Design, Testing of WiMAX Internet System in an Outdoor Environment.

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Abstract

WiMAX, meaning *Worldwide Interoperability for Microwave Access*, is a wireless digital communications system, also known as IEEE 802.16 that is intended for wireless "metropolitan area networks". It is a telecommunications technology that provides for the wireless transmission of data using a variety of transmission modes, from point-to-point links to portable internet access. The technology provides up to 75 Mb/sec symmetric broadband speeds without the need for cables. WiMAX can provide broadband wireless access (BWA) up to 30 miles (50 km) for fixed stations, and 3 - 10 miles (5 - 15 km) for mobile stations. In contrast, the WiFi/802.11 wireless local area network standard is limited in most cases to only 100 - 300 feet (30 - 100m). Soon, WiMAX will be a very well recognized term to describe wireless Internet access throughout the world. In Bangladesh, this technology is going to be deployed very shortly. A network planning is required for its successful deployment. In our work we have proposed a network planning for both fixed and nomadic WiMAX deployment for Dhaka. Considering this metropolitan city, we have attempted to give the specification of the parameters to make it cost effective with best performance. As the software that is used for this purpose is expensive and unavailable, we have done it manually only from the perspective of access network and transmission network. The work can be extended to do the planning for the whole country. By using the network simulator software we are looking forward to examine the planning and the set values parameters in your future work.

Table of Contents

Overview of WiMAX

Background on IEEE 802.16 and WiMAX

The IEEE 802.16 group was formed in 1998 to develop an air-interface standard for wireless broadband. The group's initial focus was the development of a LOS-based point-to multipoint wireless broadband system for operation in the 10GHz–66GHz millimeter wave band. The resulting standard—the original 802.16 standard, completed in December 2001—was based on a single-carrier physical (PHY) layer with a burst time division multiplexed (TDM) MAC layer. Many of the concepts related to the MAC layer were adapted for wireless from the popular cable modem DOCSIS (data over cable service interface specification) standard.

The IEEE 802.16 group subsequently produced 802.16a, an amendment to the standard, to include NLOS applications in the 2GHz–11GHz band, using an *orthogonal frequency division multiplexing* (OFDM)-based physical layer. Additions to the MAC layer, such as support for *orthogonal frequency division multiple access* (OFDMA), were also included. Further revisions resulted in a new standard in 2004, called IEEE 802.16-2004, which replaced all prior versions and formed the basis for the first WiMAX solution. These early WiMAX solutions based on IEEE 802.16-2004 targeted fixed applications, and will refer to these as fixed WiMAX [1]. In December 2005, the IEEE group completed and approved IFEEE 802.16e-2005, an amendment to the IEEE 802.16-2004 standard that added mobility support. The IEEE 802.16e-2005 forms the basis for the WiMAX solution for nomadic and mobile applications and is often referred to as mobile WiMAX [2].

The basic characteristics of the various IEEE 802.16 standards are summarized in Table 2.1. Note that these standards offer a variety of fundamentally different design options. For example, there are multiple physical-layer choices: a single-carrier-based physical layer called Wireless-MAN-SCa, an OFDM-based physical layer called Wireless MAN-OFDM, and an OFDMA based physical layer called Wireless-OFDMA. Similarly, there are multiple choices for MAC architecture, duplexing, frequency band of operation, etc. These standards were developed to suit a variety of applications and deployment scenarios, and hence offer a plethora of design choices for system developers. In fact, one could say that IEEE 802.16 is a collection of standards, not one single interoperable standard.

For practical reasons of interoperability, the scope of the standard needs to be reduced, and a smaller set of design choices for implementation need to be defined. The WiMAX Forum does this by defining a limited number of system profiles and certification profiles. A *system profile* defines the subset of mandatory and optional physical- and MAC-layer features selected by the WiMAX Forum from the IEEE 802.16-2004 or IEEE 802.16e-2005 standard. It should be noted that the mandatory and optional status of a particular feature within a WiMAX system profile may be different from what it is in the original IEEE standard. Currently, the WiMAX Forum has two different system profiles: one based on IEEE 802.16-2004, OFDM PHY, called the fixed system profile; the other one based on IEEE 802.16e-2005 scalable OFDMA PHY, called the mobility system profile. A *certification profile* is defined as a particular instantiation of a system profile where the operating frequency, channel bandwidth, and duplexing mode are also specified. WiMAX equipment are certified for interoperability against a particular certification profile.

The WiMAX Forum has thus far defined five fixed certification profiles and fourteen mobility certification profiles (see Table 2.2). To date, there are two fixed WiMAX profiles against which equipment have been certified. These are 3.5GHz systems operating over a 3.5MHz channel, using the fixed system profile based on the IEEE 802.16-2004 OFDM physical layer with a point-to-multipoint MAC. One of the profiles uses frequency division duplexing (FDD), and the other uses time division duplexing (TDD).

	802.16	**802.16-2004**	**802.16e-2005**
Status	Completed December 2001	Completed June 2004	Completed December 2005
Frequency band	10GHz–66GHz	2GHz–11GHz	2GHz–11GHz for fixed; 2GHz–6GHz for mobile applications

Application	Fixed LOS	Fixed NLOS	Fixed and mobile NLOS
MAC architec- ture	Point-to-multipoint, mesh	Point-to-multipoint, mesh	Point-to-multipoint, mesh
Transmission scheme	Single carrier only	Single carrier, 256 OFDM or 2,048 OFDM	Single carrier, 256 OFDM or scalable OFDM with 128, 512, 1,024, or 2,048 subcarriers
Modulation	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM	QPSK, 16 QAM, 64 QAM
Gross data rate	32Mbps–134.4Mbps	1Mbps–75Mbps	1Mbps–75Mbps
Multiplexing	Burst TDM/TDMA	Burst TDM/TDMA/ OFDMA	Burst TDM/TDMA/ OFDMA
Duplexing	TDD and FDD	TDD and FDD	TDD and FDD
		1.75MHz, 3.5MHz,	
Channel band-widths	20MHz, 25MHz, 28MHz	7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz	1.75MHz, 3.5MHz, 7MHz, 14MHz, 1.25MHz, 5MHz, 10MHz, 15MHz, 8.75MHz
Air-interface designation	WirelessMAN-SC	WirelessMAN-SCa WirelessMAN-OFDM WirelessMAN-OFDMA WirelessHUMANa	WirelessMAN-SC WirelessMAN-OFDM WirelessMAN-OFDMA WirelessHUMANa
WiMAX implementati on	None	256 - OFDM as Fixed WiMAX	Scalable OFDMA as Mobile WiMAX

Table 2.1 Basic Data on IEEE 802.16 Standards

Band Index	Frequency Band	Channel Bandwidth	OFDM FFT Size	Duplexing	Notes
		Fixed WiMAX Profiles			
1	3.5 GHz	3.5MHz	256	FDD	Products already certified
		3.5MHz	256	TDD	
		7MHz	256	FDD	
		7MHz	256	TDD	
2	5.8GHz	10MHz	256	TDD	
		Mobile WiMAX Profiles			
1	2.3GHz–2.4GHz	5MHz	512	TDD	Both bandwidths must be sup-ported by mobile station (MS)
		10MHz	1,024	TDD	
		8.75MHz	1,024	TDD	
2	2.305GHz–2.320GHz, 2.345GHz–2.360GHz	3.5MHz	512	TDD	
		5MHz	512	TDD	
		10MHz	1,024	TDD	
3	2.496GHz–2.69GHz	5MHz	512	TDD	Both bandwidths must be sup-ported by mobile station (MS)
		10MHz	1,024	TDD	
4	3.3GHz–3.4GHz	5MHz	512	TDD	
		7MHz	1,024	TDD	
		10MHz	1,024	TDD	
5	3.4GHz–3.8GHz, 3.4GHz–3.6GHz, 3.6GHz–3.8GHz	5MHz	512	TDD	
		7MHz	1,024	TDD	
		10MHz	1,024	TDD	

Table 2.2 Fixed and Mobile WiMAX Initial Certification Profiles

With the completion of the IEEE 802.16e-2005 standard, interest within the WiMAX group has shifted sharply toward developing and certifying mobile WiMAX1 system profiles based on this newer standard. All mobile WiMAX profiles use scalable OFDMA as the physical layer. At least initially, all mobility profiles will use a point-to-multipoint MAC. It should also be noted that all the current candidate mobility certification profiles are TDD based. Although TDD is often preferred, FDD profiles may be needed for in the future to comply with regulatory pairing requirements in certain bands

For the reminder of this chapter, focused solely on WiMAX and therefore discuss only aspects of IEEE 802.16 family of standards that may be relevant to current and future WiMAX certification. It should be noted that the IEEE 802.16e-2004 and IEEE 802.16-2005 standards specifications are limited to the control and data plane aspects of the air-interface. Some aspects of network management are defined in IEEE 802.16g. For a complete end-to-end system, particularly in the context of mobility, several additional end-to-end service management aspects need to be specified. This task is being performed by the WiMAX Forums Network Working Group (NWG). The WiMAX NWG is developing an end-to-end network architecture and filling in some of the missing pieces. The end-to-end architecture is covered in Section 2.6.

Salient Features of WiMAX

WiMAX is a wireless broadband solution that offers a rich set of features with a lot of flexibility in terms of deployment options and potential service offerings. Some of the more salient features that deserve highlighting are as follows:

- **OFDM-based physical layer:**

The WiMAX physical layer (PHY) is based on orthogonal frequency division multiplexing, a scheme that offers good resistance to multipath, and allows WiMAX to operate in NLOS conditions. OFDM is now widely recognized as the method of choice for mitigating multipath for broadband wireless. Chapter 4 provides a detailed overview of OFDM.

Very high peak data rates:

WiMAX is capable of supporting very high peak data rates. In fact, the peak PHY data rate can be as high as 74Mbps when operating using a 20MHz2 wide spectrum. More typically, using a 10MHz spectrum operating using TDD scheme with a 3:1 downlink-to-uplink ratio, the peak PHY data rate is about 25Mbps and 6.7Mbps for the downlink and the uplink, respectively. These peak PHY data rates are achieved when using 64 QAM modulation with rate 5/6 error-correction coding. Under very good signal conditions, even higher peak rates may be achieved using multiple antennas and spatial multiplexing.

- **Scalable bandwidth and data rate support:**

WiMAX has a scalable physical-layer architecture that allows for the data rate to scale easily with available channel bandwidth. This scalability is supported in the OFDMA mode, where the FFT (fast fourier transform) size may be scaled based on the available channel bandwidth. For example, a WiMAX system may use 128-, 512-, or 1,048-bit FFTs based on whether the channel bandwidth is 1.25MHz, 5MHz, or 10MHz, respectively. This scaling may be done dynamically to support user roaming across different networks that may have different bandwidth allocations.

- **Adaptive modulation and coding (AMC):**

WiMAX supports a number of modulation and forward error correction (FEC) coding schemes and allows the scheme to be changed on a per user and per frame basis, based on channel conditions. AMC is an effective mechanism to maximize throughput in a time-varying channel. The adaptation algorithm typically calls for the use of the highest modulation and coding scheme that can be supported by the signal-to-noise and interference ratio at the receiver such that each user is provided with the highest possible data rate that can be supported in their respective links.

- **Link-layer retransmissions**:

For connections that require enhanced reliability, WiMAX supports automatic retransmission requests (ARQ) at the link layer. ARQ-enabled connections require each transmitted packet to be acknowledged by the receiver; unacknowledged packets are assumed to be lost and are retransmitted. WiMAX also optionally supports hybrid-ARQ, which is an effective hybrid between FEC and ARQ.

- **Support for TDD and FDD:**

IEEE 802.16-2004 and IEEE 802.16e-2005 supports both time division duplexing and frequency division duplexing, as well as a half-duplex FDD, which allows for a low-cost system implementation. TDD is favored by a majority of implementations because of its advantages: (1) flexibility in choosing uplink-to-downlink data rate ratios, (2) ability to exploit channel reciprocity, (3) ability to implement in non paired spectrum, and (4) less complex transceiver design. All the initial WiMAX profiles are based on TDD, except for two fixed WiMAX profiles in 3.5GHz.

- **Orthogonal frequency division multiple access (OFDMA):**

Mobile WiMAX uses OFDM as a multiple-access technique, whereby different users can be allocated different subsets of the OFDM tones. As discussed in detail in Chapter 6, OFDMA facilitates the exploitation of frequency diversity and multiuser diversity to significantly improve the system capacity.

- **Flexible and dynamic per user resource allocation:**

Both uplink and downlink resource allocation are controlled by a scheduler in the base station. Capacity is shared among multiple users on a demand basis, using a burst TDM scheme. When using the OFDMA-PHY mode, multiplexing is additionally done in the frequency dimension, by allocating different subsets of OFDM subcarriers to different users. Resources may be allocated in the spatial domain as well when using the optional advanced antenna systems (AAS). The standard allows for bandwidth resources to be allocated in time, frequency, and space and has a flexible mechanism to convey the resource allocation information on a frame-by-frame basis.

- **Support for advanced antenna techniques:**

The WiMAX solution has a number of hooks built into the physical-layer design, which allows for the use of multiple-antenna techniques, such as beam forming, space-time coding, and spatial multiplexing. These schemes can be used to improve the overall system capacity and spectral efficiency by deploying multiple antennas at the transmitter and/or the receiver. Chapter 5 presents detailed overview of the various multiple antenna techniques.

- **Quality-of-service support:**

The WiMAX MAC layer has a connection-oriented architecture that is designed to support a variety of applications, including voice and multimedia services. The system offers support for constant bit rate, variable bit rate, real-time, and non-real-time traffic flows, in addition to best-effort data traffic. WiMAX MAC is designed to support a large number of users, with multiple connections per terminal, each with its own QoS requirement.

- **Robust security:**

WiMAX supports strong encryption, using Advanced Encryption Standard (AES), and has a robust privacy and key-management protocol. The system also offers a very flexible authentication architecture based on Extensible Authentication Protocol (EAP), which allows for a variety of user credentials, including username/password, digital certificates, and smart cards.

- **Support for mobility**:

The mobile WiMAX variant of the system has mechanisms to support secure seamless handovers for delay-tolerant full-mobility applications, such as VoIP. The system also has built-in support for power-saving mechanisms that extend the battery life of handheld subscriber devices. Physical-layer enhancements, such as more frequent channel estimation, uplink subchannelization, and power control, are also specified in support of mobile applications.

- **IP-based architecture:**

The WiMAX Forum has defined a reference network architecture that is based on an all-IP platform. All end-to-end services are delivered over an IP architecture relying on IP-based protocols for end-to-end transport, QoS, session management, security, and mobility. Reliance on IP allows WiMAX to ride the declining cost curves of IP processing, facilitate easy convergence with other networks, and exploit the rich ecosystem for application development that exists for IP.

WiMAX Physical Layer

The WiMAX physical layer is based on orthogonal frequency division multiplexing. OFDM is the transmission scheme of choice to enable high-speed data, video, and multimedia communications and is used by a variety of commercial broadband systems, including DSL, Wi-Fi, Digital Video Broadcast-Handheld (DVB-H), and Media FLO, besides WiMAX. OFDM is an elegant and efficient scheme for high data rate transmission in a non-line-of-sight or multipath radio environment. In this section, the basics of OFDM and an overview of the WiMAX physical layer is covered. Chapter 6 provides a more detailed discussion of the WiMAX PHY.

Adaptive Modulation and Coding in WiMAX

WiMAX supports a variety of modulation and coding schemes and allows for the scheme to change on a burst-by-burst basis per link, depending on channel conditions. Using the channel quality feedback indicator, the mobile can provide the base station with feedback on the downlink channel quality. For the uplink, the base station can estimate the channel quality, based on the received signal quality. The base station scheduler can take into account the channel quality of each user's uplink and downlink and assign a modulation and coding scheme that maximizes the throughput for the available signal-to-noise ratio.

Adaptive modulation and coding significantly increases the overall system capacity, as it allows real-time trade-off between throughput and robustness on each link.. In the downlink, QPSK, 16 QAM, and 64 QAM are mandatory for both fixed and mobile WiMAX; 64 QAM is optional in the uplink. FEC coding using convolutional codes is mandatory. Convolutional codes are combined with an outer Reed-Solomon code in the downlink for OFDM-PHY. The standard optionally supports turbo codes and low-density parity check (LDPC) codes at a variety of code rates as well. A total of 52 combinations of modulation and coding schemes are defined in WiMAX as burst profiles. More details on burst profiles are provided in Chapter 8.

PHY-Layer Data Rates

Because the physical layer of WiMAX is quite flexible, data rate performance varies based on the operating parameters. Parameters that have a significant impact on the physical-layer data rate are channel bandwidth and the modulation and coding scheme used. Other parameters, such as number of sub channels, OFDM guard time, and oversampling rate, also have an impact.

Table 2.5 lists the PHY-layer data rate at various channel bandwidths, as well as modulation and coding schemes. The rates shown are the aggregate physical-layer data rate that is shared among all users in the sector for the TDD case, assuming a 3:1 downlink-to-uplink bandwidth ratio. The calculations here assume a frame size of 5 ms, a 12.5 percent OFDM guard interval overhead, and a PUSC subcarrier permutation scheme. It is also assumed that all usable OFDM data symbols are available for user traffic except one symbol used for downlink frame overhead. The numbers shown here do not assume spatial multiplexing using multiple antennas at the transmitter or the receiver, the use of which can further increase the peak rates in rich multipath channels.

	Downlink	**Uplink**
Modulation	BPSK, QPSK, 16 QAM, 64 QAM; BPSK optional for OFDMA-PHY	BPSK, QPSK, 16 QAM; 64 QAM optional
Coding	Mandatory: convolutional codes at rate1/2, 2/3, 3/4, 5/6 Optional: convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6: repetition codes at rate 1/2, 1/3, 1/6, LDPC, RS-Codes for OFDM-PHY	Mandatory: convolutional codes at rate 1/2, 2/3, 3/4, 5/6 Optional: convolutional turbo codes at rate 1/2, 2/3, 3/4, 5/6: repetition codes at rate 1/2, 1/3, 1/6, LDPC.

Table 2.4 PHY-Layer Data Rate at Various Channel Bandwidths

Channel bandwidth	3.5MHz		1.25MHz		5MHz		10MHz		**8.75MHza**	
PHY mode	256 OFDM		128 OFDMA		512 OFDMA		1,024 OFDMA		1,024 OFDMA	
Oversampling	8/7		28/25		28/25		28/25		28/25	
Modulation and Code Rate	**PHY-Layer Data Rate (kbps)**									
	DL	UL	DL	UL	DL	UL	DL	UL	DL	UL
BPSK, 1/2	946	326	**Not applicable**							
QPSK, 1/2	1,882	653	504	154	2,520	653	5,040	1,344	4,464	1,120
QPSK, 3/4	2,822	979	756	230	3,780	979	7,560	2,016	6,696	1,680
16 QAM, 1/2	3,763	1,306	1,008	307	5,040	1,306	10,080	2,688	8,928	2,240
16 QAM, 3/4	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032	13,392	3,360
64 QAM, 1/2	5,645	1,958	1,512	461	7,560	1,958	15,120	4,032	13,392	3,360
64 QAM, 2/3	7,526	2,611	2,016	614	10,080	2,611	20,160	5,376	17,856	4,480
64 QAM, 3/4	8,467	2,938	2,268	691	11,340	2,938	22,680	6,048	20,088	5,040
64 QAM, 5/6	9,408	3,264	2,520	768	12,600	3,264	25,200	6,720	22,320	5,600

Table 2.5 PHY-Layer Data Rate at Various Channel Bandwidths

MAC-Layer Overview

The primary task of the WiMAX MAC layer is to provide an interface between the higher transport layers and the physical layer. The MAC layer takes packets from the upper layer—these packets are called *MAC service data units* (MSDUs)—and organize them into *MAC protocol data units* (MPDUs) for transmission over the air. For received transmissions, the MAC layer does the reverse. The IEEE 802.16-2004 and IEEE 802.16e-2005 MAC design includes a *convergence sub layer* that can interface with a variety of higher-layer protocols, such as ATM, TDM Voice, Ethernet, IP, and any unknown future protocol. Given the predominance of IP and Ethernet in the industry, the WiMAX Forum has decided to support only IP and Ethernet at this time. Besides providing a mapping to and from the higher layers, the convergence sub layer supports MSDU header suppression to reduce the higher layer overheads on each packet.

The WiMAX MAC is designed from the ground up to support very high peak bit rates while delivering quality of service similar to that of ATM and DOCSIS. The WiMAX MAC uses a variable-length MPDU and offers a lot of flexibility to allow for their efficient transmission. For example, multiple MPDUs of same or different lengths may be aggregated into a single burst to save PHY overhead. Similarly, multiple MSDUs from the same higher-layer service may be concatenated into a single MPDU to save MAC header overhead. Conversely, large MSDUs may be fragmented into smaller MPDUs and sent across multiple frames.

Figure 2.2 shows examples of various MAC PDU (packet data unit) frames. Each MAC frame is prefixed with a generic MAC header (GMH) that contains a connection identifier8 (CID), the length of frame, and bits to qualify the presence of CRC, subheaders, and whether the payload is encrypted and if so, with which key. The MAC payload is either a transport or a management message. Besides MSDUs, the transport payload may contain bandwidth requests or retransmission requests. The type of transport payload is identified by the sub header that immediately precedes it. Examples of sub headers are packing sub headers and fragmentation sub headers. WiMAX MAC also supports ARQ, which can be used to request the retransmission of unfragmented MSDUs and fragments of MSDUs. The maximum frame length is 2,047 bytes, which is represented by 11 bits in the GMH.

Channel-Access Mechanisms

In WiMAX, the MAC layer at the base station is fully responsible for allocating bandwidth to all users, in both the uplink and the downlink. The only time the MS has some control over bandwidth allocation is when it has multiple sessions or connections with the BS. In that case, the BS allocates bandwidth to the MS in the aggregate, and it is up to the MS to apportion it among the multiple connections. All other scheduling on the downlink *and* uplink is done by the BS. For the downlink, the BS can allocate bandwidth to each MS, based on the needs of the incoming traffic, without involving the MS. For the uplink, allocations have to be based on requests from the MS.

The WiMAX standard supports several mechanisms by which an MS can request and obtain uplink bandwidth. Depending on the particular QoS and traffic parameters associated with a service, one or more of these mechanisms may be used by the MS. The BS allocates dedicated or shared resources periodically to each MS, which it can use to request bandwidth. This process is called *polling*. Polling may be done either individually (unicast) or in groups (multicast). Multicast polling is done when there is insufficient bandwidth to poll each MS individually. When polling is done in multicast, the allocated slot for making bandwidth requests is a shared slot, which every polled MS attempts to use. WiMAX defines a contention access and resolution mechanism for the case when more than one MS attempts to use the shared slot. If it already has an allocation for sending traffic, the MS is not polled. Instead, it is allowed to request more bandwidth by (1) transmitting a stand-alone bandwidth request MPDU, (2) sending a bandwidth request using the ranging channel, or (3) piggybacking a bandwidth request on generic MAC packets.

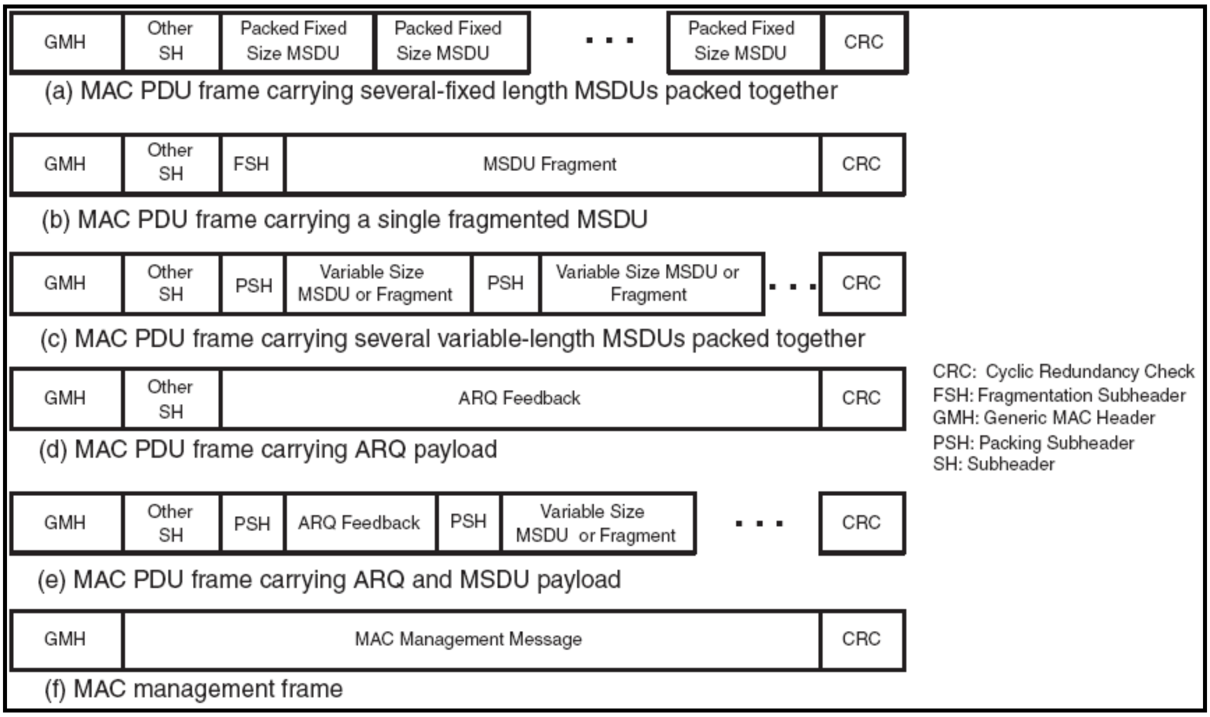


Figure 2.2 Examples of various MAC PDU frames

Quality of Service

Support for QoS is a fundamental part of the WiMAX MAC-layer design. WiMAX borrows some of the basic ideas behind its QoS design from the DOCSIS cable modem standard. Strong QoS control is achieved by using a connection-oriented MAC architecture, where all downlink and uplink connections are controlled by the serving BS. Before any data transmission happens, the BS and the MS establish a unidirectional logical link, called a *connection,* between the two MAC-layer peers. Each connection is identified by a *connection identifier* (CID), which serves as a temporary address for data transmissions over the particular link. In addition to connections for transferring user data, the WiMAX MAC defines three management connections—the basic, primary, and secondary connections—that are used for such functions as ranging.

WiMAX also defines a concept of a service flow. A *service flow* is a unidirectional flow of packets with a particular set of QoS parameters and is identified by a *service flow identifier* (SFID). The QoS parameters could include traffic priority, maximum sustained traffic rate, maximum burst rate, minimum tolerable rate, scheduling type, ARQ type, maximum delay, tolerated jitter, service data unit type and size, bandwidth request mechanism to be used, transmission PDU formation rules, and so on. Service flows may be provisioned through a network management system or created dynamically through defined signaling mechanisms in the standard. The base station is responsible for issuing the SFID and mapping it to unique CIDs. Service flows can also be mapped to DiffServ code points or MPLS flow labels to enable end-to-end IP-based QoS.

To support a wide variety of applications, WiMAX defines five scheduling services (Table 2.6) that should be supported by the base station MAC scheduler for data transport over a connection:

1. Unsolicited grant services (UGS): This is designed to support fixed-size data packets at a constant bit rate (CBR). Examples of applications that may use this service are T1/E1 emulation and VoIP without silence suppression. The mandatory service flow parameters that define this service are maximum sustained traffic rate, maximum latency, tolerated jitter, and request/transmission policy.9
2. Real-time polling services (rtPS): This service is designed to support real-time service flows, such as MPEG video, that generate variable-size data packets on a periodic basis. The mandatory service flow parameters that define this service are minimum reserved traffic rate, maximum sustained traffic rate, maximum latency, and request/transmission policy.
3. Non-real-time polling service (nrtPS): This service is designed to support delay-tolerant data streams, such as an FTP, that require variable-size data grants at a minimum guaranteed rate. The mandatory service flow parameters to define this service are minimum reserved traffic rate, maximum sustained traffic rate, traffic priority, and request/transmission policy.
4. Best-effort (BE) service: This service is designed to support data streams, such as Web browsing, that do not require a minimum service-level guarantee. The mandatory service flow parameters to define this service are maximum sustained traffic rate, traffic priority, and request/transmission policy.
5. Extended real-time variable rate (ERT-VR) service: This service is designed to support real-time applications, such as VoIP with silence suppression, that have variable data rates but require guaranteed data rate and delay. This service is defined only in IEEE 802.16e-2005, not in IEEE 802.16-2004. This is also referred to as extended real-time polling service (ErtPS).

Although it does not define the scheduler per se, WiMAX does define several parameters and features that facilitate the implementation of an effective scheduler:

- Support for a detailed parametric definition of QoS requirements and a variety of mechanisms to effectively signal traffic conditions and detailed QoS requirements in the uplink.
- Support for three-dimensional dynamic resource allocation in the MAC layer. Resources can be allocated in time (time slots), frequency (subcarriers), and space (multiple antennas) on a frame-by-frame basis.
- Support for fast channel-quality information feedback to enable the scheduler to select the appropriate coding and modulation (burst profile) for each allocation.
- Support for contiguous subcarrier permutations, such as AMC, that allow the scheduler to exploit multiuser diversity by allocating each subscriber to its corresponding strongest sub channel.

Service Flow Designation	**Defining QoS Parameters**	**Application Examples**
Unsolicited grant services (UGS)	Maximum sustained rate Maximum latency tolerance Jitter tolerance	Voice over IP (VoIP) without silence suppression
Real-time Polling service (rtPS)	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Traffic priority	Streaming audio and video, MPEG (Motion Picture Experts Group) encoded
Non-real-time Polling service (nrtPS)	Minimum reserved rate Maximum sustained rate Traffic priority	File Transfer Protocol (FTP)
Best-effort service (BE)	Maximum sustained rate Traffic priority	Web browsing, data transfer
Extended real-time Polling service (ErtPS)	Minimum reserved rate Maximum sustained rate Maximum latency tolerance Jitter tolerance Traffic priority	VoIP with silence suppression

Table 2.6 Service Flows Supported in WiMAX

It should be noted that the implementation of an effective scheduler is critical to the overall capacity and performance of a WiMAX system.

Power-Saving Features

To support battery-operated portable devices, mobile WiMAX has power-saving features that allow portable subscriber stations to operate for longer durations without having to recharge. Power saving is achieved by turning off parts of the MS in a controlled manner when it is not actively transmitting or receiving data. Mobile WiMAX defines signaling methods that allow the MS to retreat into a sleep mode or idle mode when inactive. Sleep mode is a state in which the MS effectively turns itself off and becomes unavailable for predetermined periods. The periods of absence are negotiated with the serving BS. WiMAX defines three power-saving classes, based on the manner in which sleep mode is executed. When in Power Save Class 1 mode, the sleep window is exponentially increased from a minimum value to a maximum value. This is typically done when the MS is doing best-effort and non-real-time traffic. Power Save Class 2 has a fixed-length sleep window and is used for UGS service. Power Save Class 3 allows for a one-time sleep window and is typically used for multicast traffic or management traffic when the MS knows when the next traffic is expected. In addition to minimizing MS power consumption, sleep mode conserves BS radio resources. To facilitate handoff while in sleep mode, the MS is allowed to scan other base stations to collect handoff-related information.

Idle mode allows even greater power savings, and support for it is optional in WiMAX. Idle mode allows the MS to completely turn off and to not be registered with any BS and yet receive downlink broadcast traffic. When downlink traffic arrives for the idle-mode MS, the MS is paged by a collection of base stations that form a paging group. The MS is assigned to a paging group by the BS before going into idle mode, and the MS periodically wakes up to update its paging group. Idle mode saves more power than sleep mode, since the MS does not even have to register or do handoffs. Idle mode also benefits the network and BS by eliminating handover traffic from inactive MSs.

Mobility Support

In addition to fixed broadband access, WiMAX envisions four mobility-related usage scenarios:

1. Nomadic. The user is allowed to take a fixed subscriber station and reconnect from a different point of attachment.
2. Portable. Nomadic access is provided to a portable device, such as a PC card, with expectation of a best-effort handover.
3. Simple mobility. The subscriber may move at speeds up to 60 kmph with brief interruptions (less than 1 sec) during handoff.
4. Full mobility: Up to 120 kmph mobility and seamless handoff (less than 50 ms latency and <1% packet loss) is supported.

It is likely that WiMAX networks will initially be deployed for fixed and nomadic applications and then evolves to support portability to full mobility over time.

The IEEE 802.16e-2005 standard defines a framework for supporting mobility management. In particular, the standard defines signaling mechanisms for tracking subscriber stations as they move from the coverage range of one base station to another when active or as they move from one paging group to another when idle. The standard also has protocols to enable a seamless handover of ongoing connections from one base station to another. The WiMAX Forum has used the framework defined in IEEE 802.16e-2005 to further develop mobility management within an end-to-end network architecture framework. The architecture also supports IP-layer mobility using mobile IP.

Three handoff methods are supported in IEEE 802.16e-2005; one is mandatory and other two are optional. The mandatory handoff method is called the *hard handover* (HHO) and is the only type required to be implemented by mobile WiMAX initially. HHO implies an abrupt transfer of connection from one BS to another. The handoff decisions are made by the BS, MS, or another entity, based on measurement results reported by the MS. The MS periodically does a radio frequency (RF) scan and measures the signal quality of neighboring base stations. Scanning is performed during *scanning intervals* allocated by the BS. During these intervals, the MS is also allowed to optionally perform initial ranging and to associate with one or more neighboring base stations. Once a handover decision is made, the MS begins synchronization with the downlink transmission of the target BS, performs ranging if it was not done while scanning, and then terminates the connection with the previous BS. Any undelivered MPDUs at the BS are retained until a timer expires.

The two optional handoff methods supported in IEEE 802.16e-2005 are *fast base station switching* (FBSS) and *macro diversity handover* (MDHO). In these two methods, the MS maintains a valid connection simultaneously with more than one BS. In the FBSS case, the MS maintains a list of the BSs involved, called the *active set*. The MS continuously monitors the active set, does ranging, and maintains a valid connection ID with each of them. The MS, however, communicates with only one BS, called the *anchor BS*. When a change of anchor BS is required, the connection is switched from one base station to another without having to explicitly perform handoff signaling. The MS simply reports the selected anchor BS on the CQICH.

Macro diversity handover is similar to FBSS, except that the MS communicates on the downlink and the uplink with all the base stations in the active set—called a *diversity set* here—simultaneously. In the downlink, multiple copies received at the MS are combined using any of the well-known diversity-combining techniques (see Chapter 5). In the uplink, where the MS sends data to multiple base stations, selection diversity is performed to pick the best uplink.

Both FBSS and MDHO offer superior performance to HHO, but they require that the base stations in the active or diversity set be synchronized, use the same carrier frequency, and share network entry–related information. Support for FBHH and MDHO in WiMAX networks is not fully developed yet and is not part of WiMAX Forum Release 1 network specifications.

Security Functions

Unlike Wi-Fi, WiMAX systems were designed at the outset with robust security in mind. The standard includes state-of-the-art methods for ensuring user data privacy and preventing unauthorized access, with additional protocol optimization for mobility. Security is handled by a privacy sub layer within the WiMAX MAC. The key aspects of WiMAX security are as follow.

- **Support for privacy:**

User data is encrypted using cryptographic schemes of proven robustness to provide privacy. Both AES (Advanced Encryption Standard) and 3DES (Triple Data Encryption Standard) are supported. Most system implementations will likely use AES, as it is the new encryption standard approved as compliant with Federal Information Processing Standard (FIPS) and is easier to implement.10 The 128-bit or 256-bit key used for deriving the cipher is generated during the authentication phase and is periodically refreshed for additional protection.

- **Device/user authentication:**

WiMAX provides a flexible means for authenticating subscriber stations and users to prevent unauthorized use. The authentication framework is based on the Internet Engineering Task Force (IETF) EAP, which supports a variety of credentials, such as username/password, digital certificates, and smart cards. WiMAX terminal devices come with built-in X.509 digital certificates that contain their public key and MAC address. WiMAX operators can use the certificates for device authentication and use a username/password or smart card authentication on top of it for user authentication.

- **Flexible key-management protocol:**

The Privacy and Key Management Protocol Version 2 (PKMv2) is used for securely transferring keying material from the base station to the mobile station, periodically reauthorizing and refreshing the keys. PKM is a client-server protocol: The MS acts as the client; the BS, the server. PKM uses X.509 digital certificates and RSA (Rivest-Shamer-Adleman) public-key encryption algorithms to securely perform key exchanges between the BS and the MS.

- **Protection of control messages:**

The integrity of over-the-air control messages is protected by using message digest schemes, such as AES-based CMAC or MD5-based HMAC.11

- **Support for fast handover:**

To support fast handovers, WiMAX allows the MS to use pre authentication with a particular target BS to facilitate accelerated reentry. A three-way handshake scheme is supported to optimize the re authentication mechanisms for supporting fast handovers, while simultaneously preventing any man-in-the-middle attacks.

Multicast and Broadcast Services

The mobile WiMAX MAC layer has support for multicast and broadcast services (MBS). MBS related functions and features supported in the standard include

- Signaling mechanisms for MS to request and establish MBS
- Subscriber station access to MBS over a single or multiple BS, depending on its capability and desire
- MBS associated QoS and encryption using a globally defined traffic encryption key
- A separate zone within the MAC frame with its own MAP information for MBS traffic
- Methods for delivering MBS traffic to idle-mode subscriber stations
- Support for macro diversity to enhance the delivery performance of MBS traffic

Advanced Features for Performance Enhancements

WiMAX defines a number of optional advanced features for improving the performance. Among the more important of these advanced features are support for multiple-antenna techniques, hybrid-ARQ, and enhanced frequency reuse.

Advanced Antenna Systems

The WiMAX standard provides extensive support for implementing advanced multiantenna solutions to improve system performance. Significant gains in overall system *capacity and spectral* efficiency can be achieved by deploying the optional *advanced antenna systems* (AAS) defined in WiMAX. AAS includes support for a variety of multiantenna solutions, including transmit diversity, beamforming, and spatial multiplexing.

- **Transmit diversity:**

WiMAX defines a number of space-time block coding schemes that can be used to provide transmit diversity in the downlink. For transmit diversity, there could be two or more transmit antennas and one or more receive antennas. The space-time block code (STBC) used for the 2 × 1 antenna case is the Alamouti codes, which are orthogonal and amenable to maximum likelihood detection. The Alamouti STBC is quite easy to implement and offers the same diversity gain as a 1 × 2 receiver diversity with maximum ratio combining, albeit with a 3 dB penalty owing to redundant transmissions. But transmit diversity offers the advantage that the complexity is shifted to the base station, which helps to keep the MS cost low. In addition to the 2 × 1 case, WiMAX also defines STBCs for the three- and four-antenna cases.

- **Beam forming:**

Multiple antennas in WiMAX may also be used to transmit the same signal appropriately weighted for each antenna element such that the effect is to focus the transmitted beam in the direction of the receiver and away from interference, thereby improving the received SINR. Beam forming can provide significant improvement in the coverage range, capacity, and reliability. To perform transmit beam forming, the transmitter needs to have accurate knowledge of the channel, which in the case of TDD is easily available owing to channel reciprocity but for FDD requires a feedback channel to learn the channel characteristics. WiMAX supports beam forming in both the uplink and the downlink. For the uplink, this often takes the form of receive beam forming.

- **Spatial multiplexing:**

WiMAX also supports spatial multiplexing, where multiple independent streams are transmitted across multiple antennas. If the receiver also has multiple antennas, the streams can be separated out using space-time processing. Instead of increasing diversity, multiple antennas in this case are used to increase the data rate or capacity of the system. Assuming a rich multipath environment, the capacity of the system can be increased linearly with the number of antennas when performing spatial multiplexing. A 2 × 2 MIMO system therefore doubles the peak throughput capability of WiMAX. If the mobile station has only one antenna, WiMAX can still support spatial multiplexing by coding across multiple users in the uplink. This is called multiuser collaborative spatial multiplexing. Unlike transmit diversity and beam forming, spatial multiplexing works only under good SINR conditions.

Hybrid-ARQ

Hybrid-ARQ is an ARQ system that is implemented at the physical layer together with FEC, providing improved link performance over traditional ARQ at the cost of increased implementation complexity. The simplest version of H-ARQ is a simple combination of FEC and ARQ, where blocks of data, along with a CRC code, are encoded using an FEC coder before transmission; retransmission is requested if the decoder is unable to correctly decode the received block. When a retransmitted coded block is received, it is combined with the previously detected coded block and fed to the input of the FEC decoder. Combining the two received versions of the code block improves the chances of correctly decoding. This type of H-ARQ is often called type I *chase combining*.

The WiMAX standard supports this by combining an *N*-channel *stop and wait ARQ* along with a variety of supported FEC codes. Doing multiple parallel channels of H-ARQ at a time can improve the throughput, since when one H-ARQ process is waiting for an acknowledgment, another process can use the channel to send some more data. WiMAX supports signaling mechanisms to allow asynchronous operation of H-ARQ and supports a dedicated acknowledgment channel in the uplink for ACK/NACK signaling. Asynchronous operations allow variable delay between retransmissions, which provides greater flexibility for the scheduler.

To further improve the reliability of retransmission, WiMAX also optionally supports type II H-ARQ, which is also called *incremental redundancy*. Here, unlike in type I H-ARQ, each (re)transmission is coded differently to gain improved performance. Typically, the code rate is effectively decreased every retransmission. That is, additional parity bits are sent every iteration, equivalent to coding across retransmissions.

Improved Frequency Reuse

Although it is possible to operate WiMAX systems with a universal frequency reuse plan,12 doing so can cause severe outage owing to interference, particularly along the inter cell and intersector edges. To mitigate this, WiMAX allows for coordination of sub channel allocation to users at the cell edges such that there is minimal overlap. This allows for a more dynamic frequency allocation across sectors, based on loading and interference conditions, as opposed to traditional fixed frequency planning. Those users under good SINR conditions will have access to the full channel bandwidth and operate under a frequency reuse of 1. Those in poor SINR conditions will be allocated non overlapping sub channels such that they operate under a frequency reuse of 2, 3, or 4, depending on the number of non overlapping sub channel groups that are allocated to be shared among these users. This type of sub channel allocation leads to the effective reuse factor taking fractional values greater than 1. The variety of subchannelization schemes supported by WiMAX makes it possible to do this in a very flexible manner. Obviously, the downside is that cell edge users cannot have access to the full bandwidth of the channel, and hence their peak rates will be reduced.

Reference Network Architecture

The IEEE 802.16e-2005 standard provides the air interface for WiMAX but does not define the full end-to-end WiMAX network. The WiMAX Forum's Network Working Group, is responsible for developing the end-to-end network requirements, architecture, and protocols for WiMAX, using IEEE 802.16e-2005 as the air interface.

The WiMAX NWG has developed a network reference model to serve as an architecture framework for WiMAX deployments and to ensure interoperability among various WiMAX equipment and operators. The network reference model envisions unified network architecture for supporting fixed, nomadic, and mobile deployments and is based on an IP service model. Figure 2.3 shows a simplified illustration of IP-based WiMAX network architecture. The overall network may be logically divided into three parts: (1) mobile stations used by the end user to access the network, (2) the access service network (ASN), which comprises one or more base stations and one or more ASN gateways that form the radio access network at the edge, and (3) the connectivity service network (CSN), which provides IP connectivity and all the IP core network functions.

The architecture framework is defined such that the multiple players can be part of the WiMAX service value chain. More specifically, the architecture allows for three separate business entities: (1) network access provider (NAP), which owns and operates the ASN; (2) network services provider (NSP), which provides IP connectivity and WiMAX services to subscribers using the ASN infrastructure provided by one or more NAPs; and (3) application service provider (ASP), which can provide value-added services such as multimedia applications using IMS (IP multimedia subsystem) and corporate VPN (virtual private networks) that run on top of IP. This separation between NAP, NSP, and ASP is designed to enable a richer ecosystem for WiMAX service business, leading to more competition and hence better services.

The network reference model developed by the WiMAX Forum NWG defines a number of functional entities and interfaces between those entities. (The interfaces are referred to as reference points.) Figure 2.3 shows some of the more important functional entities.

- **Base station (BS):**

The BS is responsible for providing the air interface to the MS. Additional functions that may be part of the BS are micromobility management functions, such as handoff triggering and tunnel establishment, radio resource management, QoS policy enforcement, traffic classification, DHCP (Dynamic Host Control Protocol) proxy, key management, session management, and multicast group management.

- **Access service network gateway (ASN-GW):**

The ASN gateway typically acts as a layer 2 traffic aggregation point within an ASN. Additional functions that may be part of the ASN gateway include intra-ASN location management and paging, radio resource management and admission control, caching of subscriber profiles and encryption keys, AAA client functionality, establishment and management of mobility tunnel with base stations, QoS and policy enforcement, foreign agent functionality for mobile IP, and routing to the selected CSN.

- **Connectivity service network (CSN):**

The CSN provides connectivity to the Internet, ASP, other public networks, and corporate networks. The CSN is owned by the NSP and includes AAA servers that support authentication for the devices, users, and specific services. The CSN also provides per user policy management of QoS and security. The CSN is also responsible for IP address management, support for roaming between different NSPs, location management between ASNs, and mobility and roaming between ASNs. Further, CSN can also provide gateways and interworking with other networks, such as PSTN (public switched telephone network), 3GPP, and 3GPP2.

The WiMAX architecture framework allows for the flexible decomposition and/or combination of functional entities when building the physical entities. For example, the ASN may be decomposed into base station transceivers (BST), base station controllers (BSC), and an ASNGW analogous to the GSM model of BTS, BSC, and Serving GPRS Support Node (SGSN). It is also possible to collapse the BS and ASN-GW into a single unit, which could be thought of as a WiMAX router. Such a design is often referred to as a distributed, or flat, architecture. By not mandating a single physical ASN or CSN topology, the reference architecture allows for vendor/ operator differentiation.

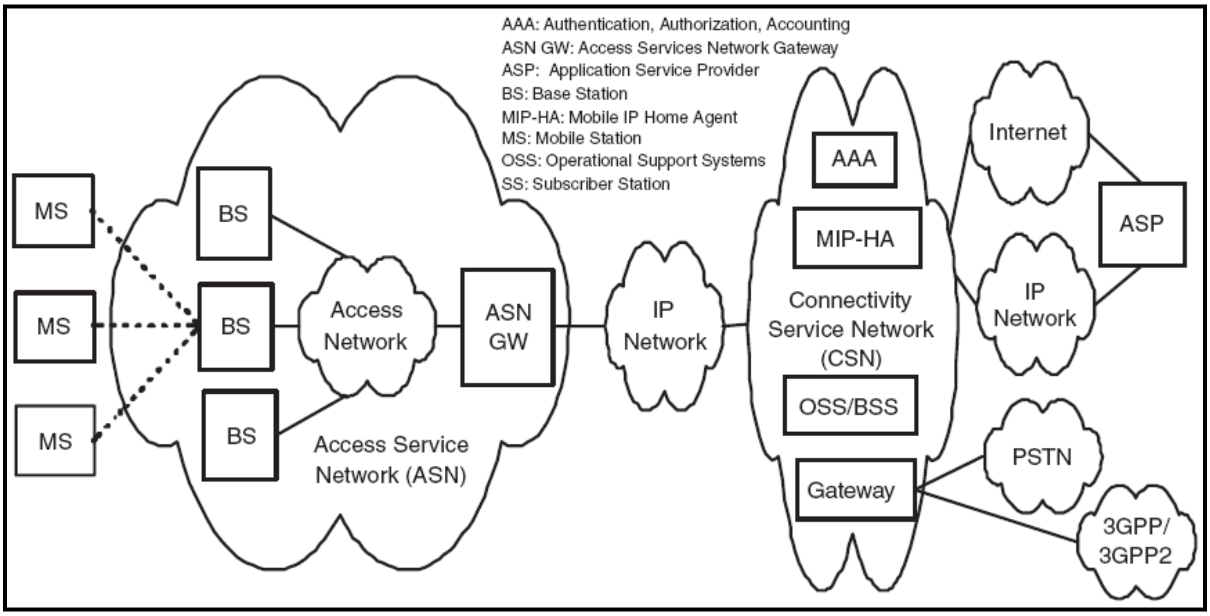


Figure 2.3 IP-Based WiMAX Network Architecture

In addition to functional entities, the reference architecture defines interfaces, called *reference points*, between function entities. The interfaces carry control and management protocols—mostly IETF-developed network and transport-layer protocols—in support of several functions, such as mobility, security, and QoS, in addition to bearer data. Figure 2.4 shows an example.

The WiMAX network reference model defines reference points between: (1) MS and the ASN, called R1, which in addition to the air interface includes protocols in the management plane, (2) MS and CSN, called R2, which provides authentication, service authorization, IP configuration, and mobility management, (3) ASN and CSN, called R3, to support policy enforcement and mobility management, (4) ASN and ASN, called R4, to support inter-ASN mobility, (5) CSN and CSN, called R5, to support roaming across multiple NSPs, (6) BS and ASN-GW, called R6, which consists of intra-ASN bearer paths and IP tunnels for mobility events, and (7) BS to BS, called R7, to facilitate fast, seamless handover.

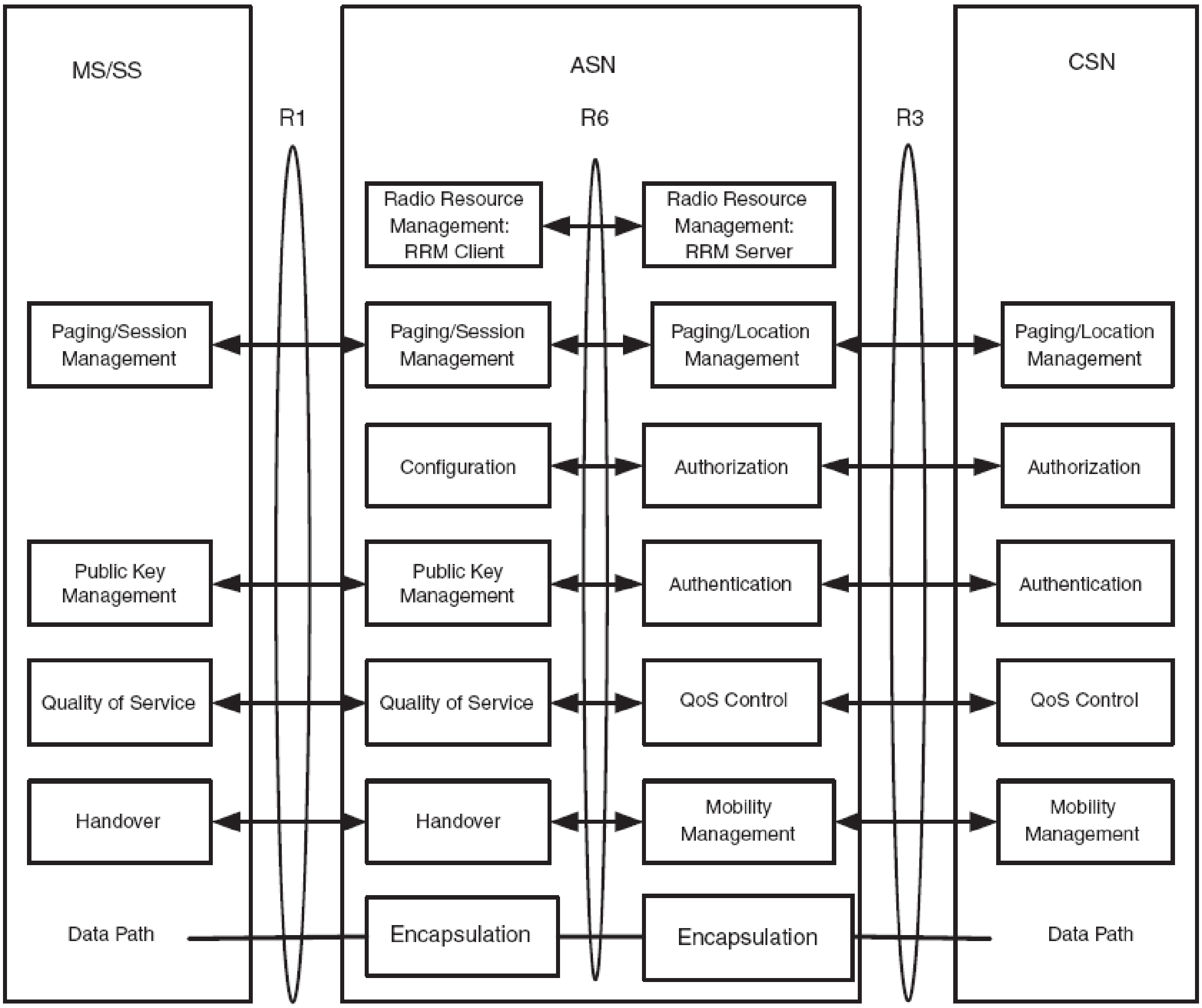


Figure 2.4 Functions performed across reference points

Performance Characterization

So far in this chapter, an overview description of the WiMAX broadband wireless standard, focusing on the various features, functions, and protocols are provided. Now briefly turned to the system performance of WiMAX networks. As discussed in Chapter 1, a number of trade-offs are involved in designing a wireless system, and WiMAX offers a broad and flexible set of design choices that can be used to optimize the system for the desired service requirements. In this section, a brief summary of the throughput performance and coverage range of WiMAX for a few specific deployment scenarios is presented.

Throughput and Spectral Efficiency

Table 2.7 shows a small sampling of some the results of a simulation-based system performance study is performed. It shows the per sector average throughput achievable in a WiMAX system using a variety of antenna configurations: from an open-loop MIMO antenna system with two transmit antennas and two receiver antennas to a closed-loop MIMO system with linear pre coding using four transmit antennas and two receive antennas.

The results shown are for a 1,024 FFT OFDMA-PHY using a 10MHz TDD channel and band AMC subcarrier permutation with a 1:3 uplink-to-downlink ratio. The results assume a multi cellular deployment with three sectored base stations using a (1,1)13 frequency reuse. This is an interference-limited design, with adjacent base stations assumed to be 2 km apart. A multipath environment modeled using the International Telecommunications Union (ITU) pedestrian B channel14 is assumed. Results for both the fixed case where an indoor desktop CPE is assumed and the mobile case where a portable handset is assumed are shown in Table 2.7.

The average per sector downlink throughput for the baseline case—assuming a fixed desktop CPE deployment—is 16.3Mbps and can be increased to over 35Mbps by using a 4 × 2 closed-loop MIMO scheme with linear pre coding. The mobile-handset case also shows comparable performance, albeit slightly less. The combination of OFDM, OFDMA, and MIMO provides WiMAX with a tremendous throughput performance advantage. It should be noted that early mobile WiMAX systems will use mostly open-loop 2 × 2 MIMO, with higher-order MIMO systems likely to follow within a few years.

Table 2.7 also shows the performance in terms of spectral efficiency, one of the key metrics used to quantify the performance of a wireless network. The results indicate that WiMAX, especially with MIMO implementations, can achieve significantly higher spectral efficiencies than what is offered by current 3G systems, such as HSDPA and 1xEV-DO.

It should be noted, however, that the high spectral efficiency obtained through the use of (1,1,) frequency reuse does entail an increased outage probability. As discussed in Chapter 12, the outage can be higher than 10 percent in many cases unless a 4 × 2 closed-loop MIMO scheme is used.

Sample Link Budgets and Coverage Range

Table 2.8 shows a sample link budget for a WiMAX system for two deployment scenarios. In the first scenario, the mobile WiMAX case, service is provided to a portable mobile handset located outdoors; in the second case, service is provided to a fixed desktop subscriber station placed indoors. The fixed desktop subscriber is assumed to have a switched directional antenna that provides 6 dBi gains. For both cases, MIMO spatial multiplexing is not assumed; only diversity reception and transmission are assumed at the base station. The numbers shown are therefore for a basic WiMAX system.

Parameter			Antenna Configuration			
			2 × 2 Open-Loop MIMO	**2 × 4 Open-Loop MIMO**	**4 × 2 Open-Loop MIMO**	**4 × 2 Closed-Loop MIMO**
Per sector average throughput (Mbps) in a 10MHz channel	Fixed indoor desk-top CPE	DL	16.31	27.25	23.25	35.11
		UL	2.62	2.50	3.74	5.64
	Mobile handset	DL	14.61	26.31	22.25	34.11
		UL	2.34	2.34	3.58	5.48
Spectral efficiency (bps/Hertz)	Fixed indoor desk-top CPE	DL	2.17	3.63	3.10	4.68
		UL	1.05	1.00	1.50	2.26
	Mobile handset	DL	1.95	3.51	2.97	4.55
		UL	0.94	0.94	1.43	2.19

Table 2.7 Throughput and Spectral Efficiency of WiMAX

The link budget assumes a QPSK rate 1/2 modulation and coding operating at a 10 percent block error rate (BLER) for subscribers at the edge of the cell. This corresponds to a cell edge physical-layer throughput of about 150kbps in the downlink and 35kbps on the uplink, assuming a 3:1 downlink-to-uplink ratio. Table 2.8 shows that the system offers a link margin in excess of 140 dB at this data rate. Assuming 2,300MHz carrier frequency, a base station antenna height of 30 m, and a mobile station height of 1 m, this translates to a coverage range of about 1 km using the COST-231 Hata model discussed in Chapter 12. Table 2.8 shows results for both the urban and suburban models. The pathloss for the urban model is 3 dB higher than for the suburban model.

Parameter	Mobile Handheld in Outdoor Scenario		Fixed Desktop in Indoor Scenario		Notes
	Downlink	**Uplink**	**Downlink**	**Uplink**	
Power amplifier output power	43.0 dB	27.0 dB	43.0 dB	27.0 dB	A1
Number of tx antennas	2.0	1.0	2.0	1.0	A2
Power amplifier backoff	0 dB	0 dB	0 dB	0 dB	A3; assumes that amplifier has sufficient linearity for QPSK operation without backoff
Transmit antenna gain	18 dBi	0 dBi	18 dBi	6 dBi	A4; assumes 6 dBi antenna for desktop SS
Transmitter losses	3.0 dB	0 dB	3.0 dB	0 dB	A5
Effective isotropic radi-ated power	61 dBm	27 dBm	61 dBm	33 dBm	A6 = A1 + 10log10(A2) – A3 + A4 – A5
Channel bandwidth	10MHz	10MHz	10MHz	10MHz	A7
Number of subchannels	16	16	16	16	A8
Receiver noise level	–104 dBm	–104 dBm	–104 dBm	–104 dBm	A9 = –174 + 10log10(A7*1e6)
Receiver noise figure	8 dB	4 dB	8 dB	4 dB	A10
Required SNR	0.8 dB	1.8 dB	0.8 dB	1.8 dB	A11; for QPSK, R1/2 at 10% BLER in ITU Ped. B channel

Macro diversity gain	0 dB	0 dB	0 dB	0 dB	A12; No macro diversity assumed
Subchannelization gain	0 dB	12 dB	0 dB	12 dB	A13 = 10log10(A8)
Data rate per subchannel (kbps)	151.2	34.6	151.2	34.6	A14; using QPSK, R1/2 at 10% BLER
Receiver sensitivity (dBm)	–95.2	–110.2	–95.2	–110.2	A15 = A9 + A10 + A11 + A12 – A13
Receiver antenna gain	0 dBi	18 dBi	6 dBi	18 dBi	A16
System gain	156.2 dB	155.2 dB	162.2 dB	161.2 dB	A17 = A6 – A15 + A16
Shadow-fade margin	10 dB	10 dB	10 dB	10 dB	A18
Building penetration loss	0 dB	0 dB	10 dB	10 dB	A19; assumes single wall
Link margin	146.2 dB	145.2 dB	142.2 dB	141.2 dB	A20 = A17 – A18 – A19
Coverage range	1.06 km (0.66 miles)		0.81 km (0.51 miles)		Assuming COST-231 Hata urban model
Coverage range	1.29 km (0.80 miles)		0.99 km (0.62 miles)		Assuming the suburban model

Table 2.8 Sample Link Budgets for a WiMAX System

Achieving high data rates in terrestrial wireless communication is difficult. High data rates for wireless local area networks, namely the IEEE 802.11 family of standards, became commercially successful only around 2000. Wide area wireless networks, namely cellular systems, are still designed and used primarily for low-rate voice services. Despite many promising technologies, the reality of a wide area network that services many users at high data rates with reasonable bandwidth and power consumption, while maintaining high coverage and quality of service, has not yet been achieved.

The goal of the IEEE 802.16 committee was to design a wireless communication system that incorporates the most promising new technologies in communications and digital signal processing to achieve a broadband Internet experience for nomadic or mobile users over a wide or metropolitan area. It is important to realize that WiMAX systems have to confront similar challenges as existing cellular systems, and their eventual performance will be bounded by the same laws of physics and information theory.

In this chapter, the immense challenge presented by a time-varying broadband wireless channel is explained. The principle effects in broadband wireless channels and present practical statistical models is quantified. With these diversity techniques, it is even possible in many cases to take advantage of what were originally viewed as impediments. The rest of Part II of the book focuses on the technologies that have been developed by many sources—in some cases, very recently—and adopted in WiMAX to achieve robust high data rates in such channels.

Communication System Building Blocks

All wireless digital communication systems must possess a few key building blocks, as shown in Figure 3.1. Even in a reasonably complicated wireless network, the entire system can be broken down into a collection of *links*, each consisting of a transmitter, a channel, and a receiver.

The transmitter receives packets of bits from a higher protocol layer and sends those bits as electromagnetic waves toward the receiver. The key steps in the digital domain are encoding and modulation. The encoder generally adds redundancy that will allow error correction at the receiver. The modulator prepares the digital signal for the wireless channel and may comprise a number of operations. The modulated digital signal is converted into a representative analog waveform by a digital-to-analog convertor (DAC) and then unconverted to one of the desired WiMAX radio frequency (RF) bands. This RF signal is then radiated as electromagnetic waves by a suitable antenna.

The receiver performs essentially the reverse of these operations. After down converting the received RF signal and filtering out signals at other frequencies, the resulting baseband signal is converted to a digital signal by an analog-to-digital convertor (ADC). This digital signal can then be demodulated and decoded with energy and space-efficient integrated circuits to, ideally, reproduce the original bit stream.

It is important that the IEEE 802.16 standard and WiMAX focus almost exclusively on the *digital* aspects of wireless communication, in particular at the transmitter side. The receiver implementation is unspecified; each equipment manufacturer is welcome to develop efficient proprietary receiver algorithms. Aside from agreeing on a carrier frequency and transmit spectrum mask, few requirements are placed on the RF units. The standard is interested primarily in the digital transmitter because the receiver must understand what the transmitter did in order to make sense of the received signal—but not vice versa.

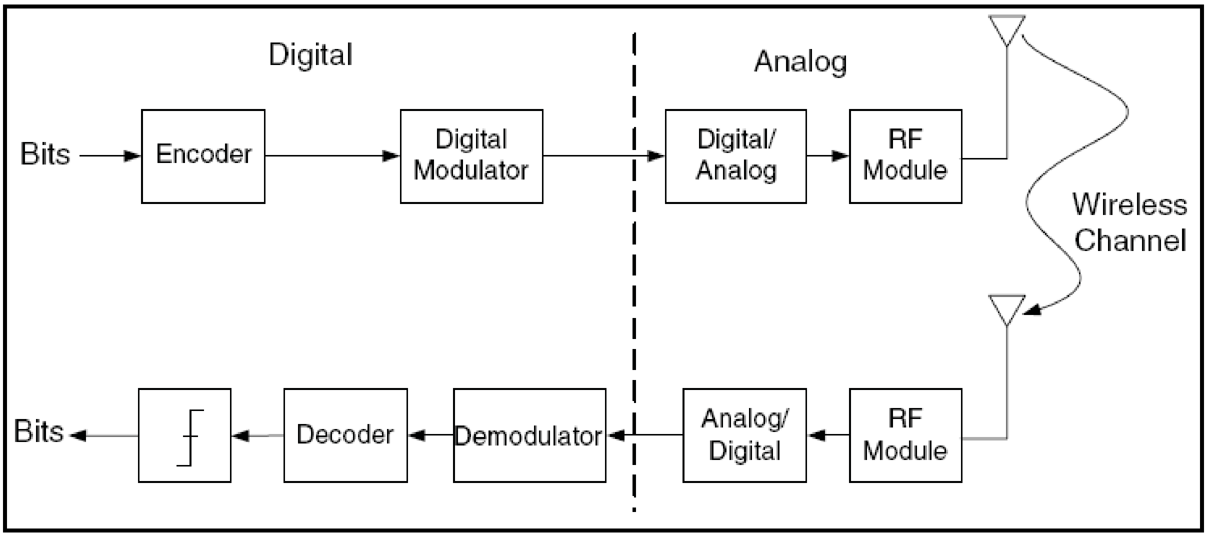


Figure 3.1 Wireless digital communication system

The Broadband Wireless Channel: Path loss and Shadowing

The main goal of this chapter is to explain the fundamental factors affecting the received signal in a wireless system and how they can be modeled using a handful of parameters. The relative values of these parameters, which are summarized in Table 3.1 and described throughout this section, make all the difference when designing a wireless communication system. In this section, the overall channel model and discuss the *large-scale* trends that affect this model is introduced.

The overall model for describing the channel in discrete time is a simple tap-delay line (TDL):

$$h[k,t] = h_0\delta[k-1,t] + \cdots + h_v\delta[k-v,t] \qquad (3.1)$$

Here, the discrete-time channel is time varying—so it changes with respect to —and has non negligible values over a span of $v+1$ channel taps. Generally, assumed that the channel is sampled at a frequency

$$f_x = \frac{1}{T}$$

where *T* is the symbol period,1 and that hence, the duration of the channel in this case is about vT. The $v+1$ sampled values are in general complex numbers.

Assuming that the channel is static over a period of $(v+1)T$ seconds, then the output of the channel is

$$y[k,t] = \sum_{j=-\infty}^{\infty} h[j,t]x[k-j] \qquad (3.2)$$

$$= h[k,t] * x[k] \qquad (3.3)$$

Where $x[k]$ is an input sequence of data symbols with rate $\frac{1}{T}$, and $*$ denotes convolution. In simpler notation, the channel can be represented as a time-varying $(v+1)\times 1$ column vector:[2]

$$h(t) = [h_0(t)h_1(t)\cdots h_v(t)]^T \quad (3.4)$$

Path loss

The first obvious difference between wired and wireless channels is the amount of transmitted power that reaches the receiver. Assuming that an isotropic antenna is used, as shown in Figure 3.2, the propagated signal energy expands over a spherical wavefront, so the energy received at an antenna distance *d* away is inversely proportional to the sphere surface area, $4\pi d^2$. The *free-space path loss formula*, or Friis formula, is given more precisely as

$$P_r = P_t \frac{\lambda^2 G_t G_r}{(4\pi d)^2} \quad (3.5)$$

where P_r and P_t are the received and transmitted powers

and λ is the wavelength. In the context of the TDL model of Equation (3.1), $\frac{P_t}{P_t}$ is the average value of the channel gain, that is, $\frac{P_t}{P_t} = E\|h\|^2$

where $E[\bullet]$ denotes the expected value, or mathematical mean. If directional antennas are used at the transmitter or the receiver, a gain of G_t and/or G_r is achieved, and the received power is simply increased by the gain of these antennae.[3] An important observation from Equation (3.5) is that since $c = f_c\lambda \Rightarrow \lambda = \frac{c}{f_c}$, the received power fall offs quadratically with the carrier frequency. In other words, for a given transmit power, the range is decreased when higher-frequency waves are used. This has important implications for high-data-rate systems, since most large bandwidths are available at higher frequencies (see Sidebar 3.1).

The terrestrial propagation environment is not free space. Intuitively, it seems that reflections from the earth or other objects would increase the received power since more energy would reach the receiver. However, because a reflected wave often experiences a 180° phase shift, the reflection at relatively large distances (usually over a kilometer) serves to create destructive interference, and the common *two-ray approximation* for pathloss is

$$P_r = P_t \frac{G_t G_r h_t^2 h_r^2}{d^4} \qquad (3.6)$$

which is significantly different from free-space path loss in several respects.

3. For an ideal isotropic radiator, *Gt* = *Gr* = 1.

Symbol	Parameter
α	Pathloss exponent
σ_s	Lognormal shadowing standard deviation
f_D	Doppler spread (maximum Doppler frequency), $f_D = \frac{vf_c}{C}$
T_c	Channel coherence time, $T_c \approx f_D^{-1}$
$\tau_{\max}$	Channel delay spread (maximum)
τ_{MAX}	Channel delay spread (RMS)
B_c	Channel coherence bandwidth, $B_c \approx \tau^{-1}$
θ_{RMS}	Angular spread (RMS)

Table 3.1 Key Wireless Channel Parameters

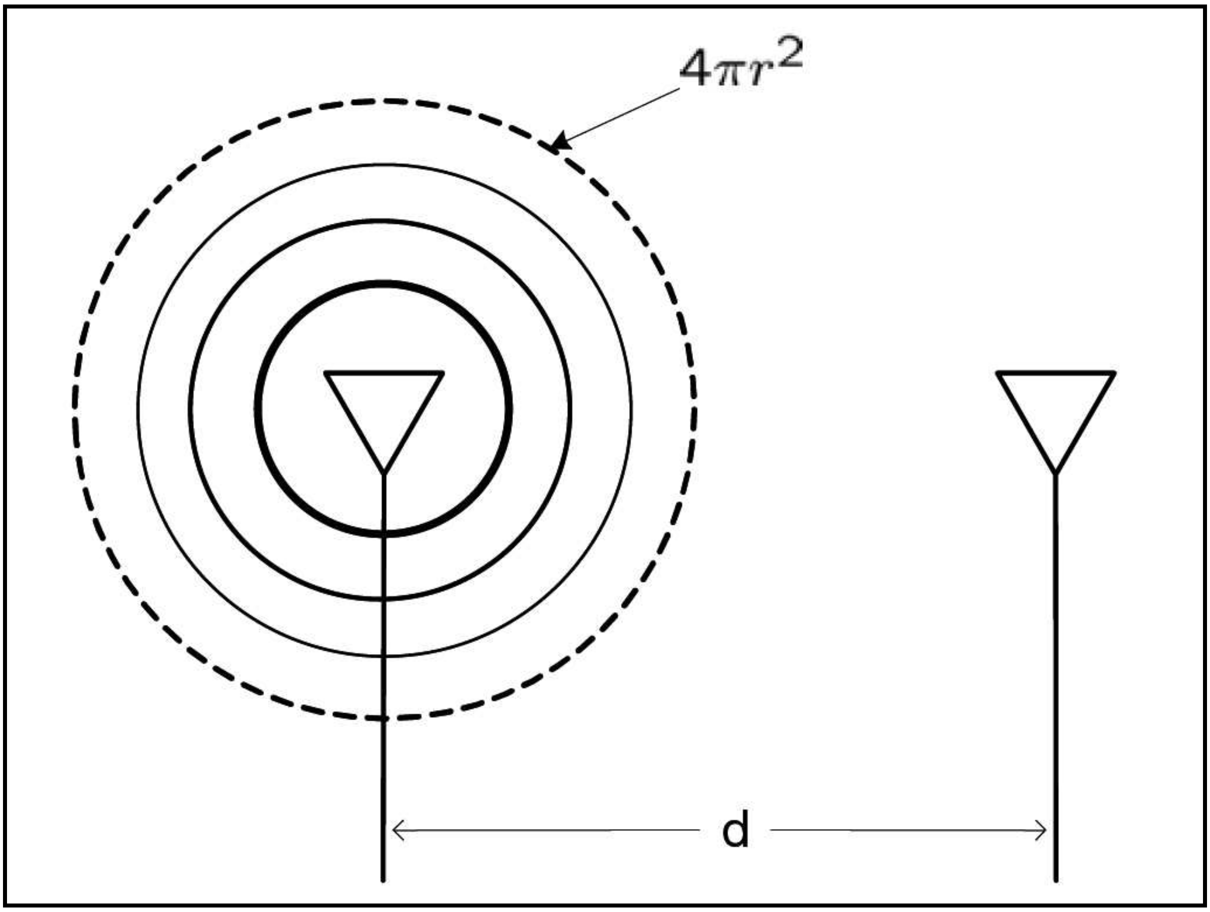


Figure 3.2 Free-space propagation

First, the antenna heights now assume a very important role in the propagation, as is anecdotally familiar: Radio transmitters are usually placed on the highest available object. Second, the wavelength and hence carrier frequency dependence has disappeared from the formula, which is not typically observed in practice, however. Third, and crucially, the distance dependence has changed to d^{-4}, implying that energy loss is more severe with distance in a terrestrial system than in free space.

In order to more accurately describe various propagation environments, empirical models are often developed using experimental data. One of the simplest and most common is the *empirical path loss formula*:

$$P_r = P_t P_0 \left(\frac{d_0}{d} \right)^{\alpha} \quad (3.7)$$

which groups all the various effects into two parameters: the pathloss exponent α and the measured pathloss P_0 at a reference distance of d_0, which is often chosen as 1 meter. Although P_0 should be determined from measurements, it is often well approximated, within several dB, as simply $\left(\frac{4\pi}{\lambda}\right)^2$ when $d_0 = 1$. This simple empirical pathloss formula is capable of reasonably representing most of the important pathloss trends with only these two parameters, at least over some range of interest (see Sidebar 3.2).

More accurate pathloss models have also been developed, including the well-known Okamura models [19], which also have a frequency-driven trend. Pathloss models that are especially relevant to WiMAX are discussed in more detail in Chapter 12.

Shadowing

Pathloss models attempt to account for the distance-dependent relationship between transmitted and received power. However, many factors other than distance can have a large effect on the total received power. For example, trees and buildings may be located between the transmitter and the receiver and cause temporary degradation in received signal strength; on the other hand, a temporary line-of-sight transmission path would result in abnormally high received power as shown in Figure 3.3. Since modeling the locations of all objects in every possible communication environment is generally impossible, the standard method of accounting for these variations in signal strength is to introduce a random effect called *shadowing*. With shadowing, the empirical pathloss formula becomes

$$P_r = P_t P_0 \chi \left(\frac{d_0}{d}\right)^{\alpha} \qquad (3.10)$$

where χ is a sample of the *shadowing* random process. Hence, the received power is now also modeled as a random process. In effect, the distance trend in the pathloss can be thought of as the mean, or expected, received power, whereas χ the shadowing value causes a perturbation from that expected value. It should be emphasized that since shadowing is caused by macroscopic objects, it typically has a correlation distance on the order of meters or tens of meters. Hence, shadowing is often alternatively called large-scale fading.

The shadowing value is typically modeled as a lognormal random variable, that is,

$$\chi = 10^{\frac{x}{10}}, \qquad \text{where } x \sim N(0, {\sigma_s}^2) \tag{3.11}$$

where $N(0, {\sigma_s}^2)$ is a Gaussian (normal) distribution with mean 0 and variance ${\sigma_s}^2$. With this formulation, the standard deviation σ_s is expressed in dB. Typical values σ_s for are in the 6–12 dB range. Figure 3.4 shows the very important effect of shadowing, where $\sigma_s = 11.8$ dB and $\sigma_s = 8.9$ dB, respectively.

Shadowing is an important effect in wireless networks because it causes the received SINR to vary dramatically over long time scales. In some locations in a given cell, reliable high-rate communication may be nearly impossible. The system design and base station deployment must account for lognormal shadowing through macrodiversity, variable transmit power, and/or simply accepting that some users will experience poor performance at a certain percentage of locations (see Sidebar 3.3). Although shadowing can sometimes be beneficial—for example, if an object is blocking interference—it is generally detrimental to system performance because it requires a several-dB margin to be built into the system. Let's do a realistic numerical example to see how shadowing affects wireless system design.

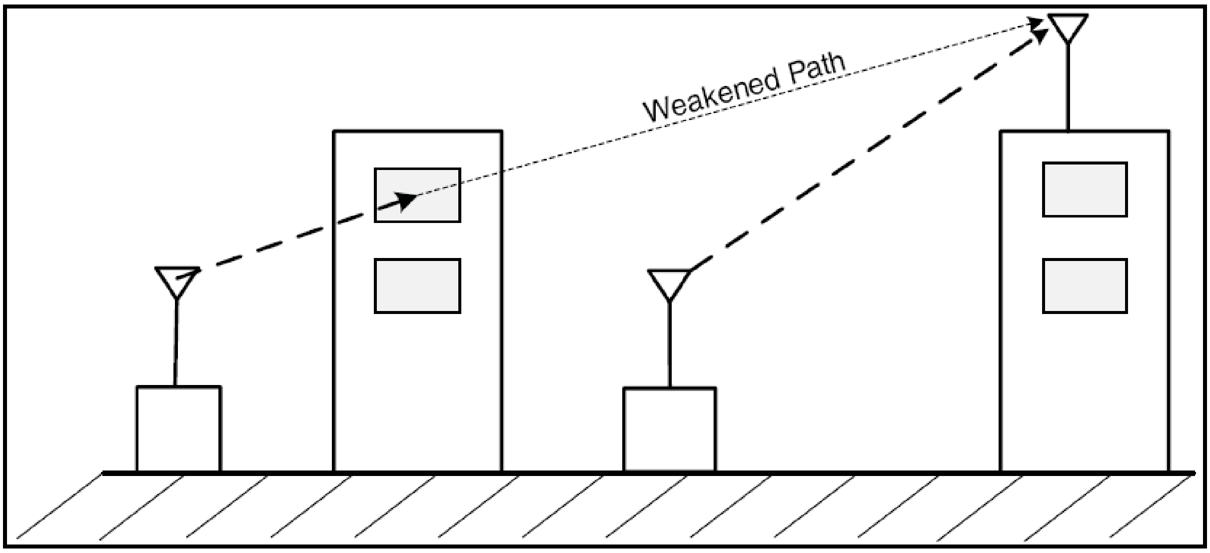


Figure 3.2 The Broadband Wireless Channel: Pathloss and Shadowing

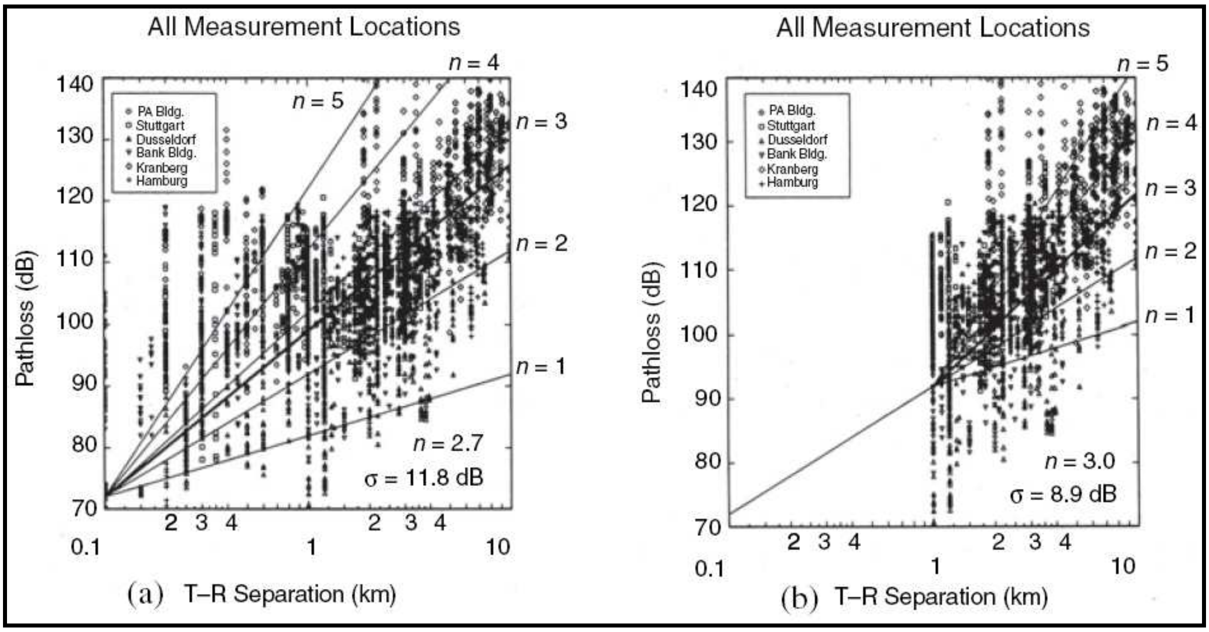


Figure 3.4 Shadowing causes large random fluctuations about the pathloss model. Figure from [28], courtesy of IEEE.

Cellular Systems

As explained in Section 3.2, owing to pathloss and, to a lesser extent, shadowing, given a maximum allowable transmit power, it is possible to reliably communicate only over some limited distance. However, pathloss allows for spatial isolation of different transmitters operating on the same frequency at the same time. As a result, pathloss and short range transmissions in fact *increase* the overall capacity of the system by allowing more simultaneous transmissions to occur. This straightforward observation is the theoretical basis for the ubiquity of modern cellular communication systems.

In this section, the key aspects of cellular systems and the closely related topics of sectoring and frequency reuse is briefly explained. Since WiMAX systems are expected to be deployed primarily in a cellular architecture, the concepts presented here are fundamental to understanding WiMAX system design and performance.

The Broadband Wireless Channel: Fading

One of the more intriguing aspects of wireless channels is fading. Unlike pathloss or shadowing, which are large-scale attenuation effects owing to distance or obstacles, fading is caused by the reception of multiple versions of the same signal. The multiple received versions are caused by reflections that are referred to as *multipath*. The reflections may arrive nearly simultaneously—for example, if there is local scattering around the receiver—or at relatively longer intervals—for example, owing to multiple paths between the transmitter and the receiver (Figure 3.10).

When some of the reflections arrive at nearly the same time, their combined effect is as in Figure 3.11. Depending on the phase difference between the arriving signals, the interference can be either constructive or destructive, which causes a very large observed difference in the amplitude of the received signal even over very short distances. In other words, moving the transmitter or the receiver even a very short distance can have a dramatic effect on the received amplitude, even though the pathloss and shadowing effects may not have changed at all.

To formalize this discussion, the time-varying tapped-delay-line channel model of Equation (3.1) is needed. As either the transmitter or the receiver moves relative to the other, the channel response $h(t)$ will change. This channel response can be thought of as having two dimensions: a delay dimension τ and a time-dimension *t*, as shown in Figure 3.12. Since the channel changes over distance and hence time, the values of $h_0, h_1, \cdots, h_v$ may be totally different at time *t* versus time $t + \Delta t$. Because, the channel is highly variant in both the τ and *t* dimensions.

The most important and fundamental function used to statistically describe broadband fading channels is the two-dimensional autocorrelation function, $A(\Delta\tau, \Delta t)$. Although it is over two dimensions and hence requires a three-dimensional plot, this autocorrelation function can usefully be thought of as two simpler functions, $A_t(\Delta t)$ and $A_\tau(\Delta\tau)$, where both and have been set to zero. The autocorrelation function is defined as

$$A(\Delta\tau, \Delta t) = E[h(\tau_1, t_1)h^*(\tau_2, t_2)] \quad (3.28)$$

$$= E[h(\tau_1, t)h^*(\tau_2, t + \Delta t)]$$

$$= E[h(\tau, t)h^*(\tau + \Delta\tau, t + \Delta t)]$$

where in the first step, it is assumed that the channel response is wide-sense stationary (WSS); (hence, the autocorrelation function depends only on $\Delta t = t_2 - t_1$). In the second step, it is assumed that the channel response of paths arriving at different times, τ_1 and τ_2, is uncorrelated. This allows the dependence on specific times τ_1 and τ_2 to be replaced simply by $\tau = \tau_2 - \tau_1$. Channels that can be described by the autocorrelation in Equation (3.28) are thus referred to as wide-sense stationary uncorrelated scattering (WSSUS), which is the most popular model for wideband fading channels and relatively accurate in many practical scenarios, largely because the scale of interest for τ (usually μsec) and *t* (usually msec) generally differs by a few orders of magnitude.

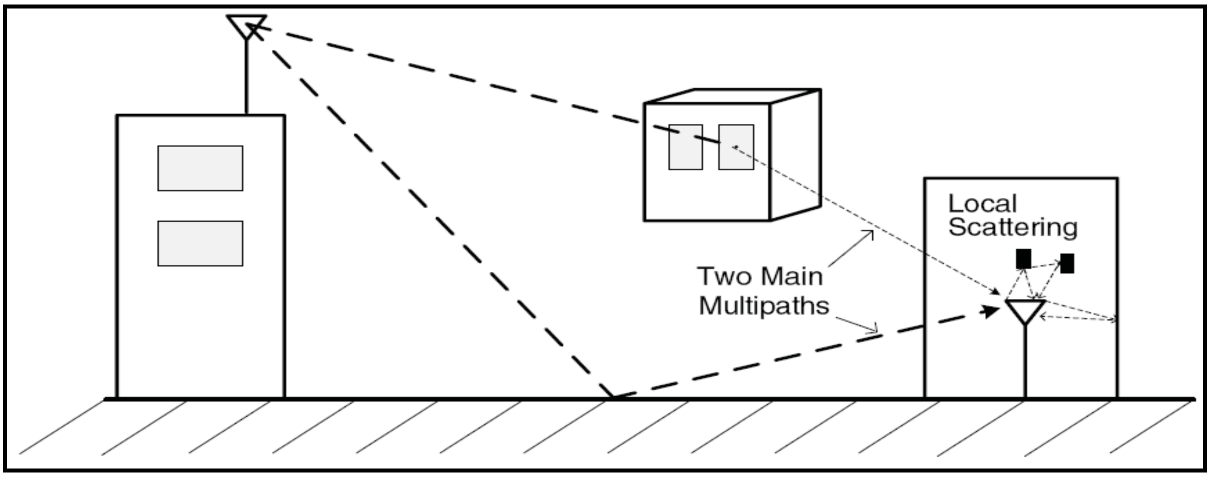
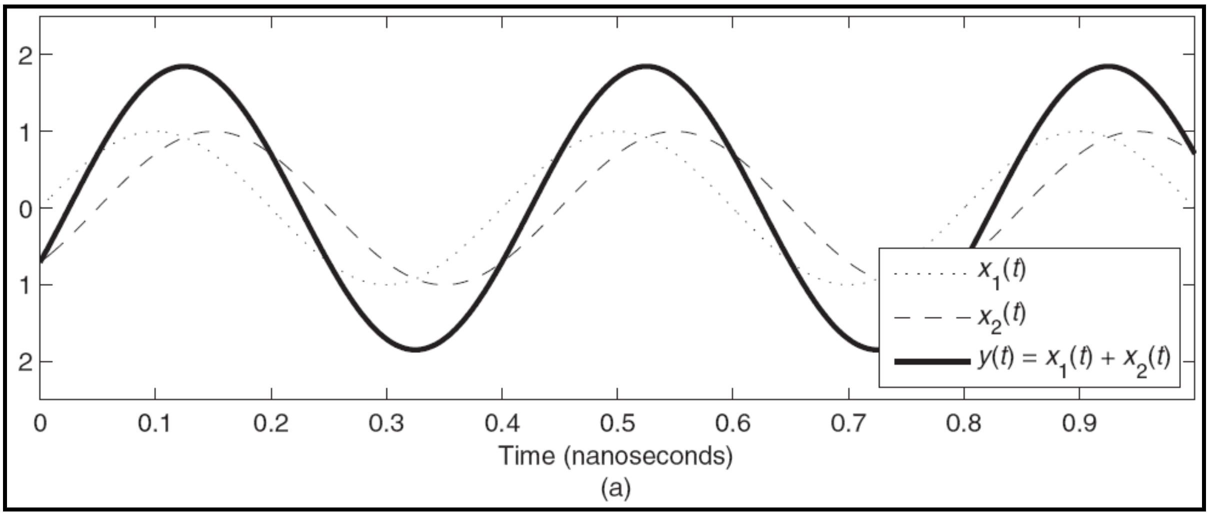


Figure 3.10 A channel with a few major paths of different lengths, with the receiver seeing a number of locally scattered versions of those paths



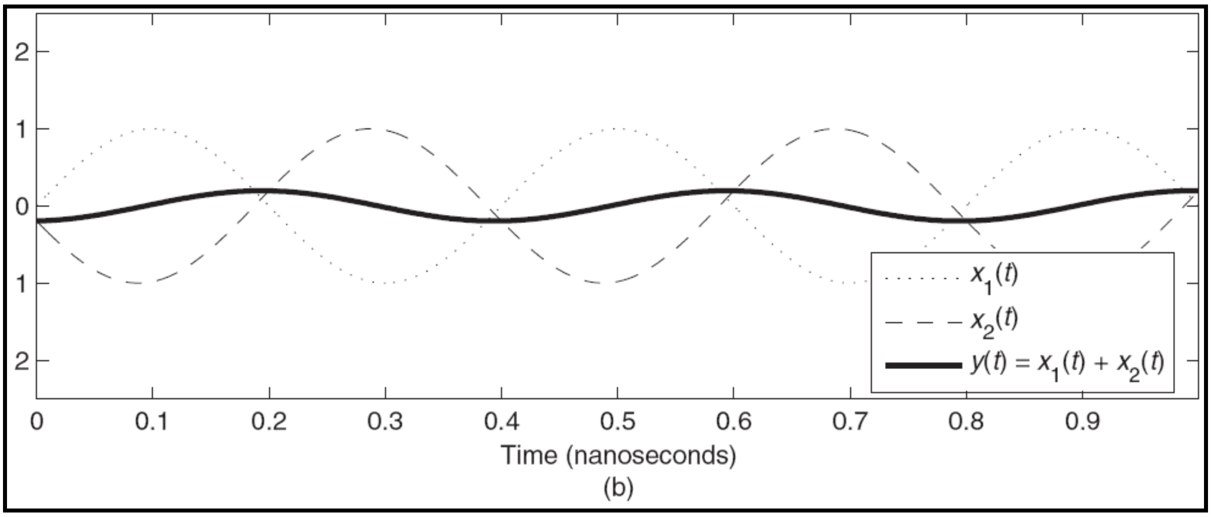


Figure 3.11 The difference between (a) constructive interference and (b) destructive interference at $f_c = 2.5GHz$ is less than 0.1 nanoseconds in phase, which corresponds to about 3 cm

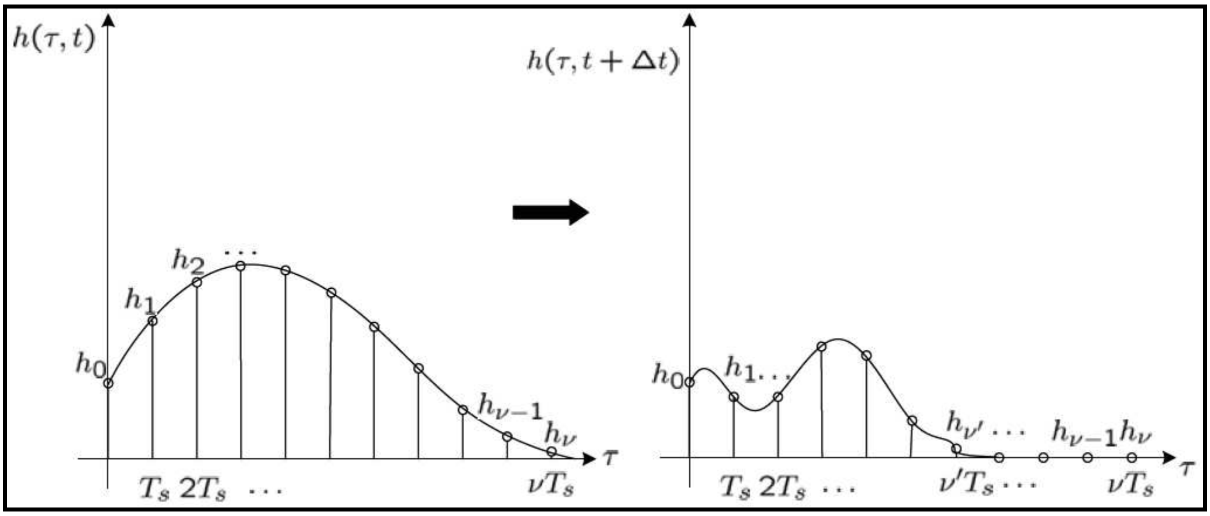


Figure 3.12 The delay τ corresponds to how long the channel impulse response lasts. The channel is time varying, so the channel impulse response is also a function of time— $h(\tau,t)$ —and can be quite different at time t + Δt than it was at time t.

The next three sections explain how many of the key wireless channels parameters can be estimated from the autocorrelation function and how they are related.

Delay Spread and Coherence Bandwidth

The delay spread is a very important property of a wireless channel, specifing the duration of the channel impulse response $h(\tau,t)$. Intuitively, the delay spread is the amount of time that elapses between the first arriving path and the last arriving (non-negligible) path. As seen in Figure 3.13, the delay spread can be found by inspecting $A_\tau(\Delta\tau) = A_\tau(\Delta\tau)$, that is, by setting $\Delta t = 0$ in the channel autocorrelation function. $A_\tau(\Delta\tau)$ is often referred to as the *multipath intensity profile, or power-delay profile*. If $A_\tau(\Delta\tau)$ has non-negligible values from $(0,\tau_{\max})$, the maximum delay spread is $\tau_{\max}$. Intuitively, this is an important definition because it specifies how many taps *v* will be needed in the discrete representation of the channel impulse response, since

$$v = \frac{\tau_{\max}}{T_s} \tag{3.29}$$

where T_s is the sampling time. But this definition is not rigorous, since it is not clear what "non negligible" means mathematically. More quantitatively, the average and RMS delay spread are often used instead of $\tau_{\max}$ and are defined as follows:

$$\mu_\tau = \frac{\int_0^\infty \Delta\tau A_\tau(\Delta\tau)d()\Delta\tau}{\int_0^\infty A_\tau(\Delta\tau)d(\Delta\tau)} \tag{3.30}$$

$$\tau_{RMS} = \sqrt{\frac{\int_0^\infty (\Delta\tau - \mu_\tau)^2 A_\tau(\Delta\tau)d(\Delta\tau)}{\int_0^\infty A_\tau(\Delta\tau)d(\Delta\tau)}} \tag{3.31}$$

Intuitively, τ_{RMS} gives a measure of the width, or spread, of the channel response in time. A large τ_{RMS} implies a highly dispersive channel in time and a long channel impulse response (large v), whereas a small τ_{RMS} indicates that the channel is not very dispersive and hence might require only a few taps to accurately characterize. A general rule of thumb is that $\tau_{\max} \approx 5\tau_{RMS}$.

Table 3.2 shows some typical values for the RMS delay spread and the associated channel coherence bandwidth for two candidate WiMAX frequency bands. This table demonstrates that longer-range channels have more frequency-selective fading.

The channel coherence bandwidth B_c is the frequency-domain dual of the channel delay spread. The coherence bandwidth gives a rough measure for the maximum separation between a frequency f_1 and a frequency f_2 where the channel frequency response is correlated. That is:

$$|f_1 - f_2| \le B_c \quad \Rightarrow \quad H(f_1) \approx H(f_2)$$

$|f_1 - f_2| > B_c \quad \Rightarrow \quad H(f_1)$ and $H(f_2)$ are uncorrelated

Just as $\tau_{\max}$ is a ballpark value describing the channel duration, B_c is a ballpark value describing the range of frequencies over which the channel stays constant. Given the channel delay spread, it can be shown that

$$B_c \approx \frac{1}{5\tau_{RMS}} \approx \frac{1}{\tau_{RMS}} \tag{3.32}$$

Exact relations can be found between B_c and τ_{RMS} by arbitrarily defining notions of coherence, but the important and prevailing feature is that B_c and τ are inversely related.

Doppler Spread and Coherence Time

Whereas the power-delay profile gave the statistical power distribution of the channel over time for a signal transmitted for only an instant, the *Doppler power spectrum* gives the statistical power distribution of the channel versus frequency for a signal transmitted at one exact frequency, generally normalized as $f = 0$ for convenience. Whereas the power-delay profile was caused by multipath between the transmitter and the receiver, the Doppler power spectrum is caused by *motion* between the transmitter and receiver. The Doppler power spectrum is the Fourier transform of $A_t(\Delta t)$, that is:

$$\rho_t(\Delta f) = \int_{-\infty}^{\infty} A_t(\Delta t) e^{-\Delta f.\Delta t} (d\Delta t) \tag{3.33}$$

Environment	fc (GHz)	RMS Delay (ns) τRMS	Coherence Bandwidth (MHz) $B_c \approx \frac{1}{5\tau_{RMS}}$	Reference
Urban	9.1	1,300	0.15	[22]
Rural	9.1	1,960	0.1	[22]
Indoor	9.1	270	0.7	[22]
Urban	5.3	44	4.5	[36]
Rural	5.3	66	3.0	[36]
Indoor	5.3	12.4	16.1	[36]

Table 3.2 Some Typical RMS Delay Spread and Approximate Coherence Bandwidths for Various WiMAX Applications

Unlike the power-delay profile, the Doppler power spectrum is nonzero strictly for $\Delta f \in (-f_D, f_D)$, where f_D is called the maximum Doppler, or Doppler spread. That is, $\rho_t(\Delta f)$ is strictly bandlimited. The Doppler spread is

$$f_D = \frac{\upsilon f_c}{c} \quad (3.34)$$

where υ is the maximum speed between the transmitter and the receiver, f_c is the carrier frequency, and *c* is the speed of light. As can be seen, over a large bandwidth, the Doppler will change, since the frequency over the entire bandwidth is *not* f_c. However, as long as the communication bandwidth B_c, the Doppler power spectrum can be treated as approximately constant. This generally is true for all but ultra wide band (UWB) systems.

Owing to the time/frequency uncertainty principle, since $\rho_t(\Delta f)$ is strictly band limited, its time/frequency dual $A_t(\Delta t)$ cannot be strictly time-limited. Since $A_t(\Delta t)$ gives the correlation of he channel over time, the channel, strictly speaking, exhibits nonzero correlation between any two time instants. In practice, however, it is possible to define a channel coherence time *TC*, which similarly to coherence bandwidth, gives the period of time over which the channel is significantly correlated. Mathematically:

$$|f_1 - f_2| \le B_c \quad \Rightarrow \quad H(f_1) \approx H(f_2)$$

$$|f_1 - f_2| > B_c \quad \Rightarrow \quad H(f_1) \text{ and } H(f_2) \text{ are uncorrelated}$$

The coherence time and Doppler spread are also inversely related:

Quantity	If "Large"	If "Small"	Wimax design Impact
Delay spread, τ	If $\tau >> T$, frequency selective	If $\tau << T$, frequency flat	The larger the delay spread relative to the symbol time, the more severe the ISI.
Coherence bandwidth, B_c	If $\frac{1}{B_c} << T$,	If $\frac{1}{B_c} >> T$,	Provides a guideline to subscriber width $B_{sc} \approx \frac{B_c}{10}$

	frequency flat	frequency selective	and hence no. of subcariers needed in OFDM: $L \geq \frac{10B}{B_c}$
Doppler spread, $f_D = \frac{f_c v}{c}$	If $f_c v >> c$, fast fading	If $f_c v \leq c$, slow fading	As $\frac{f_D}{B_{sc}}$ becomes non-negligible, subcarrier orthogonality is compromised.
Corence time, T_c	If $T_c >> T$, slow fading	If $T_c \leq T$, fast fading	T_c small necessitates frequent channel estimation and limits the OFDM symbol duration but provides greater time diversity
Angular spread, θ_{RMS}	NLOS channel, lots of diversity	Effectively LOS channel, not much diversity	Multiantenna array design, beamforming versus diversity
Coherence distance, D_c	Effectively LOS channel, not much diversity	NLOS channel, lots of diversity	Determines antenna spacing.

Table 3.3 Summary of Broadband Fading Parameters, with Rules of Thumb

$$T_c = \frac{1}{f_D} \qquad (3.35)$$

This makes intuitive sense: If the transmitter and the receiver are moving fast relative to each other and hence the Doppler is large, the channel will change much more quickly than if the transmitter and the receiver are stationary.

Table 3.4 gives some typical values for the Doppler spread and the associated channel coherence time for two candidate WiMAX frequency bands. This table demonstrates one of the reasons that mobility places extra constraints on the system design. At high frequency and mobility, the channel changes completely around 500 times per second, placing a large burden on channel-estimation algorithms and making the assumption of accurate transmitter channel knowledge questionable. Subsequent chapters (especially 5–7) discuss why accurate channel knowledge is important in WiMAX. Additionally, the large Doppler at high mobility and frequency can also degrade the OFDM subcarrier orthogonality, as discussed in Chapter 4.

f_c (GHz)	Speed (km/hr)	Speed (m/h)	Maximum Doppler f_D (Hz)	Coherence Time $T_c \approx \frac{1}{f_D}$ (msec)
2.5	2	1.2	4.6	200
2.5	45	27.0	104.2	10
2.5	100	60.0	231.5	4
5.8	2	1.2	10.7	93
5.8	45	27.0	241.7	4
5.8	100	60.0	537.0	2

Table 3.4 Some Typical Doppler Spreads and Approximate Coherence Times for Various WiMAX Applications

Angular Spread and Coherence Distance

So far, how the channel response varies over time and how to quantify its delay and correlation properties is focused. However, channels also vary over space.

The RMS angular spread of a channel can be denoted as θ_{RMS} and refers to the statistical distribution of the angle of the arriving energy. A large θ_{RMS} implies that channel energy is coming in from many directions; a small implies that the received channel energy is more focused. A large angular spread generally occurs when there is a lot of local scattering, which results in more statistical diversity in the channel; more focused energy results in less statistical diversity.

The dual of angular spread is coherence distance, D_c. As the angular spread increases, the coherence distance decreases, and vice versa. A coherence distance of *d* means that any physical positions separated by *d* have an essentially uncorrelated received signal amplitude and phase. An approximate rule of thumb [8] is

$$D_c \approx \frac{.2\lambda}{\theta_{RMS}} \tag{3.36}$$

The case of Rayleigh fading, discussed in Section 3.5.1, assumes a uniform angular spread; the well-known relation is

$$D_C \approx \frac{9\lambda}{16\pi} \tag{3.37}$$

An important trend to note from the preceding relations is that the coherence distance increases with the carrier wavelength λ. Thus, higher-frequency systems have shorter coherence distances.

Angular spread and coherence distance are particularly important in multiple-antenna systems. The coherence distance gives a rule of thumb for how far apart antennas should be spaced in order to be statistically independent. If the coherence distance is very small, antenna arrays can be effectively used to provide rich diversity. The importance of diversity is introduced in Section 3.6. On the other hand, if the coherence distance is large, space constraints may make it impossible to take advantage of spatial diversity. In this case, it would be preferable to have the antenna array cooperate and use beam forming. The trade-offs between beam forming and linear array processing are discussed in Chapter 5.

Modeling Broadband Fading Channels

In order to design and benchmark wireless communication systems, it is important to develop channel models that incorporate their variations in time, frequency, and space. Models are classified as either *statistical* or *empirical*. Statistical models are simpler and are useful for analysis and simulations. Empirical models are more complicated but usually represent a specific type of channel more accurately.

- **Statistical Channel Models**

The received signal in a wireless system is the superposition of numerous reflections, or multipath components. The reflections may arrive very closely spaced in time—for example, if there is local scattering around the receiver—or at relatively longer intervals. Figure 3.11 showed that when the reflections arrive at nearly the same time, constructive and destructive interference between the reflections causes the envelope of the aggregate received signal $r(t)$ to vary substantially.

In this section, statistical methods for characterizing the amplitude and power of $r(t)$ when all the reflections arrive at about the same time is summarized. First, consider the special case of the multipath intensity profile, where $A_\tau(\Delta\tau) \approx 0$ for $\Delta\tau \neq 0$. That is, the scenario in which all the received energy arrives at the receiver at the same instant is concerned: step 1 in our pedagogy. In practice, this is true only when the symbol time is much greater than the delay spread—$T >> \tau_{\max}$—so these models are often said to be valid for narrowband fading channels. In addition to assuming a negligible multipath delay spread, first consider just a snapshot value of $r(t)$ and provide statistical models for its amplitude and power under various assumptions. Then considered how these statistical values are correlated in time, frequency, and space: step 2. Finally, relax all the assumptions and consider how wideband fading channels evolve in time, frequency, and space: step 3.

- **Rayleigh Fading**

Suppose that the number of scatterers is large and that the angles of arrival between them are uncorrelated. From the Central Limit Theorem, it can be shown that the in-phase (cosine) and quadrature (sine) components of *r(t)*, denoted as $r_1(t)$ and $r_Q(t)$, follow two independent timecorrelated Gaussian random processes.

Consider a snapshot value of *r(t)* at time *t=0*, and note that $r(t) = r_1(0) + r_Q(0)$. Since the values $r_1(0)$ and $r_Q(0)$ are Gaussian random variables, it can be shown that the distribution of the envelope amplitude $|r| = \sqrt{r_1^2 + r_Q^2}$ is Rayleigh and that the received power $|r|^2 = r_1^2 + r_Q^2$ is exponentially distributed. Formally,

$$f_{|r|}(x) = \frac{2x}{P_r} e^{-\frac{x^2}{P_r}}, \qquad x \geq 0 \qquad (3.38)$$

and

$$f_{|r|^2}(x) = \frac{1}{P_r} e^{-\frac{x}{P_r}}, \qquad x \geq 0 \tag{3.39}$$

where P_r is the average received power owing to shadowing and pathloss, as described, for example, in Equation (3.10). The pathloss and shadowing determine the mean received power—assuming they are fixed over some period of time—and the total received power fluctuates around this mean, owing to the fading (see Figure 3.13). It can also be noted that in this setup, the Gaussian random variables r_1 and r_Q each have zero mean and variance $\sigma^2 = \frac{P_r}{2}$. The phase of $r(t)$ is defined as

$$\theta_r = \tan^1\left(\frac{r_Q}{r_1}\right) \tag{3.40}$$

which is uniformly distributed from 0 to 2π, or equivalently from $\left[-\pi, \pi\right]$ any other contiguous full period of the carrier signal.

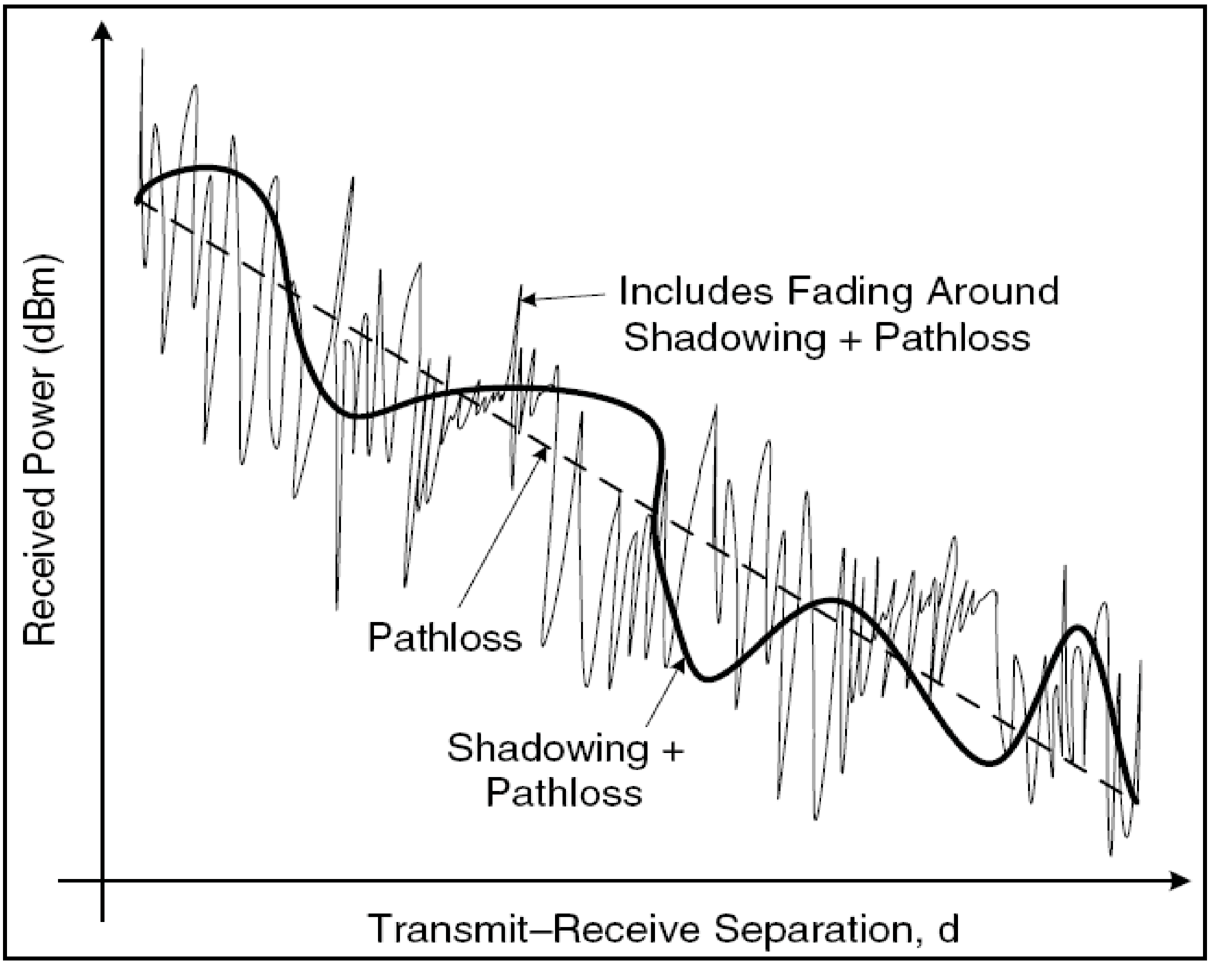


Figure 3.13 Plot showing the three major trends: pathloss, shadowing ,and fading all on the same plot: empirical, simulated, or a good CAD drawing

- **LOS Channels: Ricean distribution**

An important assumption in the Rayleigh fading model is that all the arriving reflections have a mean of zero. This will not be the case if there is a dominant path—for example, a LOS path—between the transmitter and the receiver. For a LOS signal, the received envelope distribution is more accurately modeled by a Ricean [24] distribution, which is given by

$$f_{|r|}(x) = \frac{x}{\sigma^2} e^{-\frac{(x^2+\mu^2)}{2\sigma^2}} I_0\left(\frac{x\mu}{\sigma^2}\right), \qquad x \geq 0 \qquad (3.41)$$

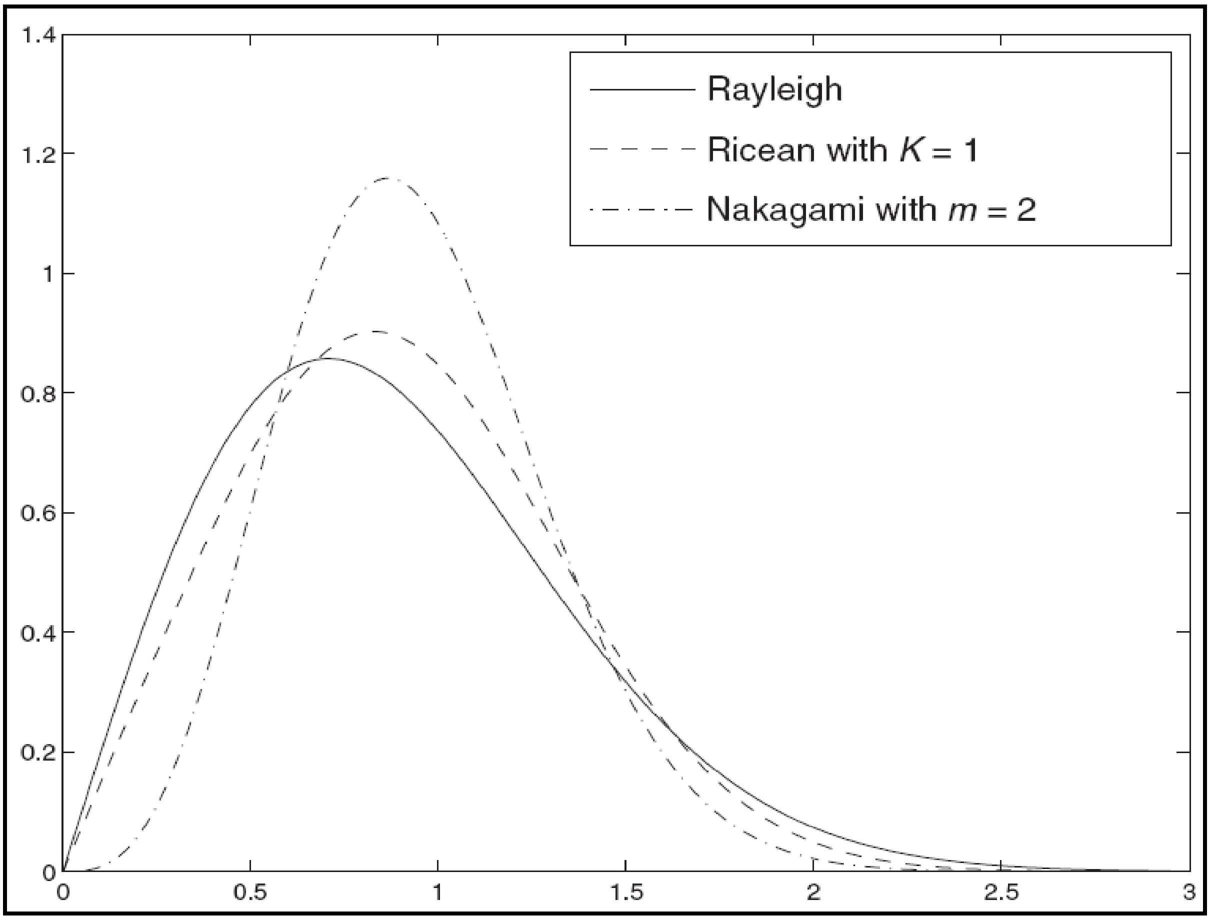


Figure 3.14 Probability distributions $f_{|r|}(x)$ for Rayleigh, Ricean with K = 1, and Nakagami with m = 2 and average received power P_r =1 for all

Where μ^2 is the power of the LOS component and I_0 is the 0th-order, modified Bessel function of the first kind. Although more complicated than a Rayleigh distribution, this expression is a generalization of the Rayleigh distribution. This can be confirmed by observing that

$$\mu = 0 \Rightarrow I_0\left(\frac{x\mu}{\sigma^2}\right) = 1,$$

so the Ricean distribution reduces to the Rayleigh distribution in the absence of a LOS component. Except in this special case, the Ricean phase distribution θ_r is not uniform in $[0,2\pi]$ and is not described by a straightforward expression.

Since the Ricean distribution depends on the LOS component's power μ^2, a common way to characterize the channel is by the relative strengths of the LOS and scattered paths. This factor, *K*, is quantified as

$$K = \frac{\mu^2}{2\sigma_2} \tag{3.42}$$

and is a natural description of how strong the LOS component is relative to the NLOS components. For *K=0*, the Ricean distribution again reduces to Rayleigh, and as $k \to \infty$, the physical

meaning is that there is only a single LOS path and no other scattering. Mathematically, as K grows large, the Ricean distribution is quite Gaussian about its mean μ with decreasing variance, physically meaning that the received power becomes increasingly deterministic.

The average received power under Ricean fading is the combination of the scattering power and the LOS power: $P_r = 2\sigma^2 + \mu^2$. Although it is not straightforward to directly find the Ricean power distribution $f_{|r|^2}(x)$, the Ricean envelope distribution in terms of *K* can be found by subbing

$$\mu^2 = \frac{KP_2}{K+1}$$

and

$$2\sigma^2 = \frac{P}{K+1}$$

into Equation (3.41).

Although its simplicity makes the Rayleigh distribution more amenable to analysis than the Ricean distribution, the Ricean distribution is usually a more accurate depiction of wireless broadband systems, which typically have one or more dominant components. This is especially true of fixed wireless systems, which do not experience fast fading and often are deployed to maximize LOS propagation.

Statistical Correlation of the Received Signal

The statistical methods in the previous section discussed how *samples* of the received signal are statistically distributed. The Rayleigh, Ricean, and Nakagami-m statistical models and provided the PDFs that giving the likelihoods of the received signal envelope and power at a given time instant (Figure 3.14) is considered. What is of more interest, though, is how to link those statistical models with the channel autocorrelation function, $A_c(\Delta\tau, \Delta t)$, in order to understand how the envelope signal $r(t)$ evolves over time or changes from one frequency or location to another.

For simplicity and consistency, is used Rayleigh fading as an example distribution here, but the concepts apply equally for any PDF. First discuss the correlation in different domains separately but conclude with a brief discussion of how the correlations in different domains interact.

- **Time Correlation**

In the time domain, the channel $h(\tau = 0, t)$ can intuitively be thought of as consisting of approximately one new sample from a Rayleigh distribution every T_c seconds, with the values in between interpolated. But, it will be useful to be more rigorous and accurate in our description of the fading envelope. As discussed in Section 3.4, the autocorrelation function $A_t(\Delta t)$ describes how the channel is correlated in time. Similarly, its frequency-domain Doppler power spectrum $\rho_t(\Delta f)$ provides a band-limited description of the same correlation, since it is simply the Fourier transform of $A_t(\Delta t)$. In other words, the power-spectral density of the channel $h(\tau = 0, t)$ should be $\rho_t(\Delta f)$. Since uncorrelated random variables have a flat power spectrum, a sequence of independent complex Gaussian random numbers can be multiplied by the desired Doppler power spectrum $\rho_t(\Delta f)$; then, by taking the inverse fast fourier transform, a correlated narrowband sample signal $h(\tau = 0, t)$ can be generated. The signal will have a time correlation defined by $\rho_t(\Delta f)$ and be Rayleigh, owing to the Gaussian random samples in frequency.

For the specific case of uniform scattering [16], it can been shown that the Doppler power spectrum becomes

$$\rho_t(\Delta f) = \begin{cases} \dfrac{P_r}{4\pi f_D \sqrt{1-\left(\dfrac{\Delta f}{f_D}\right)^2}} & , |\Delta f| \le f_D \\ 0 & , \Delta f > f_D \end{cases} \tag{3.45}$$

A plot of this realization of $\rho_t(\Delta f)$ is shown in Figure 3.15. It is well known that the inverse Fourier transform of this function is the 0th order Bessel function of the first kind, which is often used to model the time autocorrelation function, $A_c(\delta t)$, and hence predict the time-correlation properties of narrowband fading signals.

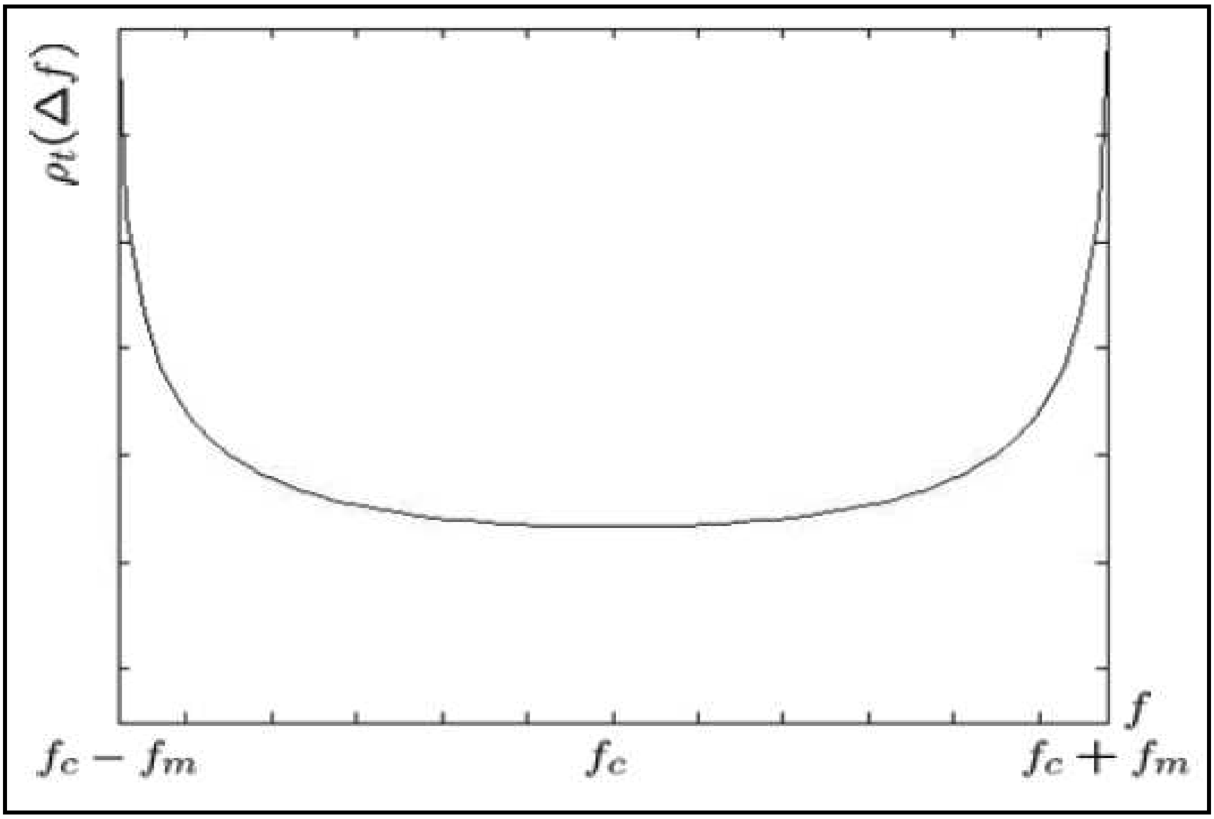


Figure 3.15 The spectral correlation owing to Doppler, for uniform scattering: Equation (3.45)

Frequency Correlation

Similarly to time correlation, a simple intuitive notion of fading in frequency is that the channel in the frequency domain, $H(f, t=0)$, can be thought of as consisting of approximately one new random sample every B_c Hz, with the values in between interpolated. The Rayleigh fading model assumes that the received quadrature signals in time are complex Gaussian. Similar to the development in the previous section where by complex Gaussian values in the frequency domain can be converted to a correlated Rayleigh envelope in the time domain, complex Gaussian values in the time domain can likewise be converted to a correlated Rayleigh frequency envelope $|H(f)|$.

The correlation function that maps from uncorrelated time-domain (τ domain) random variables to a correlated frequency response is the multipath intensity profile, $A_\tau(\Delta\tau)$. This makes sense: Just as $\rho_t(\Delta f)$ describes the channel time correlation in the frequency domain, $A_\tau(\Delta\tau)$ describes the channel frequency correlation in the time domain. Note that in one familiar special case, there is only one arriving path, in which case $A_\tau(\Delta\tau) = \delta(\Delta\tau)$. Hence, the values of $|H(f)|$ are correlated over all frequencies since the Fourier transform of $\delta(\Delta\tau)$ is a constant over all frequency. This scenario is called flat fading; in practice, whenever $A_\tau(\Delta\tau)$ is narrow $\tau_{\max} << T$, the fading is approximately flat.

If the arriving quadrature components are approximately complex Gaussian, a correlated Rayleigh distribution might be a reasonable model for the gain $|H(f)|$ on each subcarrier of a typical OFDM system. These gain values could also be generated by a suitably modified version of the provided simulation, where in particular, the correlation function used changes from that in Equation (3.45) to something like an exponential or uniform distribution or any function that reasonably reflects the multipath intensity profile $A_\tau(\Delta\tau)$.

➢ The Selectivity/Dispersion Duality

Two quite different effects from fading are *selectivity* and *dispersion*. By *selectivity*, signal's received value is changed by the channel over time or frequency. By *dispersion*, the channel is dispersed, or spread out, over time or frequency. Selectivity and dispersion are time/frequency duals of each other: Selectivity in time causes dispersion in frequency, and selectivity in frequency causes dispersion in time—or vice versa (see Figure 3.17).

For example, the Doppler effect causes dispersion in frequency, as described by the Doppler power spectrum $\rho_t(\Delta f)$. This means that frequency components of the signal received at a specific frequency f_0 will be dispersed about f_0 in the frequency domain with a probability distribution function described by $\rho_t(\Delta f)$. This dispersion can be interpreted as a time-varying amplitude, or selectivity, in time.

Similarly, a dispersive multipath channel that causes the paths to be received over a period of time $\tau_{\max}$ causes selectivity in the frequency domain, known as frequency-selective fading. Because symbols are traditionally sent one after another in the time domain, time dispersion usually causes much more damaging interference than frequency dispersion does, since adjacent symbols are smeared together.

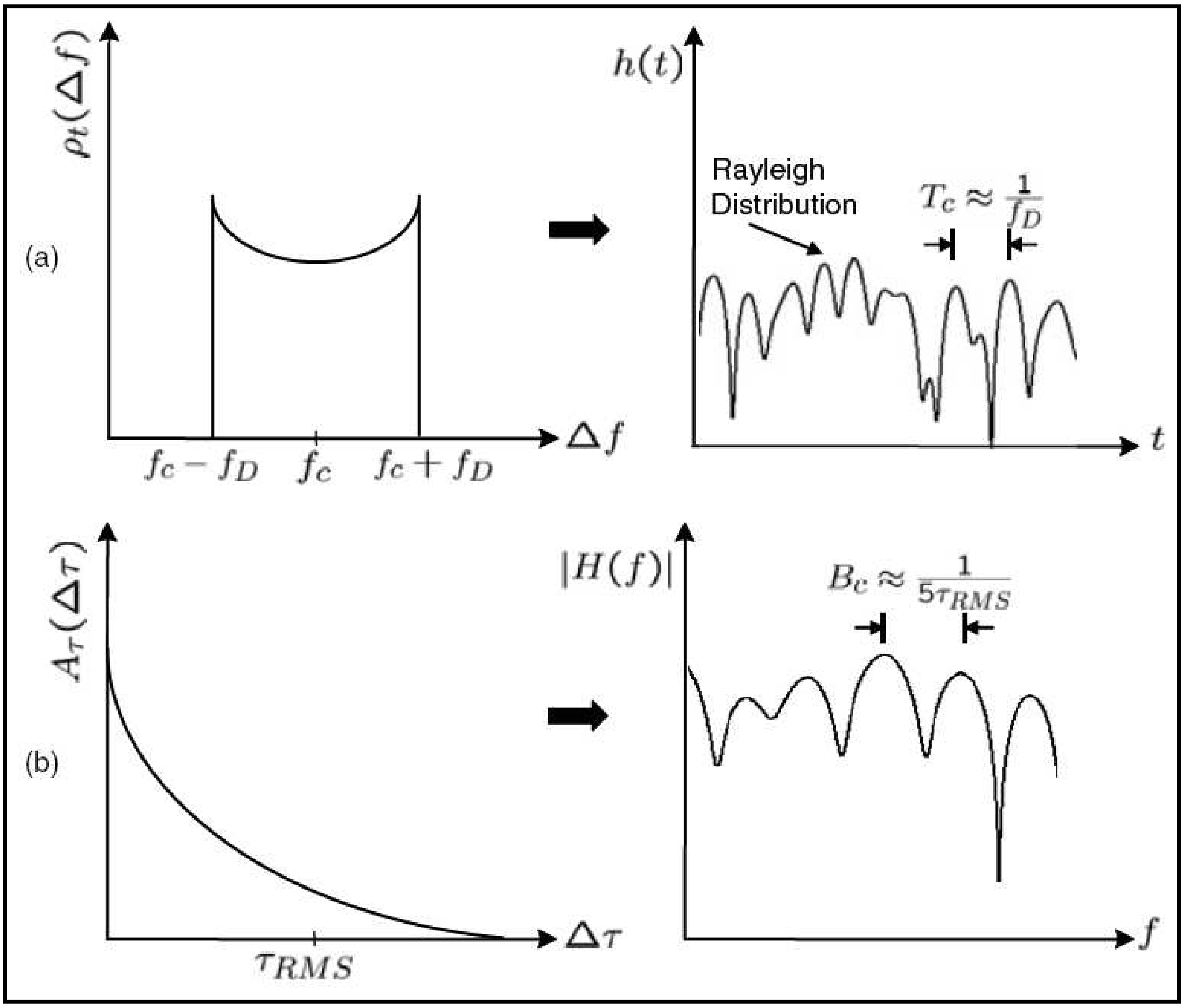


Figure 3.16 (a) The shape of the Doppler power spectrum determines the correlation envelope of the channel in time. (b) Similarly, the shape of the multipath intensity profile determines the correlation pattern of the channel frequency response.

- **Multidimensional Correlation**

A broadband wireless data system with mobility and multiple antennas is an example of a system in which all three types of fading will play a significant role. The concept of doubly selective (in time and frequency) fading channels [25] has received recent attention for OFDM. The combination of these two types of correlation is important because in the context of OFDM, they appear to compete with each other. On one hand, a highly frequency-selective channel—resulting from a long multipath channel as in a wide area wireless broadband network—requires a large number of potentially closely spaced subcarriers to effectively combat the inter symbol interference and small coherence bandwidth. On the other hand, a highly mobile channel with a large Doppler causes the channel to fluctuate over the resulting long symbol period, which degrades the subcarrier orthogonality. In the frequency domain, the Doppler frequency shift can cause significant inter carrier interference as the carriers become more closely spaced. Although the mobility and multipath delay spread must reach fairly severe levels before this doubly selective effect becomes significant, this problem facing mobile WiMAX systems does not have a comparable precedent.

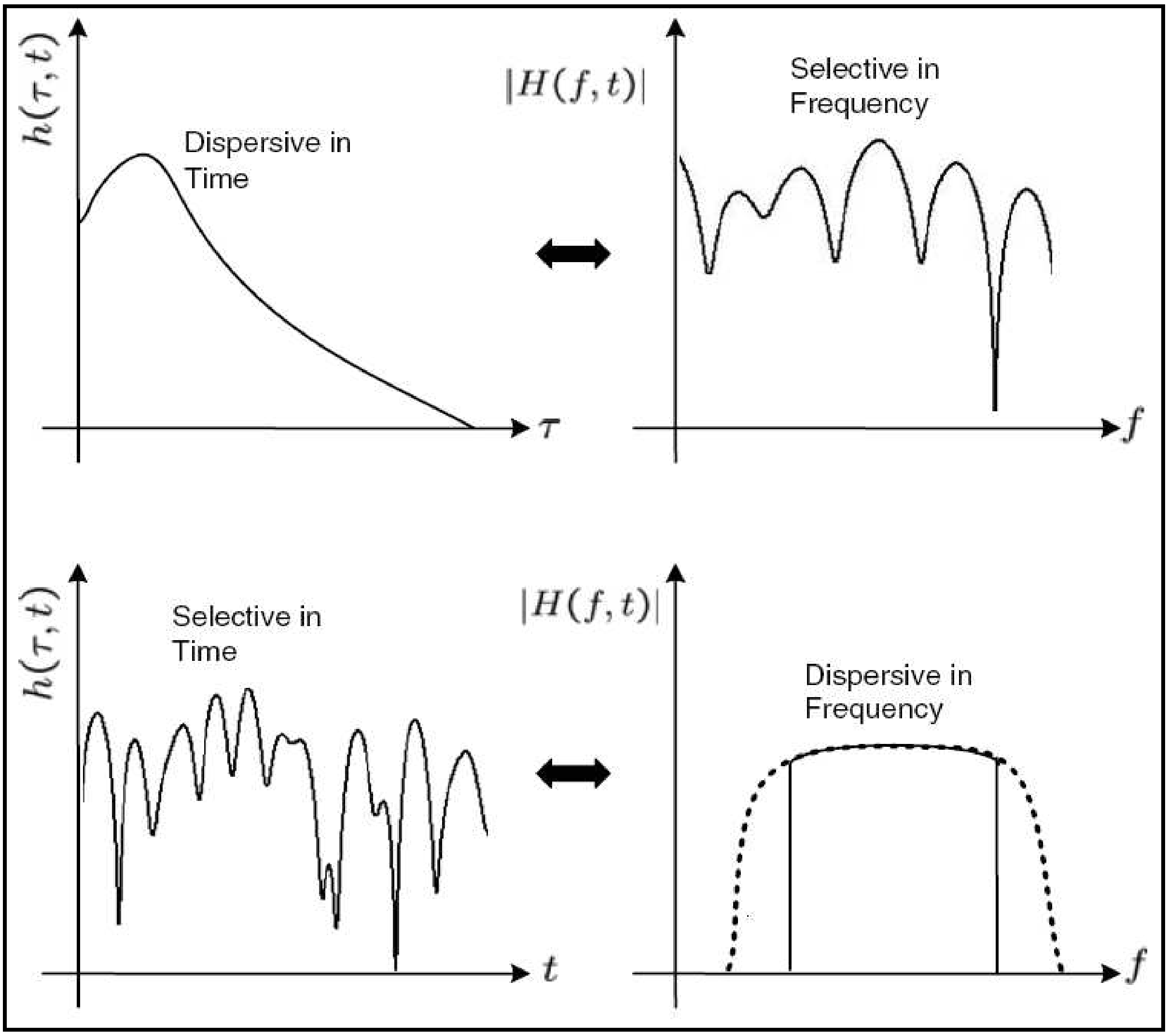


Figure 3.17 The dispersion/electivity duality: Dispersion in time causes frequency selectivity; dispersion in frequency causes time selectivity

The scalable nature of the WiMAX physical layer—notably, variable numbers of subcarriers and guard intervals—will allow custom optimization of the system for various environments and applications.

Empirical Channel Models

The parametric statistical channel models discussed thus far in the chapter do not take into account specific wireless propagation environments. Although exactly modeling a wireless channel requires complete knowledge of the surrounding scatterers, such as buildings and plants, the time and computational demands of such a methodology are unrealistic, owing to the near-infinite number of possible transmit/receive locations and the fact that objects are subject to movement. Therefore, empirical and semi empirical wireless channel models have been developed to accurately estimate the pathloss, shadowing, and small-scale fast fading. Although these models are generally not analytically tractable, they are very useful for simulations and to fairly compare competing designs. Empirical models are based on extensive measurement of various propagation environments, and they specify the parameters and methods for modeling the typical propagation scenarios in various wireless systems. Compared to parametric channel models, the empirical channel models take into account such realistic factors as angle of arrival (AoA), angle of departure (AoD), antenna array fashion, angular spread (AS), and antenna array gain pattern.

Different empirical channel models exist for different wireless scenarios, such as suburban macro-, urban macro-, and urban micro cells. For channels experienced in different wireless standards, the empirical channel models are also different. Here, aI briefly introduction of the common physical parameters and methodologies used in several major empirical channel models is given. These models are also applicable to the multiple-antenna systems.

- **3GPP**

The 3GPP channel model is widely used in modeling the outdoor macro- and microcell wireless environments. The empirical channel models for other systems, such as 802.11n and 802.20, are similar in most aspects, with subtle differences in the terminology and specific parameters. The 3GPP channel model is commonly used in WiMAX performance modeling.

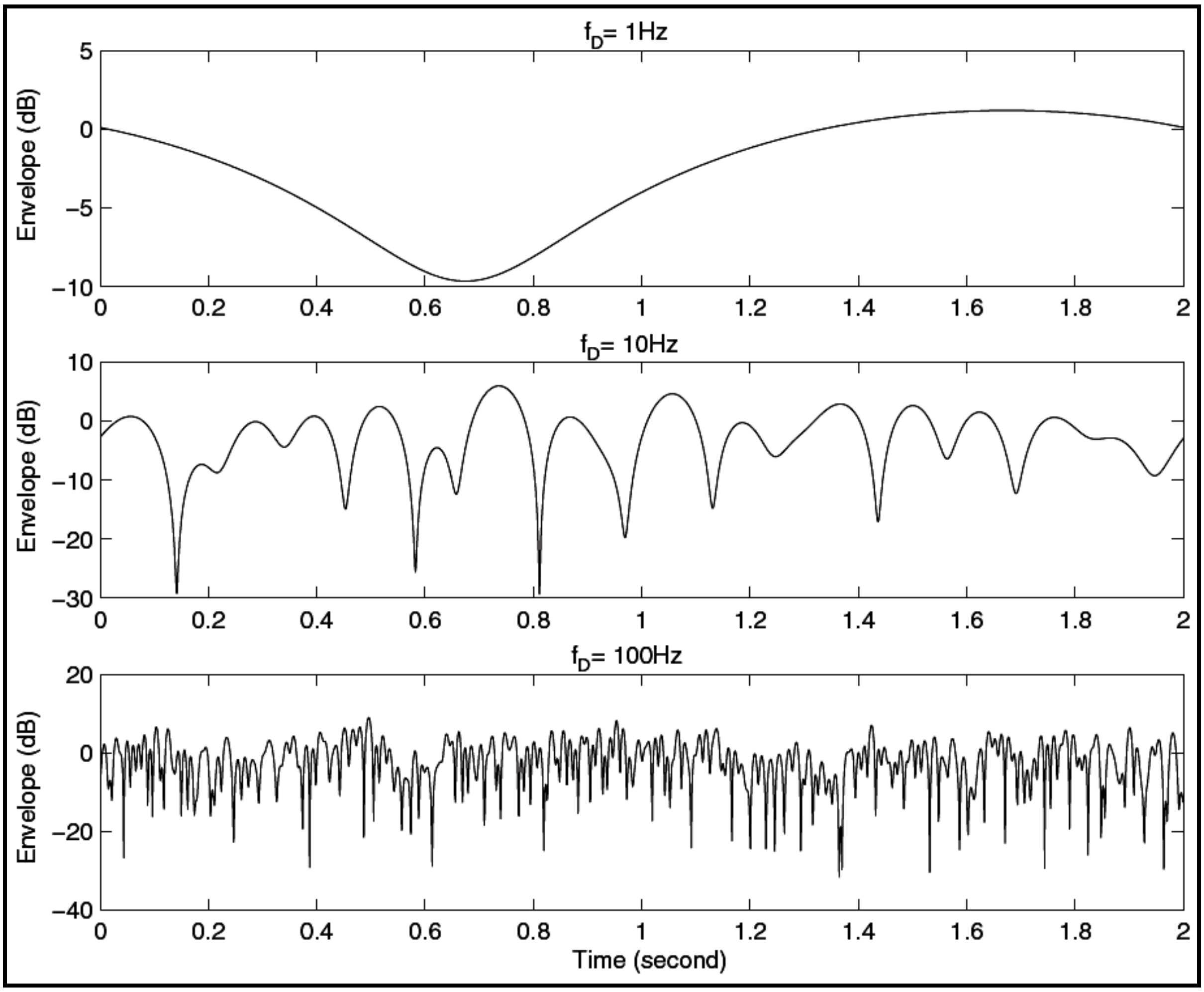


Figure 3.18 Sample channel gains in dB from the provided Rayleigh fading Matlab function for Doppler frequencies of f_D = 1Hz, 10Hz, and 100Hz

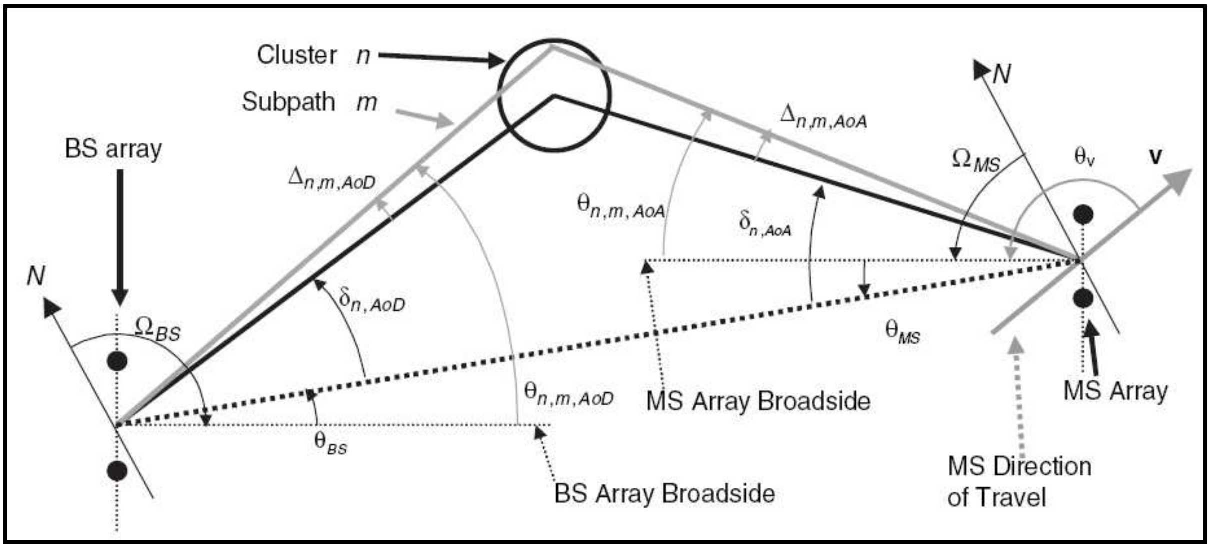


Figure 3.19 3GPP channel model for MIMO simulations

1. First, the environment in which an empirical channel model is used: suburban , urban or rural microenvironment. The BS-to-BS distance is typically larger than 3 km for a macro environment and less than 1 km for an urban microenvironment.
2. The pathloss is specified by empirical models for various scenarios. For the 3GPP macro cell environment, the pathloss is given as

$$PL[dB] = (44.9 - 6.55\log(h_{bs})\log(\frac{d}{1000}) + 45.5 + (35.46 - 1.1h_{ms})$$

$$\times \log(f_c) - 13.82\log(h_{bs}) + 0.7h_{ms} + C) \qquad (3.46)$$

where

h_{bs} is the BS antenna height in meters,

h_{ms} is the MS antenna height in meters,

f_c is the carrier frequency in MHz,

d is the distance in meters between the BS and the MS,

C is a constant factor (*C* = 0 dB for suburban macro and *C* = 3 dB for urban macro).

3. The received signal at the mobile receiver consists of *N* time-delayed versions of the transmitted signal. The *N* paths are characterized by powers and delays that are chosen according to the channel-generation procedures. The number of paths *N* ranges from 1 to 20 and is dependent on the specific channel models. For example, the 3GPP channel model has *N* = 6 multipath components. The power distribution normally follows the exponential profile, but other power profiles are also supported.
4. Each multipath component corresponds to a cluster of *M* subpaths, each of which characterizes the incoming signal from a scatterer. The *M* subpaths define a cluster of adjacent scatterers and therefore have the same multipath delay. The *M* subpaths have random phases and subpath gains, specified by the given procedure in different stands. For 3GPP, the phases are random variables uniformly distributed from 0 to 360° , and the subpath gains are given by Equation (3.47).
5. The AoD is usually within a narrow range in outdoor applications owing to the lack of scatterers around the BS transmitter and is often assumed to be uniformly distributed in indoor applications. The AoA is typically assumed to be uniformly distributed, owing to the abundance of local scattering around the mobile receiver.
6. The final channel is created by summing up the *M* subpath components. In the 3GPP channel model, the *n*th multipath component from the *u*th transmit antenna to the *s*th receive antenna is given as

$$h_{u,s,n}(t) = \sqrt{\frac{P_n \sigma_s}{M}} \sum_{m=1}^{M} \begin{pmatrix} \sqrt{G_{BS}(\theta_{n,m,AoD})}\exp[j\{kd_s \sin(\theta_{n,m,AoD} + \phi_{n,m})\}]\times \\ \sqrt{G_{BS}(\theta_{n,m,AoD})}\exp[jkd_u \sin(\theta_{n,m,AoA})]\times \\ \exp\{jk\|v\|\cos(\theta_{n,m,AoA} - \theta_v)t\} \end{pmatrix} \quad (3.47)$$

Where

P_n is the power of the *n*th path, following exponential distribution.

σ_s is the lognormal shadow fading, applied as a bulk parameter to the *n* paths. The shadow fading is determined by the delay spread (DS), angle spread (AS), and shadowing parameters, which are correlated random variables generated with specific procedures.

M is the number of subpaths per path.

$\theta_{n,m,AoD}$ is the the AoD for the *m*th subpath of the *n*th path.

$\theta_{n,m,AoA}$ is the the AoA for the *m*th subpath of the *n*th path.

$G_{BS}(\theta_{n,m,AoD})$ is the BS antenna gain of each array element.

$G_{BS}(\theta_{n,m,AoA})$ is the MS antenna gain of each array element.

k is the wave number $\frac{2\pi}{\lambda}$, where λ is the carrier wavelength in meters.

d_s is the distance in meters from BS antenna element *s* from the reference $(s = 1)$ antenna.

d_u is the distance in meters from MS antenna element *u* from the reference $(u = 1)$ antenna.

$\phi_{n,m}$ is the phase of the *m*th subpath of the *n*th path, uniformly distributed between 0 and 360° .

$\|v\|$ is the magnitude of the MS velocity vector, which consists of the velocity of the MS array elements.

θ_v is the angle of the MS velocity vector.

- **Semi empirical Channel Models**

The preceding empirical channel models provide a very thorough description of the propagation environments. However, the sheer number of parameters involved makes constructing a fully empirical channel model relatively time consuming and computationally intensive. Alternatives are semi empirical channel models, which provide the accurate inclusion of the practical parameters in a real wireless system while maintaining the simplicity of statistical channel models.

Examples of the simpler empirical channel models include 3GPP2 pedestrian A, pedestrian B, vehicular A, and vehicular B models, suited for low-mobility pedestrian mobile users and higher-mobility vehicular mobile users. The multipath profile is determined by the number of multipath taps and the power and delay of each multipath component. Each multipath component is modeled as independent Rayleigh fading with a potentially different power level, and the correlation in the time domain is created according to a Doppler spectrum corresponding to the specified speed. The pedestrian A is a flat-fading model corresponding to a single Rayleigh fading component with a speed of 3 kmph; the pedestrian B model corresponds to a multipath profile with four paths of delays [0. 11. 19. 41] microseconds and the power profile given as [1 0. 1071 0.0120 0.0052]. For the vehicular A model, the mobile speed is specified at 30 kmph. Four multipath components exist, each with delay profile [0 0.11 0.19 0.41] microseconds and power profile [1 0.1071 0.0120 0.0052]. For the vehicular B model, the mobile speed is 30 kmph, with six multipath components, delay profile [0 0.2 0.8 1.2 2.3 3.7] microseconds, and power profile [1 0.813 0.324 0.158 0.166 0.004].

Another important empirical channel model for the 802.16 WiMAX fixed broadband wireless system is the Stanford University Interim (SUI) channel model. This model provides six typical channels for the typical terrain types of the continental United States: SUI1 to SUI6 channels. Each of these models addresses a specific channel scenario with low or high Doppler spread, small or large delay spread, different LOS factors, different spatial correlations at the transmitter, and receiver antenna array. For all six models, the channel consists of three multipath fading taps whose delay and power profiles are different.

These empirical channel models follow the fundamental principles of the statistical parametric models discussed previously in this chapter, while considering empirical measurement results. As such, semi empirical channel models are suitable for link-level simulations and performance evaluation in real-world broadband wireless environments.

Mitigation of Fading

The fading characteristic of wireless channels is perhaps the most important difference between wireless and wired communication system design. Since frequency-selective fading is more prominent in wideband channels—since a wideband channel's bandwidth is usually much greater than the coherence bandwidth—referred to channels with significant time dispersion or frequency selectivity as *broadband fading* and to channels with only frequency dispersion or time selectivity as *narrowband fading*. The next several chapters of the book are devoted to in-depth exploration of techniques that overcome or exploit fading.

Narrowband (Flat) Fading

Many different techniques are used to overcome narrowband fading, but most can be collectively referred to as *diversity*. Because the received signal power is random, if several (mostly) uncorrelated versions of the signal can be received, chances are good that at least one of the versions has adequate power. Without diversity, high-data-rate wireless communication is virtually impossible. Evidence of this is given in Figure 3.20, which shows the effect of unmitigated fading in terms of the received average bit error rate (BER). The BER probability for QAM systems in additive white Gaussian noise (AWGN) can accurately be approximated by the following bound [11]:

$$P_b \leq 0.2e^{-1.5\frac{\gamma}{M-1}}, \qquad (3.48)$$

where $M \geq 4$ is the *M* QAM alphabet size.10 Note that the probability of error decreases very rapidly (exponentially) with the SNR, so decreasing the SNR linearly causes the BER to increase exponentially. In a fading channel, then, the occasional instances when the channel is in a deep fade dominate the BER, particularly when the required BER is very low. From observing the Rayleigh distribution in Equation (3.39), it requires dramatically increased to continually decrease the probability of a deep fade. This trend is captured plainly in Figure 3.20, where reasonable system BERs, such as $10^{-5} - 10^{-6}$, the required SNR is over 30 dB higher in fading! Clearly, it is not desirable, or even possible, to increase the power by over a factor of 1,000. Furthermore, in an interference-limited system, increasing the power will not significantly raise the effective SINR.

Although BER is a more analytically convenient measure, since it is directly related to the SINR—for example, via Equation (3.38), a more common and relevant measure in WiMAX is the packet error rate (PER), or equivalently block error rate (BLER) or frame error rate (FER). All these measures refer to the probability that at least one bit is in error in a block of *L* bits. This is the more relevant measure, since the detection of a single bit error in a packet by the cyclic redundancy check (CRC) causes the packet to be discarded by the receiver. An expression for PER is

$$PER \leq 1-(1-P_b)^L \tag{3.49}$$

where P_b is the BER and *L* is the packet length. This expression is true with equality when all bits are equally likely to be in error. If the bit errors are correlated, the PER improves. It is clear that PER and BER are directly related, so reducing PER and BER are roughly equivalent objectives.

Diversity is the key to overcoming the potentially devastating performance loss from fading channels and to improving PER and BER.

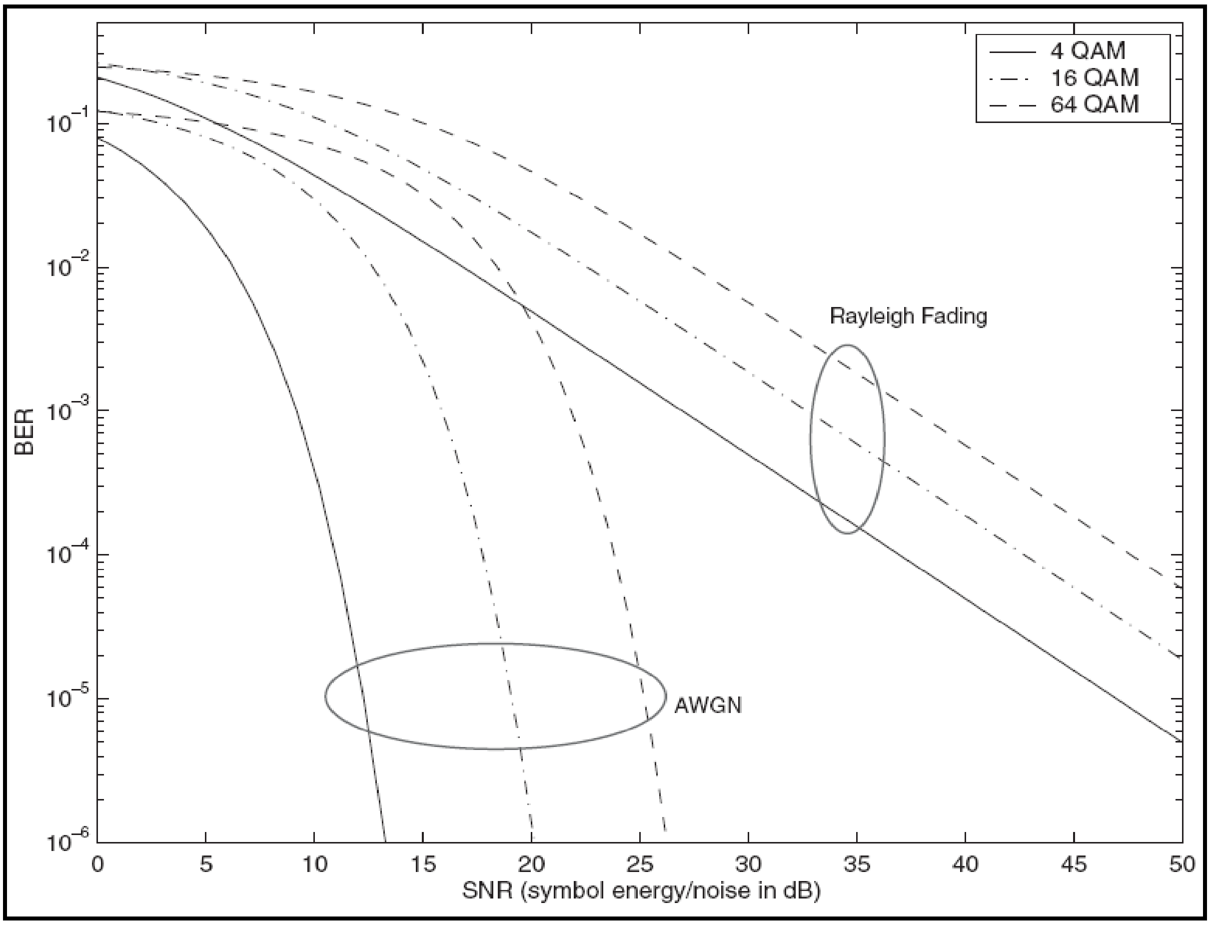


Figure 3.20 Flat fading causes a loss of at least 20 dB–30 dB at reasonable BER values.

- **Time Diversity**

Two important forms of time diversity are coding/interleaving and adaptive modulation. Coding and interleaving techniques intelligently introduce redundancy in the transmitted signal so that each symbol is likely to have its information spread over a few channel coherence times. This way, after appropriate decoding, a deep fade affects all the symbols just a little bit rather than completely knocking out the symbols that were unluckily transmitted during the deep fade. Transmitters with adaptive modulation must have knowledge of the channel. Once they do, they usually choose the modulation technique that will achieve the highest possible data rate while still meeting a BER requirement. For example, in Equation (3.48), as the constellation alphabet size *M* increases, the BER also increases. Since the data rate is proportional to $\log_2 M$. If the channel is in a very deep fade, no symbols may be sent, to avoid making errors. Adaptive modulation and coding are an integral part of the WiMAX standard and are discussed further in Chapters 5 and 9.

- **Spatial Diversity**

Spatial diversity, another extremely common and powerful form of diversity, is usually achieved by having two or more antennas at the receiver and/or the transmitter. The simplest form of

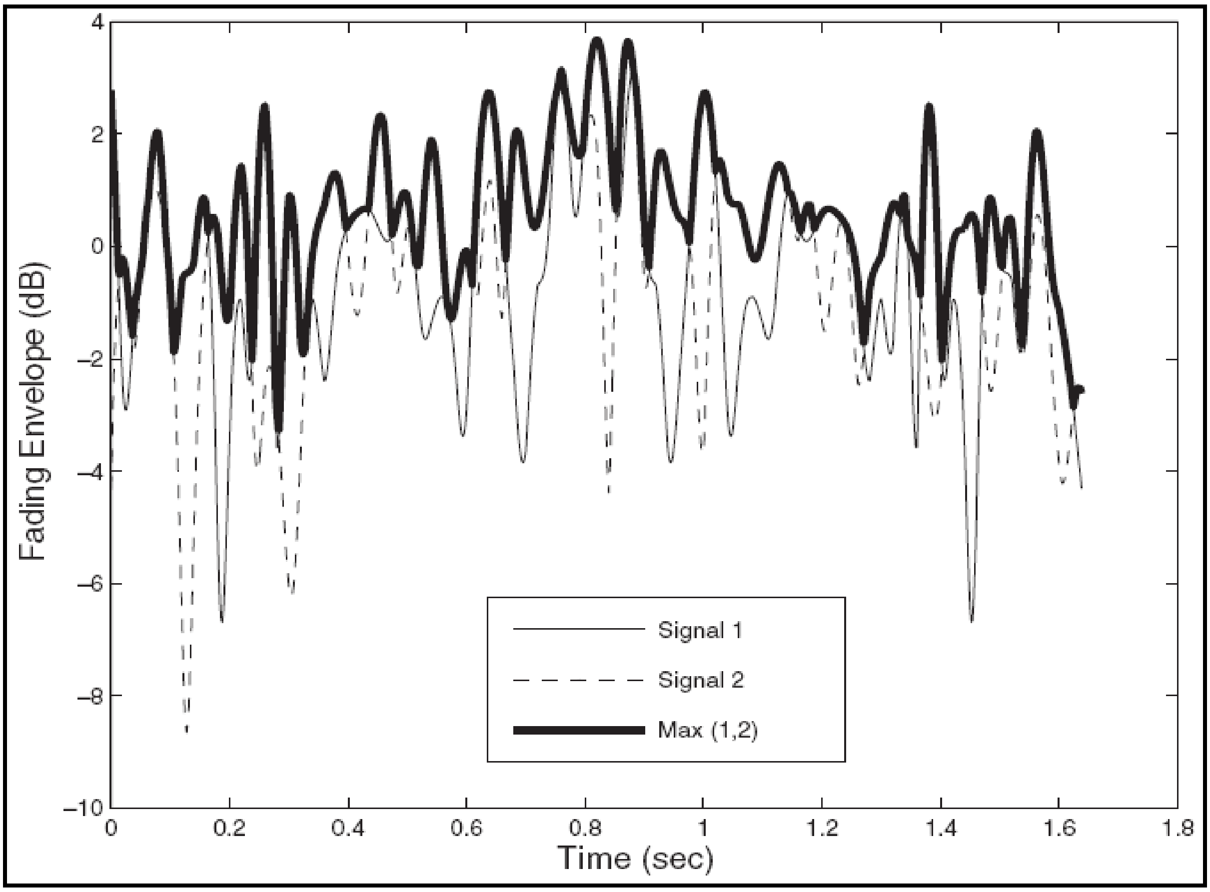


Figure 3.21 Simple two-branch selection diversity eliminates most deep fades.

Spread Spectrum and Rake Receivers

Somewhat counterintuitively, speeding up the *transmission* rate can help combat multipath fading, assuming that the *data* rate is kept the same. Since speeding up the transmission rate for a narrowband data signal results in a wideband transmission, this technique is called *spread spectrum*. Spread-spectrum techniques are generally broken into two quite different categories: direct sequence and frequency hopping. Direct-sequence spread spectrum, also known as code division multiple access (CDMA), is used widely in cellular voice networks and is effective at multiplexing a large number of variable-rate users in a cellular environment. Frequency hopping is used in some low-rate wireless local area networks (LANs) such as Bluetooth, and also for its interference-averaging properties in GSM cellular networks.

Some of WiMAX's natural competitors for wireless broadband data services have grown out of the CDMA cellular voice networks—notably 1xEV-DO and HSDPA/HSUPA—as discussed in Chapter 1. However, CDMA is not an appropriate technology for high data rates, and 1xEV-DO and HSDPA are CDMA in name only. Essentially, for both types of spread spectrum, a large bandwidth is used to send a relatively small data rate. This is a reasonable approach for low-data-rate communications, such as voice, whereby a large number of users can be statistically multiplexed to yield a high overall system performance. For high-data-rate systems, each user must use several codes simultaneously, which generally results in self-interference. Although this self-interference can be corrected with an equalizer (see Section 3.6.4), this largely defeats the purpose of using spread spectrum to help with intersymbol interference.

In short, spread-spectrum is not a natural choice for wireless broadband networks, since by definition, the data rate of a spread-spectrum system is less than its bandwidth. The same trend has been observed in wireless LANs: Early wireless LANs (802.11 and 802.11b) were spread spectrum13 and had relatively low spectral efficiency; later wireless LANs (802.11a and 802.11g) used OFDM for multipath suppression and achieved much higher data rates in the same bandwidth.

Equalization

Equalizers are the most logical alternative for ISI suppression to OFDM, since they don't require additional antennas or bandwidth and have moderate complexity. Equalizers are implemented at the receiver and attempt to reverse the distortion introduced by the channel. Generally, equalizers are broken into two classes: linear and decision directed (nonlinear).

A *linear equalizer* simply runs the received signal through a filter that roughly models the inverse of the channel. The problem with this approach is that it inverts not only the channel but also the received noise. This noise enhancement can severely degrade the receiver performance, especially in a wireless channel with deep frequency fades. Linear receivers are relatively simple to implement but achieve poor performance in a time-varying and severe-ISI channel.

A *nonlinear equalizer* uses previous symbol decisions made by the receiver to cancel out their subsequent interference and so are often called *decision-feedback equalizers* (DFEs). Recall that the problem with multipath is that many separate paths are received at different time offsets, so prior symbols cause interference with later symbols. If the receiver knows the prior symbols, it can subtract out their interference. One problem with this approach is that it is common to make mistakes about what the prior symbols were, especially at low SNR, which causes error propagation. Also, nonlinear equalizers pay for their improved performance relative to linear receivers with sophisticated training and increased computational complexity.

Maximum-likelihood sequence detection (MLSD) is the optimum method of suppressing ISI but has complexity that scales like $O(M^v)$, where *M* is the constellation size and *v* is the channel delay. Therefore, MLSD is generally impractical on channels with a relatively long delay spread or high data rate but is often used in some low-data-rate outdoor systems, such as GSM. For a high-data-rate broadband wireless channel, MLSD is not expected to be practical in the foreseeable future, although suboptimal approximations, such as delayed-decision-feedback sequence estimation (DDFSE), which is a hybrid of MLSD and decision-feedback equalization [7] and reduced-state sequence estimation (RSSE) [9] are reasonable suboptimal approximations for MLSD in practical scenarios [12].

The Multicarrier Concept

The philosophy of multicarrier modulation is that rather than fighting the time-dispersive ISI channel, why not use its diversity? For this, a large number of subcarriers (*L*) are used in parallel, so that the symbol time for each goes from $T \rightarrow LT$. In other words, rather than sending a single signal with data rate *R* and bandwidth *B*, why not send *L* signals at the same time, each having bandwidth $\frac{B}{L}$ and data rate $\frac{R}{L}$? In this way, if $\frac{B}{L} << B_c$, each signal will undergo approximately flat fading, and the time dispersion for each signal will be negligible. As long as the number of subcarriers *L* is large enough, the condition $\frac{B}{L} << B_c$ can be met.

Methodology

In our thesis work we have choose WiMAX as an upcoming deployment tools for Bangladesh to overcome the digital divide. Studying the technical features of WiMAX & comparing with the existing technologies, you can easily find out the benefits of WiMAX as a last mile access.

In Bangladesh, cellular communication already vastly established. There are 6 Mobile phone operators conducting their operation throughout the country. Bangladesh Telecommunications Company Limited (BTCL) is providing land phone connections country wide. Beside these recently formed some private PSTN company providing connection using Wireless Local Loop (WLL) in some area. Internet facilities are not available to all the area. Though we have connected with the super high way through the optical fiber, but our internal speed is not increased. The reason behind that our infrastructure is not able to cope up with the high speed data access. To ensure the high speed data & voice access around the country including highly rural area, Bangladesh Telecommunication Regulatory Commission (BTRC), the Government owned regulatory body for frequency licensing & quality maintain, has announced the licensing for Broadband Wireless Access (BWA). In our thesis work we have tried to maintain those criteria provided by the BTRC for BWA.

According to time limitations we have choose the link budgeting only for Dhaka city. Network planning is a very complex without any doubt. In Bangladesh there are extremely few people who are involving with the WiMAX network planning. Beside this they are not using any planning software for this particular job. Every organization using the planning simulation tools to design & maintain their network (like GP, Aktel, and Citycell etc.). Since WiMAX is a new technology, none of the company is currently using the tools for their proposed WiMAX planning. That’s why we had to skip some parts of our designing.

System Design:

Now, when we know that the predictions run by the planning tool can be trusted, the dimensioning of the RBS equipment, BSC and MSC is adjusted and the final cell plan is produced. As the name says, this plan is then used when installing the system. New predictions, both on coverage and interference, are run. Also, a document called CDD, Cell Design Data, is filled out, containing all cells parameters for each cell.

System Installation & Tuning:

Sometime after the system has been installed and started up, it is time to once again look at how well the system is adjusted to reality. This is called system tuning. The tasks include:

• Checking that the final cell plan was realized
• Evaluating possible customer complaints
• Checking that the network performance is acceptable
• Changing parameters and performing other measures, if needed.

System Elements in detail

This section details the system elements which comprise the following system configurations:
• HiperMAX-micro: All outdoor base station with 2x transceivers/antennas
• HiperMAX-1: ATCA based split indoor/outdoor base station with a single transceiver/antenna.
• HiperMAX-2: ATCA based split indoor/outdoor base station with 2x transceivers/antennas.
• HiperMAX-4: ATCA based split indoor/outdoor base station with 4x transceivers/antennas.

HiperMAX supports the following advanced antenna techniques associated with Fixed and Mobile WiMAX:
Fixed WiMAX:
• Space Time Coding (STC): Transmit Diversity requiring two mast head transceivers.
• Maximal Ratio Combining (MRC): Receive Diversity requiring two mast head transceivers.

Mobile WiMAX1:
• IO-MIMO: Interoperable Multiple In Multiple Out requiring at least two mast head transceivers.
• IO-BF: Interoperable Beam forming requiring four mast head transceivers.

Base Station Details

BS Type	HyperMAX4
Sector Angle	120 deg
Antenna Height	60m
EIRP (dBm)	36
Frequency Band	2.5 GHz
Duplex Method	TDD
Channel Bandwidth (MHz)	10
Network Type	Cellular
Propagation Environment:	Hilly, moderate to heavy tree density / Dense Urban
Maximum Non-LOS Range (km)	4.95
Maximum LOS Range (km)	44
Planned Cell Range (km)	4.95

Net Capacity Calculation

	Range (km)			**VoIP Service Flows** (with average 50byte packets)				**Data Service Flows** (with average 500byte packets)			
Modulation Distribution	Uplink	Downlink		Uplink		Downlink		Uplink		Downlink	
Mod			Gross Burst Rate (Mbps)	%age	Net Data Rate (Mbps)	%age	Net Data Rate (Mbps)	%age	Net Data Rate (Mbps)	%age	Net Data Rate (Mbps)
BPSK1/2	5.48	4.95	4.32	17%	**0.80**	20%	**2.13**	17%	**1.17**	20%	**2.37**
QPSK1/2	4.65	4.20	8.64	15%	1.40	16%	4.25	15%	2.35	16%	4.74
QPSK3/4	4.05	3.68	8.64	0%	1.88	0%	6.37	0%	3.52	0%	7.11
16QAM1/2	3.45	3.08	17.28	20%	1.88	21%	8.50	20%	4.69	21%	9.48
16QAM3/4	2.93	2.63	25.92	19%	2.80	19%	12.65	19%	7.04	19%	14.23
64QAM2/3	2.33	2.10	34.56	7%	2.80	6%	16.87	7%	9.39	6%	18.97
64QAM3/4	2.10	1.95	38.88	22%	2.80	18%	18.97	22%	10.56	18%	21.34
Aggregate Capacity (Mbps)				100%	2.07	100%	9.73	100%	5.83	100%	10.92
						Max Peak Rate (Mbps)			10.56		21.34

VoIP Parameters

Codec	*G729 10 ms*
Codec Data Rate (bits/s)	*8000*
VoIP Payload Header Size (octets)	*40*
Codec Frame Duration (s)	*0.01*
Codec Sample Size (octets)	*10*
Total Payload Size (octets)	*50*
Required Throughput per call (octets/s)	*5000*
Required Throughput per call (Mb/s)	*0.04*
Maximum # simultaneous calls =	*51*
Erlangs per RF	*38.9*
Erlangs per line	*0.08*
Maximum Planned VoiP Users per RF Channel	*486*

System Parameters & Link Budget Breakdown

Downlink

		NLOS	LOS
BS Tx Power	dBm	21.0206	21.0206
Tx Channel Combination Gain	dB	6	6
Tx AAS Gain	dB	3.3	3.3
AAS Pointing Loss	dB	0	0
Tx Diversity Gain	dB	0	0
BS feeder Loss	dB	1	1
Standard BS Antenna Gain	dBi	16	16
CPE Antenna Gain	dBi	13	13
CPE Feeder Loss	dB	0	0
Rx Diversity Gain	dB	0	0
BPSK_1/2 Rx Sens	dBm	-95.4	-95.4
Downlink Budget	dB	153.8	153.8

Uplink

		NLOS	LOS
CPE Tx Power	dBm	23.0206	23.0206
Tx Subchannelisation Gain	dB	0	0
Tx Diversity Gain	dB	0	0
CPE feeder Loss	dB	0	0
CPE Antenna Gain	dBi	13	13
Standard BS Antenna Gain	dBi	16	16
BS Feeder Loss	dB	1	1
BS Antenna Array Gain	dB	6	6
Rx Diversity Gain	dB	3	0
BPSK_1/2 Rx Sens	dBm	-95.4	-95.4407
Uplink Budget	dB	155.5	152.5

EIRP= BS Tx Power+ BS Antenna Gain- BS Feeder Loss

= 21.0206+16-1 = ***36.026 dB***

Propagation Model: COST 231 - Hata formulae

The basic formula for the median propagation loss given by cost 231-Hata is,

$$L(dB) = 46.3 + 33.9\log f_{MHz} - 13.82\log h_1 - a(h_2) + (44.9 - 6.55\log h_1)\log d_{km} - K$$

Urban indoor - large city

K = -3

$$a(h_2) = [1.1\log f_{MHz} - 0.7]h_2 - [1.56\log f_{MHz} - 0.8] - 15$$

Urban - large city

K = -3

$$a(h_2) = [1.1\log f_{MHz} - 0.7]h_2 - [1.56\log f_{MHz} - 0.8]$$

Urban - small city

K = 0

$$a(h_2) = [1.1\log f_{MHz} - 0.7]h_2 - [1.56\log f_{MHz} - 0.8]$$

Suburban

K = 0

$$a(h_2) = [1.1\log f_{MHz} - 0.7]h_2 - [1.56\log f_{MHz} - 0.8]$$

Rural

All rural has $a(h_2)=0$

Rural indoor (quasi-open)

$$K = 4.78(\log f_{MHz})^2 - 18.33\log f_{MHz} + 35.94 - 10$$

Rural (quasi-open) – countryside

$$K = 4.78(\log f_{MHz})^2 - 18.33\log f_{MHz} + 35.94$$

Rural (open) – desert

$$K = 4.78(\log f_{MHz})^2 - 18.33\log f_{MHz} + 40.94$$

$$L(dB) = 46.3 + 33.9\log f_{MHz} - 13.82\log h_1 - a(h_2) + (44.9 - 6.55\log h_1)\log d_{km} - K$$

= 162.95 db

For urban large city k=-3

$$a(h_2) = [1.1\log f_{MHz} - 0.7]h_2 - [1.56\log f_{MHz} - 0.8] - 15$$

= -14.95

Frequency f:	1500 – 2500 MHz
Base station height h_1:	30 – 200 m
Mobile station height h2:	1 – 10 m
Distance d:	1 – 20 km

Power Calculation

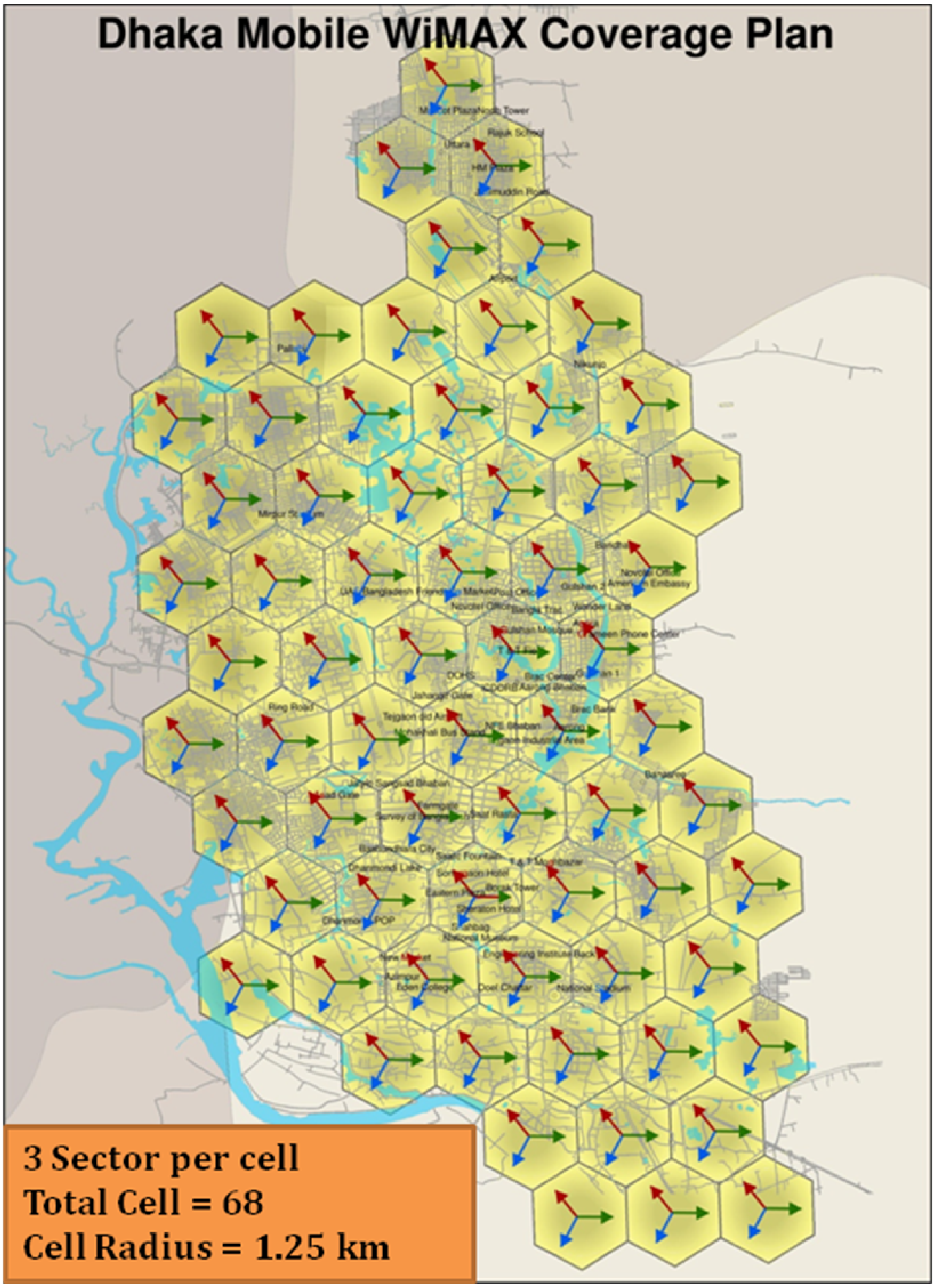
BS Tx Power in dBm= 21.0206
21.0206 = 10 Log10 (Ptx x 10^3)
Log10(Ptx x 10^3) = 2.1
Ptx = 0.12 Watt

Area of the Dhaka = 815 km²
Population: 11,918,442
BS radius r = 1.25 km

Served area by per BS = $\frac{3\sqrt{3}}{2}(1.25)^2 = 4.05 \approx 4\ \text{km}^2$

Needed Cell = $\frac{815\ \text{km}^2}{4\ \text{km}^2} = 203.75 \approx 204$

Needed BS (3 Sectored site) = $\frac{204}{3} = 68$


Dhaka Mobile WiMAX Coverage Plan
3 Sector per cell
Total Cell = 68
Cell Radius = 1.25 km

BTRC Specifications

- *At least **128 kbps** per subscriber should be ensured at all time*
- *EIRP of Central Station (Hub) should not exceed **+40dBm** per RF channel*
- *The minimum compression Codec to be used as equivalent to **Q. 729**.*
- *A contiguous 30 MHz of unpaired spectrum from **2.3 GHz** band (23xx-23xx MHz and 23xx-23xx MHz) will be assigned to 2 licensees. A contiguous 30 MHz of unpaired spectrum from **2.5 GHz** band (25xx-26xx MHz) will be assigned to 1 licensee.*
- ***30MHz** contiguous channel will be allocated to each operator to provide BWA services. Per channel bandwidth should be **either 5 or 10 MHz***
- *Subject to the availability, two pair of frequency will be assigned form any of the **18, 23, 26 and 38 GHz** band to build their own point to point link.*

Access Frequency Charge

Spectrum Charges in Taka = STU x CF x BW x AF x BF

Where,

i) STU=Spectrum Tariff Unit=1 US Dollar equivalent BDT @ published by Bangladesh Bank on the last day of each quarter.

ii) CF=Contribution Factor for Access Frequency shall be calculated considering the following table of subscriber base

iii) BW=Bandwidth Assigned for Access Frequency in MHz

iv) AF=Area Factor for Access Frequency= Geographical area of Bangladesh.

v) BF=Band Factor = 0.50

Sl.	Subscriber Base (lower limit inclusive & upper limit exclusive)	CF
1	From 0 to 200 K	0.35
2	From 200 K to 400 K	0.40
3	From 400 K to 600 K	0.45
4	From 600 K to 800 K	0.50
5	From 800 K to 1000 K	0.55
6	From 1000 K to above	0.60

Microwave Frequency Charge

Spectrum Charges in Taka = STU x CF x BW x AF x BF

Where,

i) STU=Spectrum Tariff Unit=1 US Dollar equivalent BDT @ published by Bangladesh Bank on the last day of each quarter.

ii) CF=Contribution Factor for Microwave Frequency=1

iii) BW=Bandwidth occupied for Microwave Frequency in MHz

iv) AF=Area Factor for Microwave Frequency Point to Point link=Link Length^2 x 0.273 (Minimum distance for Link Length shall be 7 km)

v) BF=Band Factor shall be calculated as per following table:

Sl.	**Band** (lower limit exclusive & upper limit inclusive)	**BF**
1	SHF1 (2.69-16 GHz)	0.25
2	SHF2 (16-31 GHz)	0.15
3	EHF1 (31-65 GHz)	0.10

Transmitted Power Charge

(d) UHF Band 2

Sl	***Output Power from the final stage of the Transmitter***	***Rate in Taka***
1	Less than 100 mW	1000.00
2	100 mW~500 mW	2000.00
3	500 mW~1 watt	3000.00
4	1 watt~3 watt	4000.00
5	3 watt~5 watt	5000.00
6	5 watt~10 watt	7500.00
7	10 watt~20 watt	10,000.00
8	20 watt~50 watt	20,000.00
9	Above 50 watt each additional watt or part thereof	2,000.00