams. Today, these systems have been augmented by many new low-cost systems that operate in the U-NII bands.

Applications for these new and legacy systems include wireless ISP providers; wireless extensions (bridges) to LANs, WLANs, and WMAN systems; and connectivity to the PSTN and PDN for remote and not-so-remote cellular telephone sites. Also, many innovative telecommunications companies have started to provide rural, infrastructure-underserved, geographic regions with high-speed data connectivity by aggregating data traffic from a group of users and backhauling it to a more central location using a network of high-capacity digital microwave radios that have line-of-sight access to the underserved geographic location.

Cellular Applications

Cellular equipment vendors have become more successful recently at providing more economical, easier-to-use, alternative transmission links to the PSTN and the PDN. By installing digital microwave systems that are used to supply voice and data connectivity to these cellular sites (see Figure 12–15), the cellular service providers are lowering their operating costs.

Typically, these microwave systems can be used as either a repeater or an end point and operate in frequency bands from 7 to 38 GHz. The basic system components are the high-gain directional antenna, an outdoor microwave radio unit, and an indoor access module that interfaces with the data streams carried by the system (see Figure 12–16). Able to be deployed in star, ring, or tree topologies, these systems offer capacity rates from E1/T1 to STM-1/OC-3. Using the managed object concept, the microwave links are typically controlled through a central network management center using a low-bandwidth side channel used specifically for these operation and maintenance (O&M) purposes or through a standard PSTN connection. On-site provisioning, maintenance, and monitoring functions are typically also available via a craft interface and a PC running the appropriate O&M software.

Other microwave systems that serve an area from a central location usually take on a point-to-multipoint architecture (see Figure 12–17). These hub systems can serve cellular transmitter sites or small to medium-size enterprises (SMEs.) These point-to-multipoint systems will use sectors with a typical coverage range of 3–6 km at an availability of 99.995%. A standard sector can support several tens of mbps of data traffic per carrier frequency and typically offer E1/T1, Ethernet, and ATM services. These systems are very similar in their operation to standardized IEEE 802.16x, Wi-Max technology.

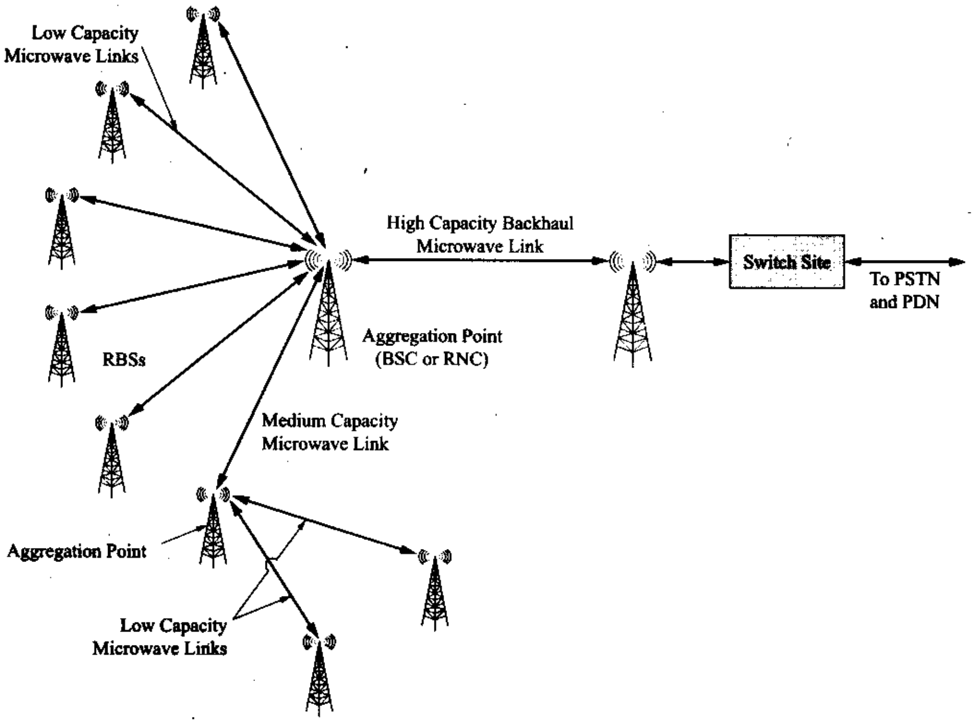


Figure 12–15 Microwave links to cell sites.

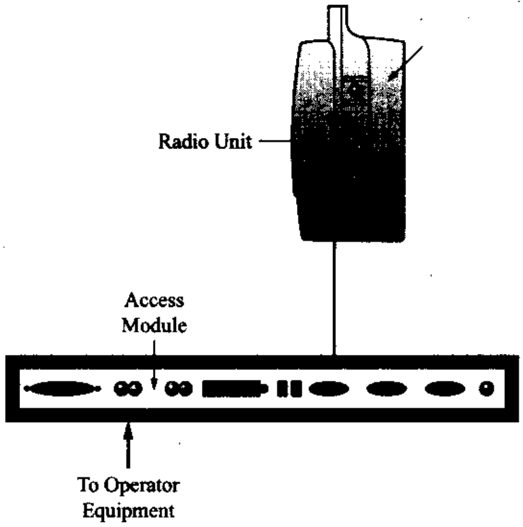


Figure 12–16 Typical microwave backhaul system.

IEEE 802.XX Applications

Digital microwave radio systems that are used in conjunction with the new and legacy IEEE 802.XX wired and wireless technologies are extremely similar to those already discussed. The only major differences are that they operate in the U-NII bands and therefore have to conform to the maximum allowable output

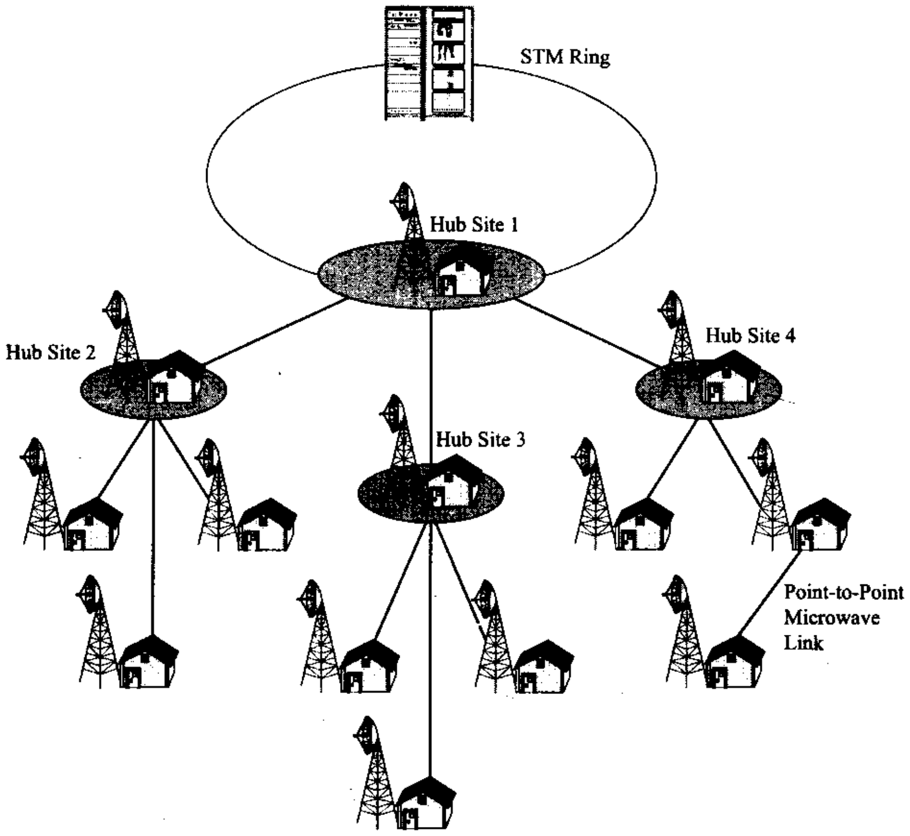


Figure 12–17 Microwave hub distribution system.

power limits and also use more complex digital modulation schemes to mitigate interference effects from other unlicensed services. Many new products have been introduced into this space in recent times. Most notable among these products are wireless bridges that allow physical extensions to wired and wireless LANs, and wireless point-to-point and point-to-multipoint digital microwave links for Wi-Max systems. Additional products like Motorola's wireless Canopy platform of broadband prestandard Wi-Max products that have been used by wireless ISPs to provide wireless Internet access over the unlicensed bands have been available for several years now. With the introduction of advanced wireless technologies (to be discussed in Chapter 13), the world is going to see an explosion of wireless products that will use digital microwave radios to provide the air interface.

QUESTIONS AND PROBLEMS

1. Research the number of users of cable modems, xDSL, and broadband satellite for high-speed Internet access. Hint: See the FCC Web site.
2. Research the number of consumers that have direct broadcast satellite TV. Compare the price of service from your local cable TV provider and an equivalent service from one of the direct broadcast TV providers.
3. Using the Friis equation, predict the received signal power on earth from a beacon transmitting from the moon with 100 watts of power. Assume that the signal frequency is 12 GHz and both receiving and transmitting antennas have a gain of 43 dB.

4. Research the Faraday effect. What effect does it have on electromagnetic signals?
5. Research the diffraction effect. What effect does it have on line-of-sight propagation?
6. Aside from signal power and noise, what is the ultimate limiting effect for terrestrial line-of-sight propagation?
7. Research the effect of "superrefraction." What effect can it have on line-of-sight propagation?
8. Go to the Boeing Satellite Web site and make a chart of the satellites made by this company over the years. Include model number and some of the satellite characteristics.
9. Discuss the characteristics and capabilities of the newest Boeing satellite design.
10. Determine the round-trip time delay for a geosynchronous satellite if the earth station is located 38,500 km from the satellite and the delay due to signal retransmission by the satellite is 25 msec.
11. A proposed geosynchronous direct broadcast satellite system is proposed for the Scandinavian countries. Explain how it can operate with only a rather low transmitter output power of 45 watts.
12. Discuss the relative difference in altitude between LEO, MEO, and GEO satellite systems.
13. Explain the difference between a satellite access network and a satellite access/core network.
14. What is the basic design issue that makes routing through a satellite networks so challenging?
15. What is the basic design issue that makes the use of TCP/IP over satellite networks so challenging?
16. Do an Internet search on New ICO. Discuss the status of its proposed satellite network.
17. Explain the bent-pipe concept in relation to satellite communications systems.
18. What is meant by a spot beam in relation to satellite communications systems?
19. Determine the loss of a fiber-optic cable used to deliver broadband connectivity over SONET if it has a length of 30 km, a loss of .5 dB/km, and coupling/connector losses of an additional 2 dB. How does such a transmission system compare with a digital microwave radio system?
20. Discuss possible reasons why a digital microwave radio system might be more appropriate than a fiber-optic cable to deliver broadband connectivity.
21. Explain the concept of a wireless ISP. Is there one in your area?

CHAPTER

13

Emerging Wireless Technologies

Upon completion of this chapter, the student should be able to:

- Discuss the rationale for the need for new wireless networks and air interface technologies.
- Explain the basic concept of cognitive radio technologies.
- Explain the fundamental concepts of MIMO technology and its applications.
- Explain the operation of ultra-wideband transmission technology.
- Discuss the integration of 3G networks and WLANs.
- Discuss the key features of 4G wireless networks.
- Explain the key concepts of wireless sensor networks.
- Explain the goals of the IEEE 802.20 standard.
- Discuss the future of high-speed network access via satellite service.

This chapter will provide an educated guess about the future directions of wireless networks and air interface technologies. Starting with a brief look at the present status of wireless technology and its current popularity, focus shifts to the driving forces that will shape the next generation of wireless technologies and networks. Next, a close look at new and emerging air interface technologies is presented. Coverage includes an introduction to the theory of cognitive radio technologies, multiple-input multiple-output antenna techniques applied to high-speed wireless systems, ultra-wideband wireless technology, wireless transmission via free space optics, and semiconductor technology issues that affect the development of new wireless technologies and networks.

Once new and emerging air interface technologies have been covered, new wireless network implementations are examined. Topics covered include the recent push by the cellular service providers to standardize the integration of WLAN and cellular networks, the emerging technology of wireless sensor networks, mesh networks and cellular push-to-talk networks, and future 4G wireless networks. The chapter finishes with a brief look at the new IEEE 802.20 mobile broadband wireless access project and the old promise of LEOS and MEOS satellite networks that can provide high-speed Internet access to remote locations.

13.1 INTRODUCTION TO EMERGING WIRELESS TECHNOLOGIES

Any attempt to predict the future direction of technology is most likely doomed to failure if the prediction is too detailed or tries to look overly far into the future. With this in mind, this chapter will discuss some probable future trends in the wireless industry and attempt to predict some new directions that will occur due to continuing technology enhancements and new technology. Before attempting to predict the future, let us pause and take a look at what has happened in the wireless industry in recent times to bring us to this point in its development. Most assuredly, the current popularity of wireless telecommunications systems will have a significant impact upon the future development and deployment of future wireless access schemes.

Wireless technology has existed for over 100 years. However, it has only been recently that it has gained such a popular status in the technologic scheme of things. Certainly, we have all been exposed to wirelessly delivered entertainment via radio and TV broadcasting in the form of AM/FM radio and television. In the United States, where the driving of an automobile has become a rite of passage for teenagers, today's vehicles come equipped with sophisticated stereo AM/FM/CD entertainment centers (and optional backseat TVs, plasma screens, DVD players, and satellite radio) that provide a wireless connection to the world (albeit only a half-duplex downlink connection). Wide-screen TVs with high-definition capabilities are becoming more commonplace in our residences and ironically more and more televisions are having signals delivered to them directly by cable connections instead of over the air interface. At the same time, the growth and use of the Internet has experienced a phenomenal expansion. This fact is certainly due, in part, to the proliferation of the home PC. Indeed, access to the Internet through one's PC has added another form of entertainment or, to use the new term, *infotainment* into our busy existences.

In a similar scenario, the adoption of wireless cellular telephone technology by the masses is unprecedented. Its use and take-up rate exceeds that of any other electronics-based technology product introduced in the past century. Recently, in early 2004, besting all earlier predictions, the number of GSM system subscribers (approximately 75% of the world's cellular subscribers) surpassed the one billion mark! The Internet is the only other technology to keep pace with the wireless (r)evolution (or is it the other way around?). As outlined in prior chapters, the cellular telephone systems of the world have undergone a very rapid evolution from their first deployments as voice networks to today's 3G capabilities. 3G technology is driven by a desire to fulfill the perceived need to provide a data connection to the Internet for the cellular subscriber. The idea of anyone, anywhere, anytime high-speed connectivity has certainly been embraced by today's highly mobile society.

Most telecommunications technology observers believe that the wireless industry will play a dominant role in this decade and beyond in the attainment of anytime and anywhere access for anybody to the core network. Furthermore, most feel that ubiquitous high-speed wireless networks will play an important role in the evolution of this still early implementation of the eventual telecommunications infrastructure that will ultimately envelop the earth.

How will the wireless part of this evolution procede? That is difficult to predict. However, what is certain is that Moore's law will come into play. The processing capacity, memory capacity, and operational speed or frequency of operation of semiconductor devices (ICs) will continue to increase and the hardware costs will continue to drop as cellular/PCS and wireless LAN, PAN, MAN, and WAN (wide area network) technology matures and becomes more widely deployed. The integration of GPS technology with wireless networks will continue and provide more location-based applications and emergency services (E911, OnStar, etc.). Whether these future location-based applications will be accepted by the users of wireless systems remains to be seen. If the public's general reaction to e-mail SPAM is any indication, the wireless industry would be wise to proceed cautiously as it rolls out these new applications. A wild card in all this is the effect that regulatory bodies will have upon new and emerging technologies. Presently, in the United States, there is a proactive approach being taken in the release of new spectrum or the reframing of old frequency allocations for use by new and emerging wireless technologies. Will this last or will a new political administration take a different stance? Only time will tell.

This chapter will consider the future of wireless telecommunications in the context of both emerging technology implementations and emerging enhancements to wireless network operation. The topics that will be considered are new wireless network implementations (i.e., push-to-talk technology, IEEE 802.20, wireless sensor networks, wireless mobile satellite networks, WLAN and cellular convergence, and 4G networks) and new air interface technologies (cognitive radio technology, MIMO technology, ultra-wideband pulse transmission, free space optics, etc.) that will be used to provide gigabit wireless service and to more effectively use the limited frequency spectrum. The topics covered in this chapter are not meant to be construed as an exhaustive list by any means. They are just the most high-profile topics at this time. As always, the market-place will be the testing ground for any new technologies and applications added to the wireless arena.

13.2 NEW AND EMERGING AIR INTERFACE TECHNOLOGIES

The next generation of wireless technologies will provide high-speed connectivity as well as high levels of security, privacy, and intrusion detection. Many in the telecommunications industry feel that broadband wireless access is one of the cornerstones of the future all-IP network and a necessity for ubiquitous access to that network. As fixed gigabit and 10-gigabit Ethernet networks become more commonplace, wireless network speeds that exceed 100 mbps and eventually approach 1 gbps are perceived to be what the public will demand and what will be necessary to support wireless applications in the home and to a lesser degree in mobile environments. To achieve these next-generation speeds, new air interface technologies will be needed that can maximize the data transfer speed over an NLOS air interface and at the same time maximize the total possible number of users by reducing interference between systems. To allow coexistence between different users and different wireless networks and to more efficiently use the limited frequency spectrum, innovative cognitive radio technologies will most likely be called upon. A combination of new and emerging wireless access technologies and new semiconductor and RF MEMs devices will be used to achieve these goals. Furthermore, a regulatory environment that is favorable to the expansion of wireless high-speed access will provide the impetus needed to extend the penetration of this form of broadband access to not only the urban and suburban areas but also to the rural heartland of America. A brief introduction to some of these new and emerging technologies will be given next.

Cognitive Radio Technology

For close to one half of a century the typical hardware used to implement an early wireless radio system remained fairly unchanged. The vacuum tube-based transmitter and superheterodyne radio receiver combination consisted of a rather fixed structure that was somewhat dependent upon the type of analog modulation employed and the frequency of operation. Except for the ability of a receiver to perform an automatic gain control (AGC) function almost all other tasks like tuning (frequency control) and output power and volume adjustments were mechanically performed by the user/operator. With the advent of the transistor and then the integrated circuit, radio designers were able to incrementally add new functionality like stereo multiplexing, color TV, and frequency synthesis using phase-locked loops (PLLs) to wireless broadcast systems and other radio services. Of course, by that time, other specialized radio systems like those used by the military or government (radar, spread spectrum, satellites, etc.) had also incorporated more sophisticated system control and signal processing and display techniques. Also, the introduction of digital radio initiated the use of more complex and sophisticated modulation techniques to obtain bandwidth efficiency (higher data rates in the same bandwidth), and wireless multiplexing and access techniques became more intricate. But all in all, basic transmitter and receive designs have remained fairly unchanged since the early days.

To some extent, this slow evolution in wireless system design was due to the regulatory structure imposed by the FCC in the United States and by other government agencies in the rest of the world. Since various wireless services were assigned particular frequency bands (very often dictated by the available RF technology of the day), wireless emissions tended to be well behaved, narrowband (NB) in nature, and occur in band-limited channels assigned within the particular service band. Other transmitters were unable to use the same frequency allocation or channel if they were going to potentially cause interference to the transmitter first assigned to the channel. As discussed in Chapter 4, the concept of frequency reuse is based on this principle. This process of allocating frequency spectra on a first-come first-served basis and the guarantee of protection from RF interference from other transmitters has formed the basis of the guiding philosophy and legal tenets of the FCC for many years.

Recently, with the very rapid expansion of wireless services and the just as rapid exhaustion of available frequency spectrum, the FCC has become much more receptive to advanced radio technologies that can provide more efficient use of the limited frequency spectrum available. At the same time, Moore's law has seemingly come to the rescue again, as the amount of embedded processing power available to the wireless system designer is sufficient to enable innovative wireless systems that can facilitate the efficient sharing of the radio frequency spectrum. In its recent *Notice of Proposed Rule Making and Order*, the FCC has commenced the process needed to eliminate regulatory barriers to the use of cognitive radio technologies and to take a position that appears to embrace and encourage their use. Cognitive radio technologies refer to the ability of a wireless device to determine its location, sense the spectrum use by its neighbor devices, change both its frequency of operation and output power, and adjust its modulation type and complexity. Essentially, a **cognitive radio** is able to adjust to the ongoing traffic that is using the spectrum that it desires to also use. According to the FCC and the research community, the ability of a cognitive radio to adapt to the real-time conditions of its operating environment offers the potential for more flexible, efficient, and comprehensive use of the limited available spectrum.

Most modern radios incorporate microcontrollers/microprocessors and software to control system operating parameters such as operating frequency and modulation type. Certainly, multimode cellular telephones and more recently IEEE 802.11x wireless LANs that are already in use are examples of this type of technology. The cognitive radio is able to modify its transmitter parameters based on interaction with its environment. Another term used for this type of wireless system functionality (more often applied to the receiver portion of the system) is the **software-defined radio** or SDR. The modern multimode cellular telephone, using cognitive radio technologies, is able to reconfigure itself to use the wireless services available within its environment. That is, it can sense and then adjust to the type of radio access method that is currently available. What is novel about the use of a SDR is that this approach does not necessarily invoke the use of different portions of its available hardware to perform different receiver functions (which is certainly possible) but that it is able to perform alternate signal processing tasks that implement the functions and operations necessary to deal with the reception of different access method technologies and modulation forms.

The FCC recently performed a study of the present use of the radio frequency spectrum in the United States (see www.fcc.gov) and came to the conclusion that in many instances various portions of the radio spectrum are underutilized and inefficiently used under the current regulatory environment. It is felt that cognitive radio technologies could be used to improve spectrum access and efficiency in several different ways. First, a licensed service provider could use cognitive radio technologies within its own wireless network to increase the network's efficiency. Cognitive radio technologies could also be used to facilitate what are known as secondary markets in spectrum use. Secondary markets are providers of radio services that negotiate with the spectrum license holder to use the licensed frequency when it would not cause interference with the primary user. Cognitive radio devices could be deployed by the secondary user that negotiate use of the spectrum with the licensee's system but only under conditions dictated by the licensed user. Cognitive radio technologies can also be used to facilitate frequency coordination schemes between coprimary services. Finally, cognitive radio technologies could be used to provide radio access to an unlicensed device that would operate at times or in locations where licensed spectrum was not presently in use.

Cognitive radio technologies have the potential to improve access to the limited available radio spectrum and at the same time provide new and enhanced wireless services that will lead to the next generation of wireless networks. As already mentioned, a cognitive radio could interact with its environment in several ways. This could be through passive sensing of the spectrum or active negotiation and communications with other spectrum users. The cognitive radio could identify different portions of the radio spectrum that are unused at a specific location or time and use these opportunities to transmit. A cognitive radio could provide interoperability between two wireless systems that operate in different frequency bands and use different modulation or access formats by relaying signals between them. The cognitive radio typically has the ability to be frequency agile, adaptively modify modulation techniques, dynamically change transmitting power, and negotiate the sharing of frequency spectrum with other services. Also, through the use of GPS the cognitive radio could determine its location and the location of other radios and thus select the correct operating parameters for its location (power, frequency, modulation type, signal polarization, etc.).

Presently, the FCC believes that these techniques could be especially useful in rural areas. If the FCC were to permit higher output power levels for unlicensed service in rural areas, greater transmission range and hence increased coverage would result for wireless internet service providers (WISPs) and wireless LANs. Cognitive radio technologies could allow for higher output powers in rural areas while still ensuring that harmful interference does not affect authorized services.

Multiple-Input Multiple-Output Wireless

In an effort to achieve wireless data rates that approach or even exceed 1 gbps, new techniques must be used when operating wireless links in NLOS environments. The use of traditional methods of increasing bandwidth for **single-input single-output** (SISO) antenna systems becomes unattractive from a regulatory standpoint and also technically impractical. With a typical practical system spectral efficiency of 4 b/s/Hz, a single channel with a bandwidth of approximately 250 MHz would be needed for a 1-gbps data transfer rate. For frequency bands below 6 GHz, finding a channel bandwidth of 250 MHz is highly improbable if not impossible. Also, if one assumes a path (propagation) loss exponent of 3 (refer back to Equation 8-6 in Chapter 8), one discovers that for every factor of eight, increase in bandwidth the useful system range is reduced by a factor of two and the cell area decreases by a factor of four. Therefore, one may show that the use of a 250-MHz channel bandwidth compared to the typical 10-MHz channel used by today's systems will result in an approximate reduction in range of slightly less than three and a corresponding cell area reduction of somewhat less than nine. This decrease in range is not entirely detrimental to a wireless system because it certainly allows for greater system frequency reuse but at the same time it also greatly increases deployment cost. One is also reminded that frequency reuse plans with $N > 1$ would require even more then the 250-MHz bandwidth figure used here to be implemented properly. Therefore, as stated before, a 1-gbps SISO-based system would require impractical amounts of bandwidth for proper operation at frequencies below 6 GHz.

Recent advances in **multiple-input multiple-output** (MIMO) wireless technology provide a means by which gbps NLOS wireless networks may be achieved. MIMO wireless operation is obtained through the use of multiple transmit and receive antennas. Figure 13–1 illustrates an $M_T \times M_R$ system with six transmit, M_T, and six receiving antennas, M_R. It is beyond the scope of this text to derive the system gains achieved by this type of technology but we can discuss the various enhancements that such a system is able to provide. The performance improvement that is attributable to the use of MIMO wireless is due to a combination of the following effects: array gain, diversity gain, interference reduction, and spatial multiplexing.

Array gain may be realized through signal processing at both the transmitter and receiver. The signals from each receiving antenna may be coherently combined to provide an increased received signal level and thus a higher average signal-to-noise ratio. The array gain is proportional to the number of transmit and receive antennas and requires that both the transmitter and receiver have some knowledge of the radio link channel. As discussed extensively in Chapter 8, the signal power received in an NLOS environment is subject to fading or random fluctuations. Diversity schemes are very useful in mitigating this effect over wireless radio links. Diversity techniques use the principle that signal fading is dependent upon the propagation path and time of transmission. Therefore, to mitigate fading effects a diversity scheme will transmit the same message over multiple independent fading paths at different times, frequencies, or spatial

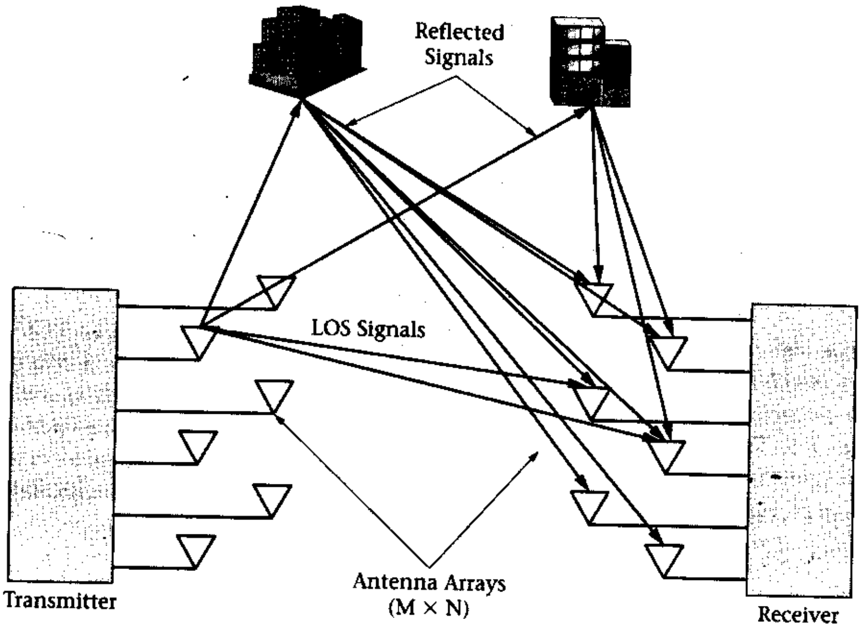


Figure 13–1 Typical multiple-input multiple-output wireless antenna system.

directions (or combinations of these parameters). Spatial diversity is actually preferred over time or frequency diversity because it does not negatively impact the system data rate or bandwidth requirements. For a MIMO wireless system, if the $M_T \times M_R$ links fade independently and the transmitted signal has been encoded and processed in the proper manner, the receiver can combine the signals from the M_R antennas in such a way as to reduce signal fading considerably. As discussed in the last chapter, spatial diversity gain may be achieved by using suitably designed transmission signals as explained during the discussions of space-time coding used by several of the IEEE 802.16a physical layers. MIMO wireless systems are also able to provide interference reduction since the multiple antennas provide more detailed spatial signatures of the desired signal and any cochannel signals. This information may be used to reduce cochannel interference.

The most important aspect of MIMO operation is the linear increase in system capacity afforded by the use of multiple transmitting antennas. Known as spatial multiplexing gain, this increase in data transfer capacity comes at no expense to either bandwidth or power. Each transmitting antenna is supplied an independent data stream that, depending upon the channel propagation conditions, can be separated at the receiver. Thus system capacity is effectively multiplied by the number of transmitting antennas. This technique is not only applicable to single-carrier operation but may be also used for OFDM-based wireless systems. MIMO-OFDM is a particularly attractive modulation scheme for use over frequency-selective fading channels. Now, the OFDM operations are performed at each of the transmitting and receiving antennas employed by the system. Any required encoding or signal processing must now be performed on a tone-by-tone basis for each OFDM signal at each antenna.

Although MIMO wireless technology appears to provide many potential benefits, it will take some time before it is implemented in practical systems. It should be pointed out that it is not possible to optimize all of these system enhancements at any one time due to conflicting design parameters and various other tradeoffs. There are several different MIMO implementation schemes that have been advanced; however, the underlying theory has used different assumptions and channel models. Therefore, various details will have to be worked out before standardized system models are available that will allow the eventual adoption of MIMO wireless techniques within the IEEE 802 wireless standards or the 3G (or 4G) cellular standards. Furthermore, MIMO wireless greatly increases the complexity of the transceivers and antenna systems needed to implement it. Moore's law will need to keep on working to provide low-cost hardware that can be used to implement this system-enhancing technique and eventually place it on a single IC chip.

Ultra-Wideband Wireless Technology

Ultra-wideband (UWB) radio technology was briefly introduced in Chapter 8 and again mentioned in Chapter 10 as a potential implementation technology for IEEE 802.15.3a. At this time, a closer look at this technology will be undertaken. The FCC defines UWB as any wireless transmission that occupies more than 500 MHz of bandwidth or has a fractional bandwidth such that:

$$BW/f_C \geq 20\% \qquad \textbf{13-1}$$

where, BW is the transmission bandwidth and f_C is the band center frequency. The FCC has recently approved the use of UWB in the 3.1–10.6 GHz frequency range on an unlicensed basis. Furthermore, the ruling provides for a spectral mask that limits the power spectral density (PSD) in a 1-MHz bandwidth to that shown in Figure 13–2. This output power limitation allows a UWB transceiver to be overlaid on existing systems and to also limit interference to services already operating or proposed for operation in the 1–3.1 GHz frequency range (i.e., radar, GPS, PCS, AWS, and WLANs). Therefore, the UWB specifications effectively limit its use to very short-range applications like those envisioned for WPANs.

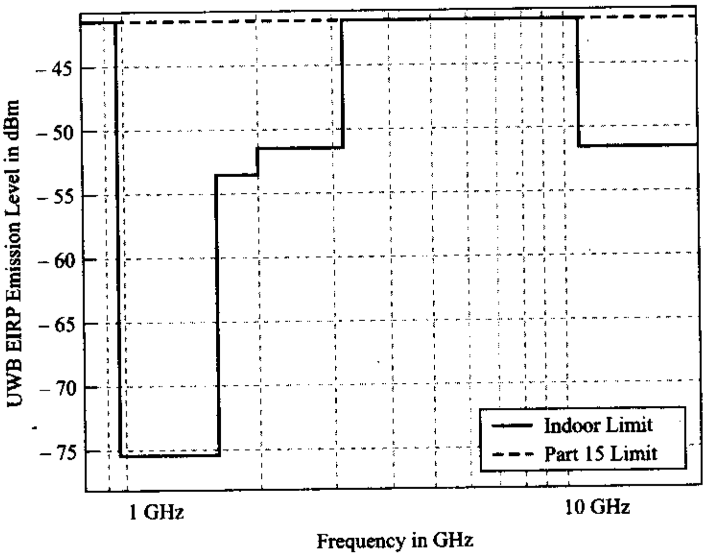


Figure 13–2 UWB power spectral density mask (Courtesy of IEEE).

A simple comparison of UWB capacity with other technologies shows that for distances less than ten meters, involving a single-user scenario, UWB is best suited for high-speed data throughput compared to more traditional technologies. For distances greater than ten meters these other more traditional technologies provide higher data throughput. Multiuser environments are sure to lower the overall effectiveness of UWB even at distances in the ten-meter-and-less range. The IEEE 802.15.3a physical layer specification calls for a data transfer rate of 110 mbps at ten meters and 200 mbps at four meters with higher rates up to 480 mbps at distances less than four meters. To achieve these rates, UWB-enabled devices must use pulse shapes and modulation schemes that conform to the FCC spectral mask and allow high data transfer rates. Typical proposed UWB schemes use a Hanning-shaped pulse (see Figure 13–3) and some form of binary pulse amplitude modulation (PAM) or pulse position modulation (PPM) encoding of the data to be transferred.

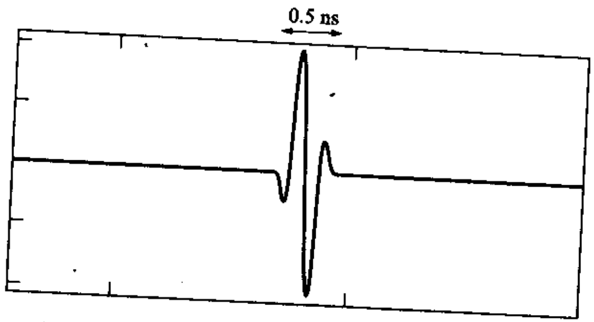


Figure 13–3 UWB Hanning pulses (Courtesy of IEEE).

The UWB multiple access techniques that have been proposed are based on TDM and use either direct sequence spread spectrum (DSSS) encoding or time-hopped PPM (TH-PPM). For UWB-DSSS operation, each user transmits a unique short chip pulse sequence similar to CDMA operation. For UWB-TH-PPM operation each user's unique short chip pulse sequence is used to encode the position of the pulse during the user's time interval. Other interesting designs use multiband schemes that divide the 3.1–10.6 GHz frequency range into smaller subbands (minimum bandwidth must be 500 MHz). These systems use sequential frequency hopping schemes that can employ any number of modulation techniques within each subband including those already mentioned and OFDM. For the coexistence of multiple UWB based piconets operating in close proximity of one another, various suitably designed frequency hopping sequences can be deployed that will lower the probability of data collisions between two users in different piconets.

At present, there are several circuit implementation issues that need to be addressed before low-cost implementation of UWB based systems is possible. Circuit efficiency and speed are critical to UWB operation. The need to perform an analog-to-digital conversion (ADC) of the received signal for a single-band UWB system at a rate of several gigasamples per second with 8–10 bits of resolution is today still a relatively costly proposition. If a multiband implementation is desired to reduce the stringent ADC requirements, there is a need for a very fast frequency-hopping generator that operates in the GHz range. Again, this is also an expensive proposition in today's RF CMOS or BJT technologies. Therefore, until Moore's law allows UWB technology to be implemented on a single low-power IC chip, this technology will not enjoy widespread use. The reader is urged to go to www.timedomain.com to see more details about products that use emerging UWB technology.

Free Space Optics

In Chapter 9, the use of the IEEE 802.11 infrared physical layer specification was basically treated as a "dead" or superceded technology. IR technology was able to support the 1- and 2-mbps data rates of the first WLAN standard but was not included in any of the higher-rate follow-on 802.11x standards. Infrared technology has resurfaced as "free space optics" or "optical wireless," another form of wireless broadband access under the Wi-Max banner. As stated in Chapter 9 there are presently no regulatory (other than safety) restrictions anywhere in the world on the use of IR. Several companies sell LOS point-to-point systems that use free space 1550-nm optical signals to deliver duplex OC-3/12 and higher data rates over links several kilometers in length. These systems are sold as alternative solutions that compete with other technologies (i.e., microwave and fiber-optic cables) without the need for a spectrum license. Typical applications provide high-speed data links from building to building in metro areas but use of these systems is certainly not restricted to only one type of telecommunications link deployment. The use of this type of technology appears limited to temporary high-speed links and other special cases where the economics or time constraints argue compellingly against other technologies.

Wireless Semiconductor Technology

Numerous times in this textbook references have been made to Moore's law and its effect on the advancement and future implementation of advanced high-speed wireless systems. Since most references to Moore's law are made about the density of integrated circuits (i.e., total number of transistors per IC chip), it is appropriate to point out here that the type of RF front-end circuit components to be used in present and proposed wireless systems poses but one of the many design challenges that wireless system designers face. However, the obstacles to advances in RF circuitry are somewhat unique and not the same challenges as those presented by the need for increased processor or memory capacity for other mobile station or subscriber device functions. For over twenty years technology advances for these latter functions have been driven by the PC industry. Today, many observers of the technology scene (including this author) believe that the cellular telephone is now the major driver of the semiconductor industry!

The design parameters of wireless RF front-end circuitry call for higher-frequency, extremely linear, and more efficient operation. These characteristics coupled with more complex modulation schemes (with their requirements of higher adjacent channel power ratios [ACPRs] and less phase noise) have pushed RF semiconductor technology to its limits. Researchers have been pursuing new semiconductor materials and structures to achieve advances in performance at higher frequencies. Achieving these advances has typically been slower paced than those involving semiconductor memory densities. However, with the new focus on the wireless industry, improvements in exotic semiconductor materials and transistor designs have started to become higher-profile activities as have advances in RF microelectromechanical systems (MEMS) that can replace traditional passive RF devices like switches, antennas, filters, and other LC-resonant circuits. Together, new semiconductor technologies and RF MEMS are being designed into system-on-a-package (SOP) implementations that will be used to provide the gigabit wireless systems of the future. As this technology matures and grows, the cost of these components will decrease and they will become embedded in more products. Some technology visionaries believe that the IC of the future will have short-range wireless connectivity built into it, thus giving any IC or system-on-a-chip (SOC) the ability to talk to any other nearby IC! This type of functionality is off in the future but it makes one pause and give some thought to the implications of where wireless technology might lead to.

13.3 NEW WIRELESS NETWORK IMPLEMENTATIONS

The cellular service providers are presently in the process of upgrading their systems to full 3G functionality and the IEEE 802.XX working groups are standardizing new data access technologies. At the same time, the research community is hard at work defining the next generation of wireless networks for LANs, MANs, PANs, and WANs. Although much of this research focuses on the improvement of air interface technologies (higher data transfer rates, NLOS operation, coexistence, etc.), considerable attention is being paid to the networks themselves. In general, the next generation of wireless technologies (4G wireless systems) will provide support for higher data rates, larger system capacity, next-generation Internet support, seamless services, and flexible network architectures. To reach these last several goals, the networks of the future must be able to provide support for heterogeneous networking with support for both horizontal and vertical handovers (e.g. WLAN to cellular and vice versa), seamless roaming, and mobile IP.

The general consensus in the wireless research community is that the air interface hardware and networks used to provide wireless connectivity in the future will become "softer" as time moves forward. By this, we mean that the wireless terminals and base stations will become SDR based and equipped with cognitive radio technologies. Furthermore, the networks themselves, including the core backbone network, will exhibit adaptive and reconfigurable behavior as we move toward the cognitive network of the future. The amount of software in telecommunications systems will continue to increase in every part of the system infrastructure. This section will look briefly at some of the newest network initiatives including the move to integrate 3G and WLAN systems, mesh networks, push-to-talk (PTT) network technology, and the possible future proliferation of wireless sensor networks. The section concludes with a short overview of the technology profile of 4G wireless.

Integration of WLAN and 3G Cellular Networks

The very rapid deployment and success of WLANs has led many wireless telecommunications observers and financial analysts to doubt the future success of 3G cellular. However, as time has passed since the first deployment of WLAN hot spots a more objective assessment has been made of the two technologies and the business models for both have been rethought. It has started to become apparent that the two technologies are complementary to each other but the business models are still unclear. WLAN access provides higher data throughput speeds but in smaller areas with higher user demand whereas 3G offers slower speeds in much larger areas with less user demand. In response to the success of WLAN hot spots, the cellular equipment vendors and service providers have taken steps to integrate wireless LANs with 3G networks. In the 3G standards area both the 3GPP and 3GPP2 partnership projects are actively working on 3G/WLAN integration standards. Several equipment vendors have already marketed prestandard systems that have added a wireless LAN serving node to the packet core network of a cdma2000 system as shown by Figure 13–4. As indicated by the figure, the wireless LAN serving node provides IP transport connectivity between subscriber devices that can support IEEE 802.11 wireless LAN operation and the public data network.

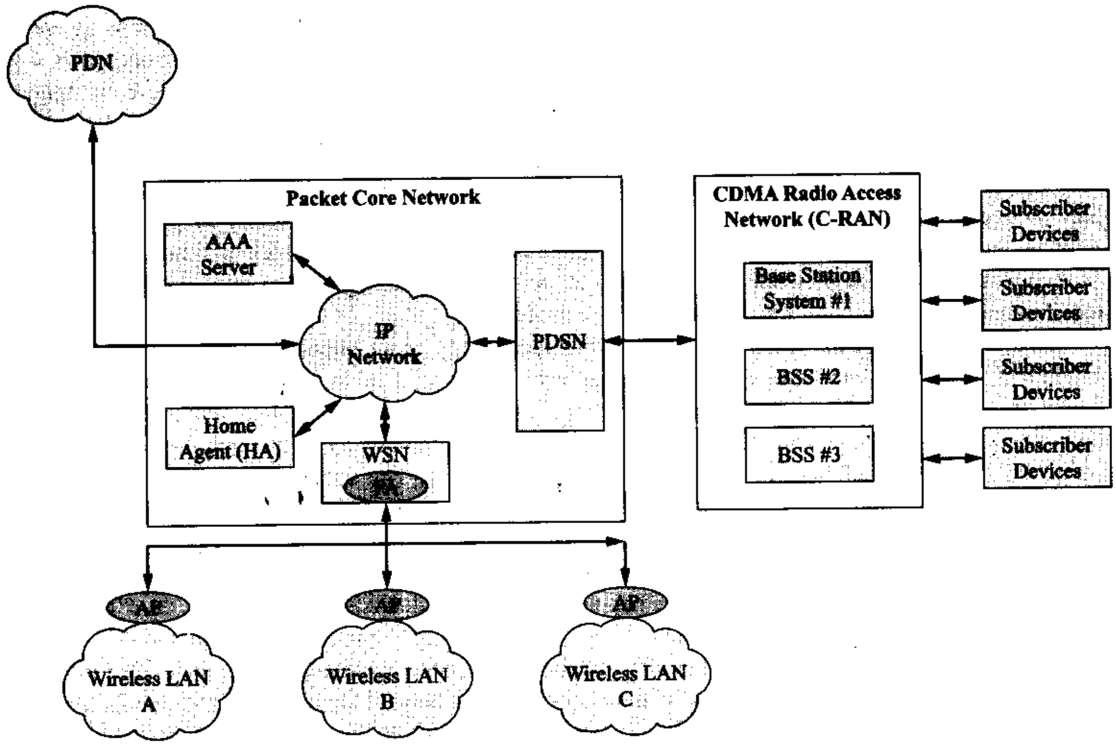


Figure 13–4 CDMA wireless LAN serving node (Courtesy of Ericsson).

Typically, a group of WLAN access points can be connected to the WLAN serving node via Ethernet connections. The WLAN serving node (WSN) interfaces the WLAN with the packet core network's home agent (HA) and the authentication, authorization, and accounting (AAA) server via an IP connection. Thus the WSN node serves as the connection point between the WLAN and the IP network. It further provides IP service management, delivers foreign agent (FA) functionality that is used to register and facilitate services for mobile IP users, and also establishes, maintains, and terminates secure communications with the home agent. The WLAN access points act as RADIUS clients and the AAA server contains a RADIUS server implementation. **RADIUS** (remote authentication dial-in user service) is an authentication, authorization, and accounting protocol widely used for operations involved in the accessing of Internet networks. The reader is referred back to Chapter 6 for more complete explanations of the functions performed by these network elements (i.e., HA and AAA). However, from the service provider's point of view the most important functionality provided by this 3G/WLAN network integration is the provisioning of chargeable public WLAN services for mobile operator subscribers.

Recently, there has been speculation that a future morphing of the combined 3G/WLAN network that would provide more efficient operation and higher data throughput speeds is possible through the use of Voice over IP (VoIP). That is, the cellular system subscriber's device uses the wide area network (WAN) coverage of the 3G wireless cellular network when not in range of a WLAN and then uses the WLAN for connectivity when within its coverage area. The delivery of voice services is provided via VoIP over the WLAN to the multimode subscriber device when within range of an integrated WLAN. This idea has recently started to receive a large amount of attention since it allows an evolutionary expansion path for the service providers. Time will tell.

Mesh Networks and Push-to-Talk Technology

Currently, the typical wireless network uses a "single hop" or "single radio link" approach to its operation. Cellular wireless networks and WLAN technology are based on a design criterion that only uses a single wireless link to connect a user to the fixed network infrastructure. Recently, to facilitate greater operational functionality and NLOS wireless operation, both IEEE 802.15 and IEEE 802.16 standards have included mesh or multihop network technology within their possible air interface implementation schemes. This very new technology has not really had an opportunity to mature as of yet and there are only a few examples of operational broadband wireless systems with mesh capability actually in place. The reader is referred back to Chapters 10 and 11 for actual system operation details, which will not be repeated here. Suffice to say that mesh networks use multihop capability with messages being routed onward to their correct destination by the mesh network nodes of the system.

Some see the use of multihop or mesh network technology as an important means to provide extended capabilities to future wireless networks. The general idea would be to build heterogeneous overlay networks that would be able to move messages from, say, a narrowband wireless sensor network toward a broadband wireless network and eventually to a fiber-optic core network or the opposite scenario. Another proposed scheme would involve the use of ad hoc networking. The use of massive ad hoc networks that could provide the same connectivity as just outlined has been proposed as a multihop solution to the same class of problems. Mobile ad hoc network (MANET) standardization activities have been progressing in the area of routing but the implementation of such a system is still off somewhere in the future.

Push-to-talk (PTT) technology is a rather new innovation that has been overlaid on existing wireless cellular systems. This technology, which allows a cellular telephone to be used in a mode similar to a walkie-talkie, has become very popular with cellular subscribers. As one might expect, in an effort to promote interoperability between different cellular systems and networks, the 3GPP and 3GPP2 partnerships as well as the Open Mobile Alliance (OMA) (see www.openmobilealliance.org) have started to standardize PTT technology as PTT over cellular or PoC. PTT technology uses a form of half-duplex operation over the wireless cellular system's data network that is somewhat similar to short message service (SMS). The PTT-enabled cellular telephone has a push-to-talk button that, when depressed, signals either a single other cellular telephone (one-to-one operation) or a group of other cellular telephones (one-to-many operation). The functional entities that compose a PTT system are the PoC client that resides on the PTT-enabled cellular telephone, the PoC server that implements the application-level network functionality of the PoC service, and the group and list management server (GLMS) that is used to manage a PoC user's groups and lists necessary for PoC service. Additionally, there are several external entities that provide services to PoC systems: the session initiation protocol/IP (SIP/IP) core and the presence server. The SIP/IP core routes SIP signaling between the PoC client and the PoC server, provides discovery and address resolution functions, provides authentication and authorization, and performs charging functions. The presence server maintains the presence status of PoC clients (reachable, unavailable, offline, and do-not-disturb, etc.). For the interested reader more information is available at the OMA or the 3G partnership Web sites.

Wireless Sensor Networks

During the past decade, there has been an ever increasing use of sensors and embedded microcontrollers used for the control and monitoring of various system operations in almost every type of product that makes use of any electronics during its operation. The trend of using sensors and embedded control is likely to increase as we move forward. However, to the people who design and manufacture these products it is becoming apparent that the integration of the sometimes numerous control and sensing systems poses a communications/networking problem. A connectivity bottleneck exists between the various subsystems and also with the outside world. Furthermore, there are areas of industrial and commercial control, automotive sensing, home automation and networking, consumer electronics, home security, and so forth that have similar connectivity problems. These types of applications have been receiving a great deal of attention by the IEEE 802.15.4 working group. Chapter 10 presented the details of IEEE 802.15.4 and mentioned wireless sensor networks as a potential application for WPANs.

Wireless sensor networks (WSNs) are a class of wireless networking applications that are concerned with providing connectivity to sensors, controls, and actuators without the use of wires. There are numerous types of sensor networks that are usually classified according to the type of sensors, application area, environment, and network type. One might question, what driving forces are behind the desire to implement WSNs? In an industrial environment sensor/actuator installation costs are high. A small limit switch might cost less than a dollar but its installation may run into the many hundreds of dollars due to wiring regulations and materials costs (conduit, wire, etc.). Wireless connectivity would eliminate much of these costs. Most field technicians and repair personnel will confirm that an extremely high percentage of technical problems are caused by faulty interconnections between subsystems or the components that make up a system. Wireless connectivity would reduce these types of problems. Lastly, the use of a dense WSN would provide abundant data that an intelligent monitoring system could use for overall maintenance or to improve productivity in an industrial environment. This type of sensor network becomes impractical very quickly if it is deployed by hardwiring the sensors. There are also applications like tire pressure monitoring (see Figure 13–5) that are physically impractical without a wireless link, or situations where dangerous conditions prohibit access to a sensor or control system. In all cases, the use of battery power is implied, which further implies low output power and therefore short-range operation. However, as pointed out previously, the IEEE 802.15 standard provides for the interconnection of networks that allow for data transfers that extend beyond the original piconet joined by a WPAN device.

One can envision numerous other different WSN applications (severe weather and tornado forecasting, precision agriculture, security and safety situations, etc.) where a very large number of wireless sensors provide data about a particular area or process that heretofore presented itself as an intractable situation to analyze due to insufficient data points. At the same time, one can envision the time when the ubiquitous nature of WSNs causes us to consider social and ethical questions about privacy, authentication, and the use of information that can be gathered by these networks. Today these concerns go beyond the "big brother" society. With advances in nanotechnology, biotechnology, the possibility of networked bioelectronics, and so forth, complex issues can be envisioned that have no past precedents to fall back on. If today one can purchase a small, fairly low-cost, concealable, wireless camera on the Internet, what will tomorrow bring? There are many WSN applications that one can envision that can be used to improve the human

Figure 13–5 Wireless sensor application—tire pressure sensing (Courtesy of Schrader Electronics).

condition. However, at the same time, there are many uses that unscrupulous individuals or, for that matter, governments might choose to employ for personal gain or other deceitful purposes. As we go forward with these new wireless technologies, particular attention must be given to the network functions that provide for secure operation and privacy of users' data.

4G Wireless Networks

In Chapter 2 a short introduction to 4G wireless was presented. This short overview was given from the perspective of a comparison of 4G with the other predecessor wireless generations. At that time, emphasis was placed on the fact that the essence of future 4G wireless networks is an all-IP core network, with all services (voice, data, multimedia, etc.) being delivered to and from the radio access network via IP. At this time, we will discuss the main technological requirements of 4G systems. Table 13–1 provides as comprehensive a list of the basic system objectives of 4G as will be found anywhere. As shown by the table, in

Table 13–1 4G wireless characteristics.

Characteristics of 4G Wireless
High-speed transmission rate (peak rate 50–100 mbps, average rate of 20 mbps)
Larger system capacity (approximately 10 times greater than 3G systems)
Next-generation Internet support (IPv6, QoS)
Seamless services between heterogeneous systems
Flexible network architecture
Use of lower microwave frequencies (3–6 GHz)
Low system implementation cost (approximately, 1/10 to 1/100th of 3G systems

what should be no surprise to the reader, faster peak data transmission speeds of approximately 50–100 mbps with average data transfer rates of 20 mbps are expected for 4G systems. Increases in data transfer rates have been the measuring stick that has been adopted for use in the determination of the next generations of wireless access and for the time being will continue to be used for that purpose. Furthermore, the subscriber capacity of a 4G system is expected to be approximately ten times or more that of a 3G system.

With the wireless service providers experiencing very high costs for their deployment of 3G, this system objective is necessary or else 4G will never be deployed! This becomes more certain if 4G only brings about marginal changes to the operation of 3G. Certainly, 4G will need to support IPv6 and provide the required QoS capabilities that will allow VoIP and new, sophisticated multimedia applications that have yet to be brought to market. IPv6 support will be necessary to support the concept of mobile communications for anything that moves. With the deployment of wireless sensor networks and other potential home applications, the amount of person-to-machine and machine-to-machine non voice wireless telecommunications is going to increase greatly and the additional IP addresses that can be supplied by IPv6 will be most surely needed. Seamless services refer to the ability of the future 4G wireless network to provide connectivity seamlessly to the user regardless of the type of wireless network(s) that they are in proximity of. 4G should be able to provide services across whatever wireless access system is available. This means that the network architecture must also be flexible enough to support this type of functionality. The reader might recall the concept of the cognitive network recently introduced in another section of this chapter. Certainly, the potential for a wireless network middleware layer to provide this network flexibility is extremely likely for any 4G network realization.

The need for additional spectrum usage in the 2–6 GHz or other frequency ranges is also necessary to support the higher data transfer rates and increased number of users. Lastly, to increase system usage, the cost of accessing data must be reduced to approximately one one-hundredth or less of what it is for 3G systems. This fact is derived from the usage scenarios that have been suggested for 4G. Users are not going to be downloading huge files at 20 mbps rates on a regular basis if the cost per megabit or second of access time does not drop to reasonable values. In summary, it is felt by many that mobile telecommunications will experience the fastest and largest growth of any of the telecommunications sectors. Whether the next wireless generation (3G) is soon superceded by a fourth wireless generation or these predictions are a decade or more in the future is going to play out as dictated by the marketplace and the public's future demand for these types of services. It will be interesting to watch.

13.4 IEEE 802.20/MOBILE BROADBAND WIRELESS ACCESS

In Chapter 2 a brief overview of the new IEEE 802.20 initiative was also provided. This new project is concerned with the delivery of mobile broadband wireless access in the licensed frequency bands in the range of 450 MHz to 3 GHz and supports vehicular speeds of up to 250 km/hour (approximately 200 mph). At the first formal meeting about this project, there were over 100 organizations represented, with many of the major wireless systems equipment manufactures and semiconductor vendors present. According to the 802.20 working group, the deployment of a broadband wireless access infrastructure, based on IP mobility, has a market that consists of all Internet users. Apparently, the rationale for pursuing this project is that the IEEE 802 group had no project that was addressing the support of vehicular mobility at speeds greater than 5 mph or less than 200 mph. Therefore, the project's goal is to support mobile wireless MAN access at vehicular speeds.

This IEEE 802 project is in its early stages so there is not much information available yet about system details. The use of FDD and TDD channel structures and data rates that may be allocated on a flexible and adaptive basis as allowed by the IEEE 802.16 standard seem to be the early target of the working group. The proposed system will rely on IP and OFDM technologies (for NLOS interference mitigation) with inter-metro roaming supported. Where this initiative will lead is anyone's guess since the 3GPP and 3GPP2 partnerships have already been working on some of the issues addressed by 802.20. As discussed in

Chapter 11, sometimes the work of one IEEE group is rolled into the work of another group. However, in this case, this might be an opportunity for the IEEE 802 standards groups and the cellular industry to find some common ground. Historically, the IEEE 802 groups have dealt with systems that transfer data over computer networks (i.e., LANs, MANs, PANs, and WANs) whereas the cellular industry started with simple voice services and is rapidly morphing into a MAN/WAN data delivery service provider and possibly in the near future a LAN (via 3G/WLAN integration) data delivery provider.

My prediction for this project is that it will start to bring together two industries that are going to eventually merge into one. Will it end up in an adopted standard? That is anyone's guess. At the present time, there is not enough history to give one a feel for where the project is headed. As always, time will tell. The interested reader should visit the IEEE 802.20 Web site by going to www.ieee.org and following the links under Standards, 802 Std. Info, IEEE 802 Working Group & Executive Committee Study Group Home Pages, and 802.20. This Web site will provide more information about the IEEE 802.20 project.

13.5 SATELLITE VENTURES AND OTHER FUTURE POSSIBILITIES

During the mid to late 1990s, the telecommunications boom was at its peak and many innovative schemes were put forward to supply broadband connectivity. Among these schemes was Bill Gates' "Internet in the sky" satellite system. Up until that time, the vast majority of communications satellite systems relied upon geostationary earth orbit (GEO) satellites to deliver signals to vast regions of the earth's surface. These newly proposed systems would make use of constellations of either **low earth orbit (LEO) satellites** or **medium earth orbit (MEO) satellite** systems to eliminate the delay time inherent with geosynchronous systems. Broadband Internet access via satellite is particularly attractive to remote rural areas of the United States and other countries that have very little installed telecommunications infrastructure. However, as time has passed, the deployment dates for some of the higher-profile proposed systems have been pushed back not once but several times and are now years behind their initial originally scheduled start-up dates. This fact coupled with the financial problems experienced by other telecommunications satellite start-up ventures like Globalstar and Iridium have led many, including this author, to doubt whether this type of delivery system has much of a future as a major player in the delivery of broadband access. With this in mind, this section will not concentrate on the details of satellite technology but instead will focus more on some of the regulatory issues affecting it and the long-term outlook for its success.

In fairly recent rulings during the late 1990s, the FCC authorized mobile satellite service (MSS) in the 2-GHz band (this was in addition to already allocated spectrum in L band at 1.6 GHz) and at approximately 2.5 GHz. In one case, a satellite system operator proposed a system to the FCC in 2001 that consisted of sixty-four nongeostationary satellites and four geostationary satellites. As was its customary practice, the FCC set milestone dates for the construction of the system. In this instance, the company was unable to comply with these dates due to financial problems. The net result was the dismissal of the proposal and a loss of the MSS license. This does not mean that other proposed systems will not be built and eventually become operational; however, it certainly does not put a positive light on the situation. Also, the FCC originally allocated the 1990–2025 MHz and the 2165–2200 MHz bands for 2-GHz MSS operation. Since this first frequency allocation, the FCC has reallocated both the amount of spectrum for MSS and the frequency ranges to be used. One of the reasons for this action was to accommodate advanced wireless services (AWS) with its own band and to align the United States' frequency allocations with the international community. One of the most recent rulings by the FCC about MSS is that operators of this service could integrate an ancillary terrestrial component into their MSS networks using the frequency bands allocated to MSS. This ruling is in conformance with the FCC's stance to bring broadband wireless access to rural America.

Today, it is possible to get unidirectional or asymmetric two-way Internet access from a geostationary satellite system (see www.direcway.com). However, whether additional satellite service providers will enter this field and actually launch their own LEOS or MEOS systems remains to be seen. Certainly, for the most remote locations most all of these future systems will be able to provide high-speed Internet access and some systems might even service niche markets like the airline industry (i.e., Internet in-the-air service). Again, any predictions of the future are risky and in the case of a technology that has a very high-start-up cost the risk factor is already high. Eventually, satellite technology will be but one part of the telecommunications network infrastructure that will surround this planet. However, that day is sometime off in the future!

QUESTIONS AND PROBLEMS

1. What are location-based services?
2. How does use of the Global Positioning System fit into future wireless systems and applications?
3. Describe the basic concept of cognitive radio technology.
4. Contrast cognitive radio technology with software defined radio technology.
5. What is the most important aspect/ advantage of cognitive radio technology?
6. Why would cognitive radio technology be particularly useful in rural areas?
7. Describe the basic concept behind the operation of MIMO wireless.
8. What are the basic advantages that MIMO wireless can provide?
9. Describe the basic concept of ultra-wideband radio transmission technology.
10. Describe the basic concept of wireless transmission using free space optics.
11. If the integration of WLAN and 3G networks occurs, what technology will deliver voice traffic over the WLAN?
12. Of what use are "mesh" and "multihop" wireless technology?
13. What is the basic transmission technology employed by push-to-talk technology?
14. What additional system elements are needed to support push-to-talk operation?
15. Describe the basic concept of a wireless sensor network.
16. Describe the basic characteristics of a 4G wireless network.
17. What is the average data transfer rate expected to be for 4G wireless networks?
18. What is the basic purpose of the IEEE 802.20 initiative?
19. Contrast the IEEE 802.20 initiative with the IEEE 802.16e project.
20. Describe the concept behind the operation of a LEOS system that can be used to deliver high-speed Internet access.

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