THE UNIVERSITY OF CALGARY

The Design of a Multimedia Wireless Access Network

by

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Abstract

This thesis proposes data link protocols for a wireless access system that uses a COFDM physical layer to provide connectivity for multimedia services between moveable terminals and centralized base-stations connected to an ATM network. The requirements and constraints of the physical layer, the multiple access control sublayer, and the logical link control sublayer of a wireless ATM network are developed. A MAC sublayer is proposed that exploits the centralized architecture and allows for enforcement of ATM traffic contracts. The proposed LLC sublayer is based on the IEEE 802.2 protocol with suitable modifications for a wireless medium. The protocols are proposed in sufficient detail to allow for the development of a prototype system. Conclusions about the suitability of these protocols are presented, and recommendations for future research topics are provided to allow for the continuation of this work.

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Dedication

I dedicate this thesis to my "loved ones". Without you, this thesis would never have been written.

$$MSc = (sh + dshl) \bullet \int_{1994}^{1996} njs^{(w(t)+k(t))} dt + e^{ac/s}$$

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List Of Symbols And Abbreviations

AAL	Asynchonrous Transfer Mode (ATM) Adaptation Layer
ABR	Available Bit Rate
ack	acknowledgment
AGC	Automatic Gain Control
ARQ	Automatic Repeat reQuest
ATM	Asynchronous Transfer Mode
BER	Bit Error Rate
BS	Base Station
CAD	Computer Aided Design/Drawing
CBR	Constant Bit Rate
CDD	Code Division Duplexing
CDMA	Code Division Multiple Access
CLP	Cell Loss Priority
COFDM	Coded Orthogonal Frequency Division Multiplexing
CPU	Central Processing Unit
CSMA	Carrier Sense Multiple Access
dB	decibel
DLC	Data Link Control
DQPSK	Differential Quadrature Phase Shift Keying
DSAP	Destination Service Access Point
DSP	Digital Signal Processing
E1	A digital circuit consisting of thirty-two 64 kbps channels for a total capacity of 2.048 Mbps (European service)
FCS	Frame Checksum Sequence
FDD	Frequency Division Duplexing
FECC	Forward Error Control Coding
FIFO	First In First Out
f_s	Digital Signal Processing Sample Rate

G	Giga, 10^9, billion
Gbps	Gigabits per second
GFC	Generic Flow Control
GHz	GigaHertz
HDTV	High Definition Television
HEC	Header Error Control
IEEE	International Electrical and Electronics Engineers
IFFT	Inverse Fast Fourier Transform
isochronous signals	Signals that carry embedded timing information, or that are dependent on uniform timing.
ISDN	Integrated Services Digital Network
ISO	International Standard Organization
k	kilo, 10^3, thousand
kbps	kilobits per second
kHz	kiloHertz
LAN	Local Area Network
LBT	Listen Before Talk
LLC	Logical-Link Control
LLC-PDU	Logical Link Control Protocol Data Unit
LLC-SDU	Logical Link Control Service Data Unit
LNA	Low Noise Amplifier
LWT	Listen While Talk
M	Mega, 10^6, million
MAC	Multiple-Access Control
MAC-PDU	Multiple Access Control Protocol Data Unit
MAN	Metropolitan Area Network
Mbps	Megabits per second
MDR	Multiservices Dynamic Reservation
MHz	MegaHertz
min	minutes

MPEG	Motion Pictures Expert Group
MT	Moveable or Mobile Terminal
N	Number of Subcarriers
nack	negative-acknowledgment
ns	nanoseconds
OFDM	Orthogonal Frequency Division Multiplexing
OSI	Open System Interconnection
PA	Power Amplifier
PDU	Protocol Data Unit
PT	Payload Type
QoS	Quality of Service
RF	Radio Frequency
RSSI	Received Signal Strength Indication
RX	Receiver
SAP	Service Access Points
SDU	Service Data Unit
SEAL	Simple Efficient Abstraction Layer
SONET	Synchronous Optical Network
SSAP	Source Service Access Point
T1	A digital circuit consisting of twenty-four 64 kbps channels for a total capacity of 1.544 Mbps
TAXI	Transparent Asynchronous Xceiver Interface
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TX	Transmitter
UBR	Unspecified Bit Rate
UNI	User Network Interface
UTP	Unshielded Twisted Pair
VBR	Variable Bit Rate
VCI	Virtual Channel Identifier

VCXO	Voltage Controlled Crystal Oscillator
VPI	Virtual Path Identifier
W-ATM	Wireless Asynchronous Transfer Mode (ATM)
WAN	Wide Area Network

1. INTRODUCTION

1.1 Motivation

Technological innovation has resulted in many changes and improvements in the communications field. New communication networks are using a mixture of wired links and wireless links to carry a wide range of traffic types simultaneously. Although many of the traffic types are generated by conventional voice, video, and data sources, the low error rate and high capacity of the new networks have motivated the development of advanced applications.

The changes in network technology have affected three industries: the computing industry, the data communications industry, and the telecommunications industry.

In the past, these fields were primarily distinct. Data communications companies developed networks to carry data between terminals provided by the customers; telecommunication companies designed networks to carry voice conversations between terminals produced by telecommunication companies; and computing companies created equipment to provide functionality that was occasionally augmented by a communications network.

Today, the distinctions between data communication companies and telecommunication companies are blurring. With the volume of voice traffic increasing by 3% per year and data traffic increasing by 20% [Partridge], the telecommunication industry is trying to obtain a portion of the data market by developing networks that can carry voice, video, and data. The data communications industry is developing schemes to connect remote networks into larger compound networks. Both industries have a goal of developing a data transportation system that is independent of the particular type of information being carried by the network. Meanwhile, the computing industry is using the availability of high performance peripherals and processing units to develop new applications. These applications exploit the improved characteristics of the network, and stimulate the growth of the size, capacity, and quality of the networks.

The development of Asynchronous Transfer Mode (ATM) has been supported by all three industries. ATM has the potential to be a technology that is universally appealing as a transportation system for a wide range of traffic types that possess a wide range of data throughput requirements. A single ATM network will be able to carry voice, high-quality video, CD quality sound, secure data, bulk data, and many other traffic types. The design of ATM is independent of transmission technology, so ATM may be useful in the full range of network sizes from office-sized, local-area networks to continent-spanning, wide-area networks. Connections made with unshielded, twisted pairs of copper conductors are often used in office-environments, and connections of fiber-optic cables are often used for long distance systems.

In some situations, such as an office environment, the use of a tetherless access system offers many benefits: ease of installation and maintenance, and mobility of terminals. But, the need to mitigate the high-error rate of a wireless channel increases the complexity and cost of wireless communication systems. If the higher complexity and cost, in comparison with tethered systems, can be justified, then wireless communication systems have considerable attraction.

Research work into wireless ATM is split into two distinct fields: mobility-related; and wireless-related. Investigations into the mobility aspects of wireless ATM are focused on topics such as the management and maintenance of virtual circuits, and location tracking mechanisms for terminals. [Acampora] contains a proposal for a scheme to handle hand-over in a wireless ATM system.

Meanwhile, the wireless-related field of research is concerned with developing systems that provide high-speeds and low error rates over wireless channels, and support the traffic contracts and quality of service requirements of ATM. [Leslie], [Falconer1], and [Bernhard] present some alternatives for the development of wireless systems capable of delivering ATM directly to a desktop in an indoor environment.

This thesis considers the design of a wireless access system that is suitable for transporting ATM cells in an in-building environment between wireless terminals and a wired network. In the next section, the objectives of this thesis are discussed.

1.2 Thesis Objectives

This thesis uses the Open System Interconnection (OSI) reference model (standard [ISO7498-1]) developed by the International Standard Organization (ISO) as the framework for considering the functionality that must be provided in the designed wireless access system. The OSI model assigns particular roles and responsibilities to individual components in a layered structure. This thesis considers the functionality located in the physical and data link layers.

Researchers have focused considerable effort on the design of physical layers that may be suitable for high-speed, multimedia networks, such as ATM. We have elected to use the work in [McGibney] and [Morris] on Coded Orthogonal Frequency Division Multiplexing (COFDM) as the physical layer for the proposed wireless access system. By making this selection, we are able to summarize the characteristics, the constraints and the requirements of the physical layer, and then focus on the design alternatives of the data link layer, composed of MAC and LLC sublayers.

The primary objectives of this thesis are:

- to design a MAC layer and to identify the essential services it must provide to the LLC layer to form part of a wireless access system that is capable of carrying ATM data (cells) between wireless terminals and a wired backbone network;
- to summarize the design criteria for a wireless access system; and
- to provide sufficient system specifications for the development of a trial system.

1.3 Thesis Organization

The remainder of this thesis is organized as follows. Chapter 2 provides a more detailed overview of the issues that must be resolved in providing wireless access. Chapter 3 discusses the use of a COFDM physical layer, and Chapter 4 discusses the logical link control layer. Chapter 5 discusses the assumptions, requirements, and alternatives for the MAC layer. Chapter 6 presents our proposed multiple access control layer. Finally, Chapter 7 presents our conclusions and recommendations for future research.

2. OVERVIEW OF PROBLEM

2.1 Introduction

This chapter introduces the concepts associated with providing access to multimedia services using wireless access links. The architecture of a wide-area network is presented first. Then, examples of different types of multimedia traffic are presented. Finally, the problems associated with providing wireless access to a wired backbone network carrying multimedia services are discussed. When necessary, any network-wide assumptions that impact the design of the wireless access system are mentioned.

2.2 Networking Context

A discussion of the specific problems associated with wireless access cannot be undertaken without some knowledge of the architecture and principles used to construct the larger network.

2.2.1 Architecture

The geographical coverage area of a network may range from a small area, such as an office, to a large area, such as a continent. By interconnecting subnetworks, the effective geographical coverage that a user has access to may be increased dramatically. This is the concept of an internet.

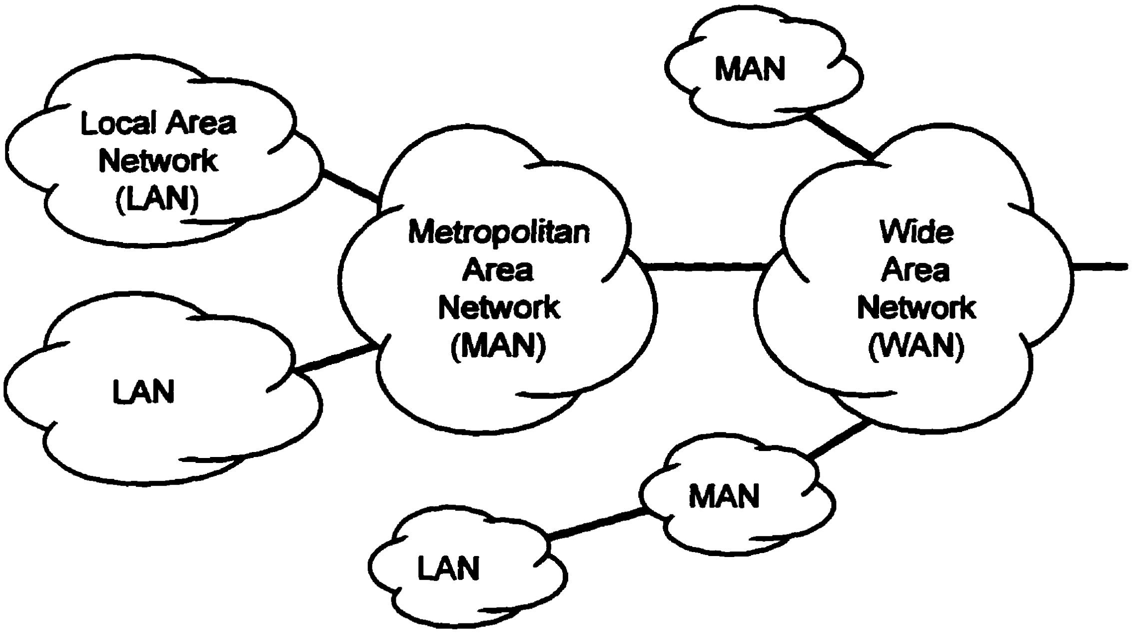

Figure 2.1: An Internet

In an internet (Figure 2.1), the majority of users connect to a local area subnetwork. Many of the services that the local users require are provided within the local subnetwork. However, for services and information outside the local subnetwork, a connection to a first-level wider area network, called a Metropolitan Area Network (MAN), is available. The MAN may itself be connected to a second-level wider area network, called a Wide Area Network (WAN).

The requirements for a local area subnetwork are quite different from those of a wide area subnetwork. In general, the technology deployed for LANs has been quite different from that used for WANs. However, the characteristics of ATM are suitable for a broad range of networking environments [Leslie]. ATM may be used in the local area, as well as the wide-area.

In the local subnetwork, terminals may be attached to the network system using wired technology, or wireless technology. These two types of attachment technologies may be used as a basis for splitting the local area subnetwork into two subnetworks as shown in Figure 2.2: wired-access, and wireless-access.

Wired-access and wireless-access can be used in a complementary fashion to provide access to a range of different services. Wireless-access is unlikely to replace wired-access because of the significantly higher cost and greater complexity; however, wireless-access may be used to increase the range of applications served by the subnetwork. This opportunity for wireless-access is also cited in [Leslie], [Armbrüster], [Bernhard], and [Falconer1].

In this thesis, the local area subnetworks are assumed to be deployed in an indoor office environment. The geographical area of such an environment is small (i.e., often less than 100 metres in diameter). A diverse mixture of terminals, such as desktop computers, workstations, fileservers, telephones, facsimile machines, video equipment, etc., is in use, with a wide range of traffic characteristics.

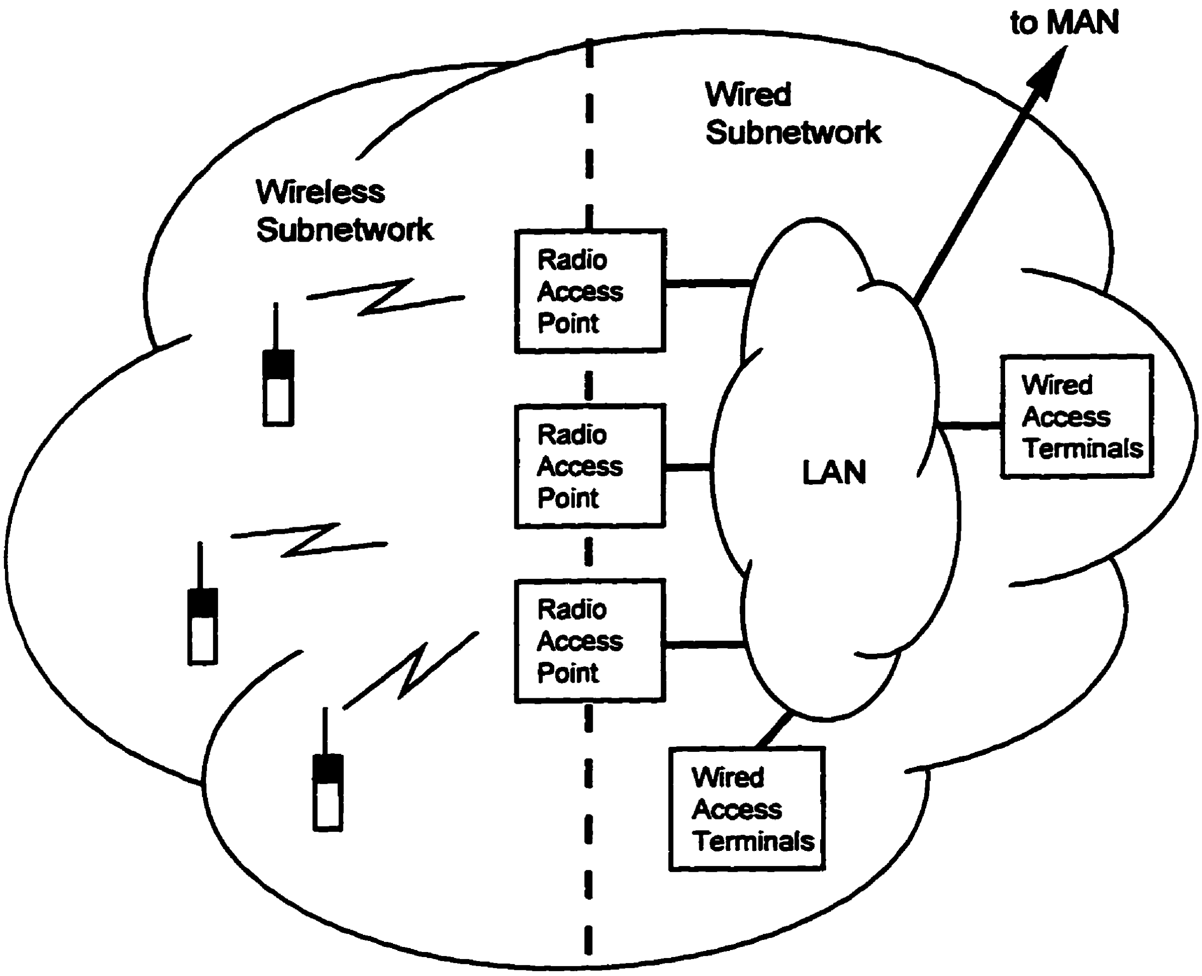

Figure 2.2: Local Subnetwork

2.2.2 ATM Principles

In the past, the number of traffic types was small, and each type of traffic had a separate distribution network (e.g., television, telephone). From the beginning, ATM was intended to carry a broad range of traffic types. In this section, the principles behind ATM are discussed.

With older network standards, the quality of service that an application received was chosen by the network (implicitly supplied). With ATM, an application negotiates a quality of service (explicitly supplied) [Shenker].

Early network standards were designed to overcome the frequent errors introduced on the communication channels. ATM assumes that errors are infrequent (i.e., BER < 10^{-9}). This assumption results in considerably simpler communication protocols, because complex error control and retransmission mechanisms are not required on each link. The error control problem has become an end-to-end problem, rather than a link-by-link problem. A discussion of the evolution of networking standards in the context of Broadband-ISDN (B-ISDN) development[1] is presented in [DePryker].

Also, technological innovation has allowed the data rate to increase tremendously from kilobits-per-second to gigabits-per-second. This wealth of capacity has freed the network designers from the need to design protocols to minimize the overhead of each message. This allows for more flexibility; however, the designer must be able to justify the expense of bandwidth.

ATM has been specified independently from a particular physical layer implementation, so wireless-ATM is possible. Also, ATM is not based on a particular data rate [Bernhard].

2.3 Refinement of the Local Environment

In this section, three significant factors in the local environment are considered:

- mobility characteristics of terminals;
- traffic definitions; and
- wireless network topology.

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[1] The development of ATM forms one part of the broader B-ISDN development.

2.3.1 Mobility Characteristics of Terminals

One of the significant advantages of wireless-access for users is the lack of a fixed communication tether between a terminal and the subnetwork. For the network, the movement of terminals requires the use of a 'mobility management scheme' to track the actual location of terminals, and to support hand-over of active calls.

To characterize the mobility of terminals, we must consider the movement of terminals between calls, and during calls. With these considerations, three types of terminals may be defined:

- fixed -- no movement between calls; no movement during calls;
- moveable[2] -- movement between calls; no movement (or, very limited movement) during calls; and
- mobile -- movement between calls; movement during calls.

Fixed terminals require the network to maintain a static location of each terminal within the network, and moveable terminals require that the network provide a dynamic location tracking scheme. Neither of these types of terminals need a call hand-over scheme. Mobile terminals require that the network provide a location tracking scheme, and a call hand-over scheme.

Another effect of mobility, that must be considered by the system designer, is the method of providing electrical power to terminals. This necessity of providing electrical power to each terminal is often overlooked by researchers who rave about the advantages of wireless. Fixed terminals can be wired directly to a source of electricity; moveable terminals may be powered from a wired connection, or from a battery; and mobile terminals likely need batteries.

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[2]In [IEEE 802.11], portable is used to refer to a mobile station that can move from location to location, but can only be used while at a fixed location.

This thesis considers only fixed and moveable terminals because most high data rate multimedia applications involve devices that remain stationary (or, at least, remain within a single geo-cell) during a call. Low speed applications, such as voice, are more likely to be mobile, and could be considered as an extension to this thesis. This assumption eliminates the need to consider hand-over, and is supported in [Bernhard] and [Falconer1]. A discussion of hand-over in ATM systems is provided by [Acampora].

2.3.2 User Traffic

The data that flows between a terminal and the subnetwork can be either network protocol information, or application information. In later chapters, the protocol information is considered in detail. In this section, we discuss the application information that may be conveyed between terminals.

An application is a service that generates and/or uses information passed over a network. Fundamentally, the transfer of application information is the reason for networks to exist. The application information that is transferred is referred to as user traffic. Signalling traffic is generated to support the transfer of the user traffic.

Older networking standards were designed to carry a single type of application information. Improvements in technology have allowed newer networks to be designed with the objective of transferring a variety of information: multimedia, or multiservices.

An examination of user traffic types requires the use of a suitable set of classification criteria. Three criteria are needed: (a) service type; (b) data rate; and (c) quality of service requirements.

2.3.2.1 Service Type

Applications may be either connection-oriented, or connectionless (e.g., a voice conversation versus an e-mail message) However, the view that an application has of the connection type may be independent of the type of connection that is actually present in the network. A network may transfer the output of a connectionless traffic generator over a connection-oriented route, or may transfer connection-oriented traffic over a connectionless route. The former case is much simpler than the latter, because the latter requires the presence of additional functionality within the network.

The source of a stream of traffic data may generate that data stream in a number of different ways. The following four categories are suggested in the literature to model the knowledge that the source has of the rate at which traffic is generated:

- Constant Bit Rate
- Variable Bit Rate
- Available Bit Rate
- Unspecified Bit Rate

2.3.2.1.1 Constant Bit Rate (CBR)

Applications that generate traffic at a constant bit rate are often real-time applications, such as digitized voice, that have a very low tolerance to delay. By minimizing the variation of delay, the buffering requirements at the endpoints of the ATM connections are very small. Another interesting example of a CBR connection is circuit emulation of T1/E1 channels.

2.3.2.1.2 Variable Bit Rate (VBR)

The development of more sophisticated source coding techniques for voice and video has resulted in a set of applications that generate data at non-constant rates. A popular example of such an application is an MPEG coder.

2.3.2.1.3 Available Bit Rate (ABR)

Early work on ATM revealed a large set of applications that required no firm guarantee of bandwidth. Instead, these applications are satisfied by receiving a data rate that is convenient to the network and within some limits required by the application. In exchange, the network guarantees a particular cell-loss ratio. The network can adjust the data rate offered to a particular connection to compensate for congestion within the network by using an end-to-end signalling feedback loop. [Bonomi] and [Kung] present discussions on the motivations for the development of the ABR traffic models, and explanations of possible rate-control algorithms.

2.3.2.1.4 Unspecified Bit Rate (UBR)

Some applications require the use of a network, but do not have an associated data rate requirement (other than as-soon-as-possible). Applications, such as file transfers from a server to a work station, have a minimal set of service requirements.

2.3.2.2 Data Rate

This criteria refers to the set of quantitative parameters that describe the rate at which user traffic is generated. The type of data generation process determines the number of parameters that are required to provide sufficient information about the traffic source. For example, an application that generates data at a constant rate may be described by a single parameter; a more complex application may generate data at a variable rate that must be described by a set of parameters.

2.3.2.3 Quality of Service (QoS) Requirements

An application may have particular requirements for the quality of service that the network must provide. These QoS requirements may be divided into three categories: accuracy, dependability, and speed. Accuracy and dependability criteria measure the ability of the network to deliver reliable, error-free service, and speed criteria relate to the ability of the network to deliver cells across the network in a timely fashion suitable for the application. Some examples of QoS requirements are: cell error ratio (accuracy), cell loss ratio (dependability), cell transfer delay (speed), and cell delay variation (speed) [Freeman] [ATMForum].

Application data may or may not be sensitive to delay introduced by the network. Generally, the variation in the delay, known as jitter, is more of a concern than the absolute delay. Often, applications that generate timing sensitive data expect that the destination can reproduce the timing of the source (i.e., the data is isochronous). For example, audio or video information must be converted at the destination at a particular rate to avoid distortion. Conversely, data may be delay sensitive, but not jitter sensitive (e.g., a real-time control system in a factory).

An application includes its QoS requirements in its call setup request. If the call setup is successful, then the network has agreed to meet the set of QoS requirements provided that the application does not violate the traffic contract.

2.3.2.4 Examples

This section contains examples of applications that may use a multimedia network. Table 2.1 and Table 2.2 have been adapted from [Falconer1] and [Barton] respectively.

Table 2.1: Multimedia Services

	Service Type		Data Rate		Quality of Service
Application	**Type**	**Typical Session Duration**	**Peak Rate [Mbps]**	**Mean Rate [Mbps]**	**Maximum Packet Loss Rate**
Video Teleconferencing	VBR	30 minutes	10	0.3 - 2	10^{-5}
Video Telephony	VBR	3 minutes	6	0.06 - 2	10^{-5}
High-Volume Transfer (e.g., CAD)	ABR, UBR	10 - 100 Mbytes	1 - 20	1 - 20	10^{-9}
High-resolution image retrieval (e.g., medical applications)	ABR, UBR	8 Mbytes	4 - 45	4 - 45	10^{-9}
Video Entertainment (e.g., HDTV)	VBR	15 minutes - 2 hours	150	3 - 32	10^{-7}
Portable multimedia	-	30 minutes	10 - 100	1 - 10	10^{-9}
Manufacturing (e.g., robotics)	-	continuous	0.01 - 3	0.01 - 3	10^{-9}

Table 2.2: Multimedia Services

	Data Rate	Quality of Service	
Application	**Throughput [kbps]**	**Maximum Delay [ms]**	**Target Bit Error Rate**
Voice Telephony	2.4 - 32	30 - 40	10^{-3}
Video Teleconferencing	64 - 684	40 - 90	-
Digital Video	1,000 - 6,000	100	10^{-6}
Data	100 - 10,000	30 (low delay) 300 (high delay) >300 (database access)	10^{-6}
Electronic Mail	9.6 - 128	100	10^{-6}

2.3.3 Wireless Topology

The topology of a wireless network specifies the interaction between terminals and other terminals, and the interaction between terminals and wired-network access points. Two distinct types of topology are possible:

- centralized; and
- distributed.

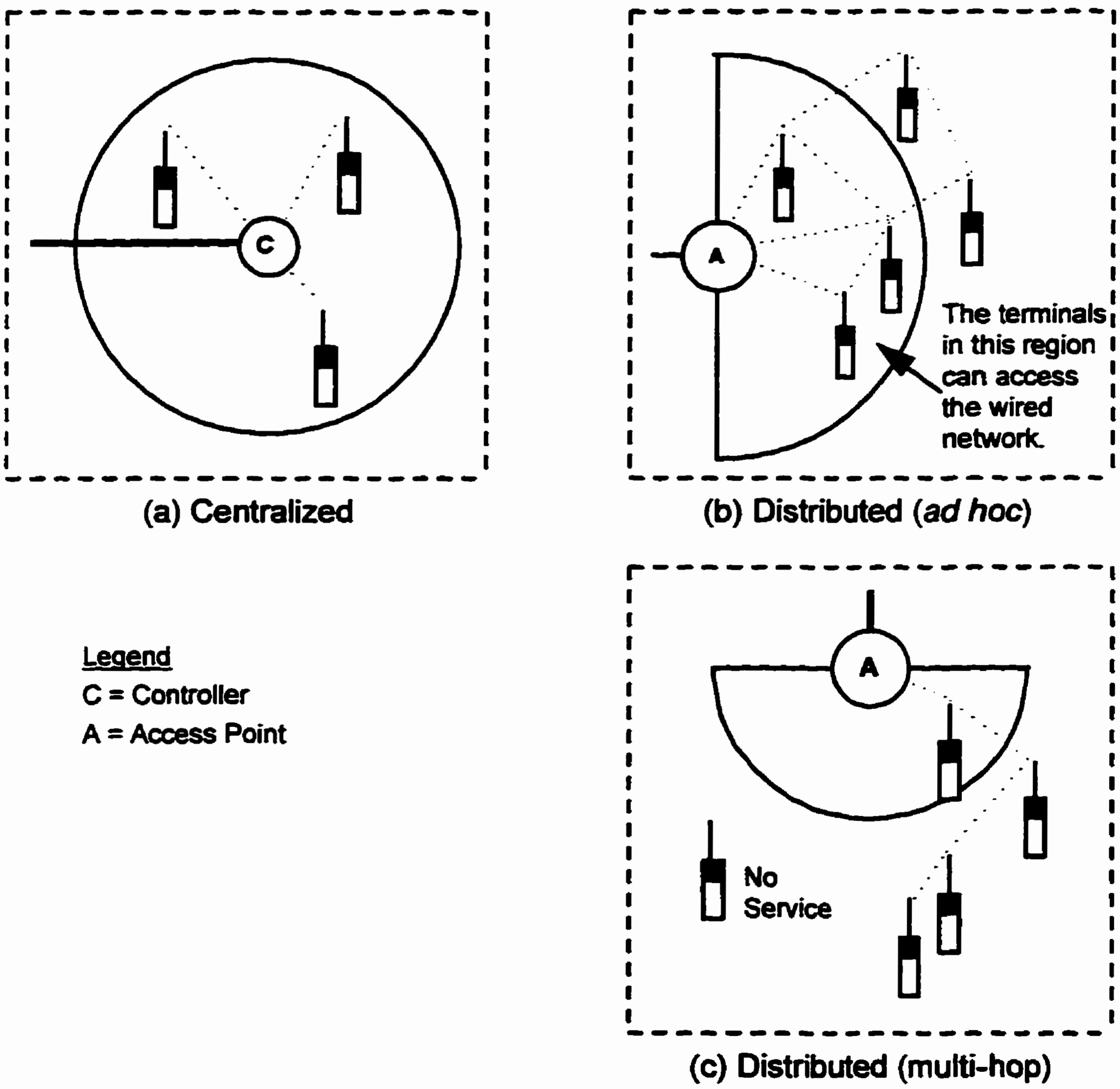

Figure 2.3: Wireless Topologies

2.3.3.1 Centralized

A centralized topology uses a base-station, or centralized-hub, to provide service to the terminals located in an area. The area covered by a base-station is referred to as a geo-cell (to prevent any possible confusion with ATM-cells). All data is passed through the base-station, regardless of the proximity of the destination to the source (Figure 2.3(a)). The base-station usually assumes the role of geo-cell controller, and is often referred to as a port, or gateway, into the wired network [Falconer2] [Smulders].

2.3.3.2 Distributed

A distributed topology (also known as an *ad hoc* topology) allows nodes that are within range of each other to communicate directly without the use of a centralized hub or base-station. Connectivity with remote terminals is provided by a wired network that is accessed at strategically placed Access Points (Figure 2.3(b)). With a pure *ad hoc* topology, terminals are always communication end-points.

Another distributed topology, that is mentioned in the literature, is the Multi-Hop topology (Figure 2.3(c)). This scheme is a more general form of the distributed topology with terminals permitted to be both communication end-points, and routers between distant nodes. This approach involves considerable complexity, and is not considered in this thesis.

2.3.3.3 Comparison

An extensive selection of literature exists comparing centralized and *ad hoc* network topologies: [Bantz], [Bernhard], [Falconer1], [Goodman2], [Halls], [Pahlavan], [Phipps], [Rypinski]. A summarized comparison of the two approaches follows (Table 2.3).

Table 2.3: Comparison of Centralized and Distributed Wireless Topologies

Criteria	Centralized	Distributed(*Ad hoc*)
RF Signal Coverage	Predictable (preconfigured).	Access points provide predictable coverage, but the coverage associated with the individual terminals is unpredictable.
Reliability	The base-station is a single point of failure.	An access point may fail, preventing access to the wired network, but direct interterminal communications would still be possible.
Asymmetrical Complexity on Wireless Links	Yes. Complex base-station, simple terminals.	No. All terminals and access points have the same complexity.
Configuration	Comparatively simple.	May be complex to configure individual terminals.
Channel Access Control	Centralized, may be simple.	Distributed, likely complex.
Ease of Upgrading Wireless Access Algorithms	Simple (if the base-station has control over the aspects being improved).	Difficult.

The asymmetrical complexity, predictable RF signal coverage, and simple configuration are considered desirable for a small indoor system. The single point of failure may be acceptable for some applications, or may be overcome by the use of a redundant hardware design. Therefore, a centralized topology is assumed in the remainder of this thesis.

2.4 Wireless Access Protocol Layers

To provide a useful connection, an access link, between a terminal and a network requires that the designer develop protocol solutions for a variety of problems that may occur on the link. For example, the protocols associated with providing access may need to implement techniques for dealing with problems such as corrupted data, congestion, and duplicate data messages. To manage the complexity of network protocols, the ISO developed the OSI model that partitions network functionality into seven layers. The bottom two layers, the physical layer and the data link layer, are of interest in this thesis.

2.4.1 Definition of Wireless ATM Access

The objective of the wireless access protocol layers is to allow wireless terminals to connect to and then to use a wired network infrastructure by using a well-defined interface to a set of protocols that implement a reliable communication link. The layers[3] that are considered to be part of a wireless access system are:

- Physical layer (layer 1);
- Multiple-Access Control (MAC) layer (lower half of layer 2); and
- Logical-Link Control (LLC) layer (upper half of layer 2).

Considerable literature has been produced by researchers discussing the position of the ATM layer in the classic OSI model: physical layer, link layer, or network layer? This thesis is based on the answer presented in [Alles]: "The question is moot." According to [Alles], the OSI model is just a model, and as a model it is unable to fit every possible situation. ATM provides functionality that could be assigned to the data link layer, and other functionality that is commonly associated with the network layer. With the system that is proposed in this thesis, the ATM layer is carried over (tunnelled through) a different networking layer: our wireless access protocol stack. Therefore, an adaptation of ATM that is suitable for a wireless link is located above the LLC layer in our protocol stack.

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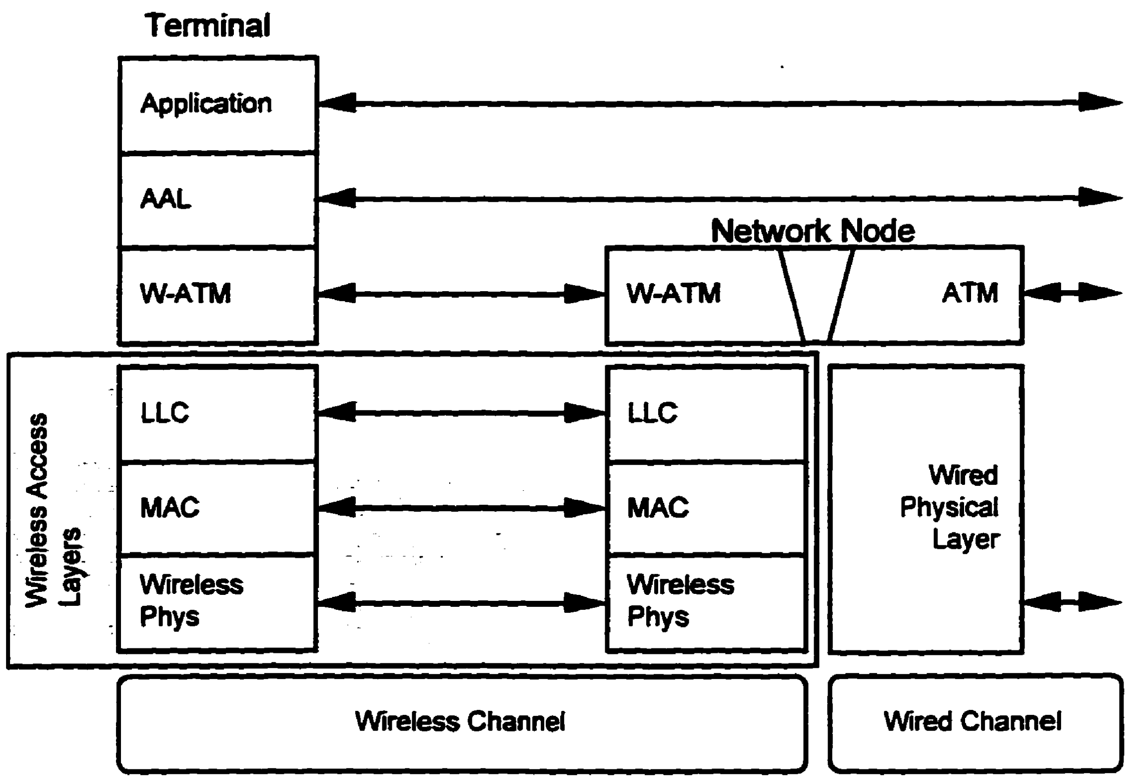
[3] The use of a layered architecture is a useful abstraction for examining functionality, but the layering should not be considered an essential characteristic of the actual implementation.

In the next three subsections, a brief summary of each of the layers in the wireless access protocol stack is presented. Figure 2.4 shows the layered structure of a wireless ATM terminal and a network node. This thesis is focused on the three layers that are contained in the gray region of that diagram: the wireless access layers.



Legend

AAL - ATM Adaptation Layer
LLC - Logical Link Control Layer
MAC - Multiple Access Control Layer
W-ATM - Wireless ATM

Figure 2.4: Wireless Access Protocol Layers

2.4.1.1 Physical Layer

The physical layer is concerned with the physical and electrical aspects of data communications. It is responsible for transmitting data bits over a communication channel.

The characteristics and responsibilities of the physical layer are discussed in Chapter 3.

2.4.1.2 Data Link Layer

The data link layer is responsible for achieving reliable, efficient communications between two machines connected by a single link. In broadcast communication systems, the data link layer is split into two parts: the Multiple Access Control (MAC) layer, and the Logical Link Control (LLC) layer.

2.4.1.2.1 Multiple Access Control Layer

The Multiple Access Control (MAC) layer is responsible for controlling access to a shared communication channel. This layer is also commonly known as the Media Access Control layer.

The MAC layer is discussed in Chapter 5 and Chapter 6.

2.4.1.2.2 Logical Link Control Layer

The Logical Link Control (LLC) layer is responsible for controlling the flow of information between adjacent nodes, such as a terminal and the base-station in a centralized architecture.

The LLC layer is discussed in Chapter 4.

2.4.2 Assumptions about the Higher Layers

The wireless access layers are involved in the tunnelling of ATM-cells across wireless links. Therefore, the higher layers include the ATM layer, the ATM adaptation layer, application layers, and layers related to the control of

ATM networks. In the following subsections, the assumptions about these layers above the wireless access layers are detailed.

2.4.2.1 Location Tracking

The current location of each terminal is known by the network, and can be accessed by the call delivery system to route calls to a terminal.

2.4.2.2 ATM Address Resolution

A terminal is identified by a global address. In a public network, a "telephone number-like" E.164 address is used; for a private network, the ATM Forum defined a 20-byte address format [Alles]. At the subnetwork attachment point, a MAC address identifies a particular terminal. Therefore, an address resolution protocol is required to cross-reference ATM addresses with MAC addresses.

2.4.2.3 Size of ATM Cell

The size of an ATM cell in the wireless portion of a network may be reduced from the size that is used in the wired portion. In Table 2.4 a comparison between the size of a wired ATM cell header, and our proposed wireless ATM cell header is presented. The size of a cell payload must remain unchanged at 48 octets.

Table 2.4: Comparison of Cell Headers for Wired ATM and Wireless ATM

Field Name	Field Size Wired ATM [bits]	Field Size Wireless ATM [bits]
Generic Flow Control (GFC)	4	0
Virtual Path Identifier (VPI)	8	0
Virtual Channel Identifier (VCI)	16	12
Payload Type (PT)	3	3
Cell Loss Priority (CLP)	1	1
Header Error Control (HEC)	8	0
Total Size [bits]	40	16

The GFC field may be eliminated because it serves no useful purpose, and is only present at the user-network interface (UNI). The VPI field is eliminated because terminals are intended to be terminating stations in the ATM network and do not need to switch a large number of virtual circuits. The size of the VCI field is reduced to fit the entire header into 2 octets (the number of channels at each base-station at the periphery of a network can likely be served with an address space of 4096, less a few addresses for ATM signalling). The PT field is not altered since it is used for end-to-end signalling (AAL 5 -- SEAL). Similarly, the CLP field is left untouched. The HEC field may be eliminated with the assumption that the error control used in the wireless access layers has at least the same probability of preventing an incorrectly addressed ATM-cell from entering the wired network as the error control provided by the HEC field does.

2.5 Summary

This chapter has provided a framework in which to consider the development of a physical layer, a logical link control layer, and a multiple access control layer as part of a wireless access system suitable for a wireless ATM system. Several assumptions about the overall system, such as the use of a centralized geo-cell topology and the elimination of hand-over, have been made in this chapter.

In the next chapters, the specific details of the three layers of the wireless access system are considered.

3. THE PHYSICAL LAYER

3.1 Introduction

This chapter is focused on providing a complete description of the lowest protocol layer of the wireless access protocol stack: the physical layer.

3.2 Purpose of the Physical Layer

The physical layer is responsible for the transmission of data bits over a particular type of transmission medium. A complete description of a physical layer protocol includes details about the following four characteristics [Spragins] [Stallings]:

- mechanical (e.g., the physical connector);
- electrical (e.g., voltage levels, signal timing, etc.);
- functional (e.g., assign meanings to pins of the connector); and
- procedural.

This chapter is concerned primarily with the procedural characteristics of the COFDM physical layer that has been chosen for the proposed wireless access system. The procedural specifications detail the sequences of control and data messages that are needed to set up, use, and deactivate physical layer connections.

3.3 The Wireless Channel

The IEEE standard for wireless LANs, IEEE 802.11, summarizes the differences between a wireless channel and a wired channel as: "A wireless medium is quite different from a wired medium: limited physical point-to-point range; shared medium; unprotected from outside signals; significantly less reliable; and dynamic topologies." The next five subsections briefly examine each of these differences.

3.3.1 Limited Point-to-Point Range

Firstly, signals in a wireless medium cannot be easily directed along a precise point-to-point path, but signals in a wired medium are channelled within that medium. Therefore, the energy in a wireless signal is often dispersed across a wider area than desired.

Secondly, the wireless channel is a complex environment in which signals must pass through objects such as walls, partitions, people, and fabric. This wireless environment typically has a higher propagation loss than a wired environment.

3.3.2 Shared Medium

All the users of a wireless system in a geo-cell share the same medium; therefore, techniques must be developed to control the access to the medium by these users. Without coordination, the users would be unable to communicate effectively.

3.3.3 Unprotected from Outside Signals

The use of a shared medium allows other devices to interact intentionally or unintentionally with the communication medium. These other devices may introduce interference, and may represent a security risk for the information being transmitted.

3.3.4 Significantly Less Reliable

Wireless systems may experience transmission errors introduced by a variety of sources: shadowing, reflections from outside the system, Doppler shift, channel fading due to multipath interference, thermal noise, and co-channel interference. These problems may be alleviated, but at the expense of greater complexity in the system.

3.3.5 Dynamic Topologies

One of the greatest benefits of wireless communications is the ability of terminals to move. However, when terminals move, the topology of the network changes, and the network must be able to handle these changes dynamically. Some of the alternatives for network topologies are presented in Chapter 2.

3.4 The Chosen Physical Layer Technology

Coded Orthogonal Frequency Division Multiplexing (COFDM) has been selected as the modulation scheme for the physical layer of our wireless access system. A description and analysis of this wide-band form of OFDM is available in [Morris] and [McGibney1]. A survey of some other physical layer modulation schemes proposed in the literature can be found in [Raychaudhuri].

COFDM works by splitting a high-speed data stream into many slower signals that are frequency multiplexed. Each transmitted symbol is composed of a set of these low speed signals, and carries a large amount of information, on the order of 40 to 60 octets. An OFDM-symbol is referred to as an OFDM-block. The use of forward error correcting coding (FECC) for each block of data, and combinational antenna diversity at the base-station, results in a system that achieves an exceptionally low bit error and a high data rate even in the presence of severe multipath fading.

COFDM has many attractive characteristics, such as:

- high data rate;
- low block-error-rate;
- no equalization;

- no carrier recovery; and
- large tolerance to timing errors.

However, COFDM has disadvantages:

- requires significant DSP resources;
- has a very high power consumption; and
- needs a wide-band linear power amplifier.

The characteristics of a COFDM system implemented by TRLabs, and a proposed future generation, are presented in Table 3.1 [McGibney]. Of particular note in this table is the high net data rate, 88 Mbps, achieved by a working prototype.

Table 3.1: Wireless LAN Specification

System Parameters	Future System	Implemented System
Number of Subcarriers (N)	202 (2 reference, 200 data)	202 (2 reference, 200 data)
Subcarrier Modulation	DQPSK (2 bits per symbol)	DQPSK (2 bits per symbol)
Total Bits per Block	400	400
RF Bandwidth	141 MHz	80 MHz
RF Centre Frequency (f_c)	> 10 GHz	1.8 GHz
DSP Sample Rate (f_s)	178.5 MHz	100 MHz
Total Block Length (M)	324 samples	308 samples
Block Duration	1613 ns	2880 ns
Guard Time between Blocks	200 ns	200 ns
Total Time per Symbol	1813 ns	3080 ns
Error Control Coding	Reed-Solomon (8 bytes per block)	Reed-Solomon (8 bytes per block)
Raw Bit Rate	220 Mbps	130 Mbps
Net Data Rate	150 Mbps	88 Mbps
Coding Overhead	32%	32%

3.5 Physical Layer Characteristics

Before the multiple access control (MAC) layer can be considered, a detailed model of the physical layer is required. This model is based on the following characteristics:

- data rate;
- error control coding;
- diversity;
- block error rate;
- duplexing;
- synchronization requirements;
- PA requirements (TX/RX guard times);
- power control; and
- pipelining effects.

Each of these characteristics is discussed in the following subsections.

3.5.1 Data Rate

Two data rates may be considered at the physical layer: (a) the raw data rate that is actually transmitted over the air; and (b) the effective data rate that is available to the MAC layer. The physical layer adds forward error correction coding to each MAC-SDU[1], so the raw data rate is higher than the effective data rate. For the purposes of the physical layer model to be used by the MAC layer, the effective data rate is most useful, and should be specified using two values:

- the size of a block (octets per block); and
- the block transmission rate (blocks per second).

3.5.2 Error Control Coding

The physical layer in a transmitter adds forward error control coding to each MAC-SDU. The receiver may use the FECC to attempt to correct any errors that have been introduced by the transmission channel.

One option that exists is to control the amount of FECC that is added to each MAC-SDU based on the characteristics of the channel. A channel with few errors may require less coding than a channel with many errors. Unfortunately, considerable complexity is introduced by allowing for a selectable amount of coding.

---

[1] A MAC-SDU (service data unit) is passed from the MAC layer to the physical layer, and is accompanied by an ICI (information control information) field. The physical layer, after interpreting the ICI, generates a PHYS-PDU composed of the MAC-SDU and some header information needed by the physical layer at the receiver. If necessary, the physical layer may fragment each SDU into separate PDUs, but the physical layer at the receiver must be able to reconstruct the SDU. From the perspective of the LLC layer, that same MAC-SDU may be viewed as a MAC-PDU containing a LLC-SDU with header information added by the MAC layer [Tanenbaum].

3.5.3 Diversity Options

The error rate of the physical layer may be improved by the use of some form of diversity: frequency, time, or antenna.

OFDM inherently provides a form of frequency diversity by transmitting the subcarriers across a wide bandwidth. The use of FECC in each block of data is exploiting this diversity by transmitting coding information rather than the same information on other frequencies.

Antenna diversity is another effective technique for improving the error performance. Multiple antennas, separated by a distance that allows for statistically independent signals to be received by each antenna, may be located at the receiver. The receiver may either demodulate the signal from multiple antennas and then combine the resulting signals before making a decision (combinational diversity), or the receiver may choose to use the signal from one of the antennas (switched-antenna diversity). The combinational diversity scheme generally produces better results than the switched-antenna scheme, but the combinational diversity scheme requires that much of the receiver hardware be duplicated.

The cost and size associated with multiple antennas may be acceptable at a base station, but not at a terminal. One approach that may be attractive is for a base-station to transmit on a single antenna, and to switch the transmit antenna at the request of the receiving terminal. A second approach (time-diversity) would have the base-station transmit each data block multiple times (e.g., twice) using a different antenna each time. The receiving terminal would then demodulate and store each block until all copies of the block had been received. Then, the terminal could combine the received copies before making a decision. This second solution compromises speed and efficiency for significantly better error performance.

3.5.4 Block Error Rate

The physical layer uses a combination of FECC and diversity to achieve a highly reliable (i.e., low block error rate) data transmission facility. The block error rate is determined by the pattern of errors introduced by the channel within each block rather than just the number of bits in errors.

3.5.5 Duplexing

Data flows bidirectionally between a terminal and a base-station. The uplink (from terminal to base-station) and downlink (from base-station to terminal) may be separated in one of three ways: frequency (FDD), code (CDD), or time (TDD).

In the proposed system, a single frequency band has been assigned to each geo-cell. Therefore, the uplink and downlink paths are multiplexed in time, time-division duplex.

An advantage of TDD is that the uplink and downlink data bandwidths may be dynamically controlled according to the type of traffic in the cell [Karol] [Falconer2]. Also, because of the reciprocal channel, antenna diversity needs only be implemented at the base-station. The use of TDD is possible because channel equalization is not required in an OFDM system [Smulders].

The choice of TDD significantly affects the MAC layer, since a device that is receiving information must delay returning any information to the transmitter until a later time.

3.5.6 Frequency and Time Synchronization

Frequency synchronization is required so that the subcarriers of the OFDM signal are not frequency shifted into a position where they might interfere with each other.

Timing synchronization is needed to position the signal in the optimum sampling window, and to ensure that the phases of the subcarriers are properly aligned. Once synchronized, the physical layer can adjust the start of its transmit window to account for the propagation delay, and thereby ensure that each transmitted symbol is received at the destination in the correct time window.

A joint time and frequency synchronization technique is suggested for the OFDM system [McGibney2]. The proposed scheme requires that the base-station transmit a characteristic header block periodically to allow new terminals to achieve synchronization. Once a terminal has achieved synchronization, it must decode approximately 20 blocks per second from the base-station to maintain synchronization. These blocks may be header blocks, or normal data blocks transmitted by the base-station.

3.5.7 Power Amplifier Limitations

A portion of a transceiver (transmitter and receiver) for a TDD system is shown in Figure 3.1. A time guard band is essential between the transceiver actively transmitting a symbol and the transceiver successfully receiving a symbol because the output power level must be allowed to drop sufficiently if the receiver is to be able to correctly demodulate a received signal (the received signal strength may be more than 80 dB below the transmitted signal strength). Similarly, a guard band is necessary between receiving and transmitting to allow the power amplifier to "ramp up".

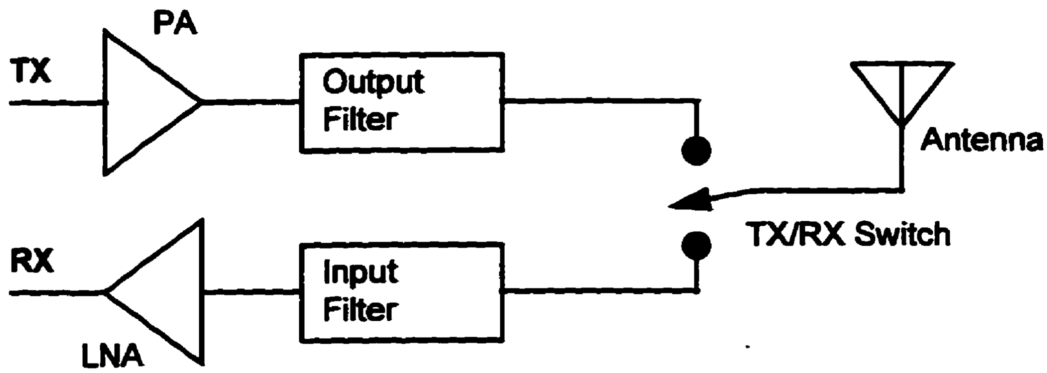


Figure 3.1: Transceiver Front-End for a TDD System

In comparison, a transceiver built for an FDD system does not require any guard bands because the input and output bandpass filters would be tuned to block any undesirable energy.

3.5.8 Power Control

The physical layer has control over:

- the transmit power, and
- the automatic gain control (AGC) of the receiver.

3.5.8.1 Transmit Power Control

The power level used by terminals to transmit can be altered to prevent "ringing" effects between adjacent time slots. A simple open-loop control scheme is proposed in which the base-station sends power control messages to individual terminals to increase or decrease transmit power. This requires that the base-station maintain a concept of power level for each terminal.

3.5.8.2 Automatic Gain Control

The automatic gain control of the receiver can be completely controlled within the receiver based on the level of the input signal. AGC is needed to control the RF gain of an input signal so that the signal arriving at the A-to-D converter is neither clipped, nor poorly quantized.

3.5.9 Pipelining Effects

Considerable data processing is required to produce an encoded OFDM signal. The elements of an OFDM transmitter and receiver are constructed using a pipelined architecture to improve the performance of the system. Two timing effects that are crucial to the effective operation of the physical layer are:

- pipeline processing delay; and
- pipeline blocking.

These timing effects are explained in the next two subsections.

3.5.9.1 Pipeline Processing Delay

Delay is introduced by each component in the data processing path of a transmitter and a receiver. Fortunately, the delay is constant for all data blocks transmitted and received by a particular physical layer design. Unfortunately, the amount of delay is particular to the design of that physical layer, so a base-station may be controlling a mixture of terminals with different delays. With a COFDM system, the processing delay of a transmitter, $t_{tx\text{-}processing}$, is likely to be different from the processing delay of a receiver, $t_{rx\text{-}processing}$.

3.5.9.2 Pipeline Blocking

The internal design of a pipeline may require that the user of the pipeline prevent access to the pipeline for a period of time after each use. This situation may arise if an element or a set of elements in the pipeline is required for a longer time than the other elements. This problem is illustrated using the three pipelines shown in Figure 3.2.

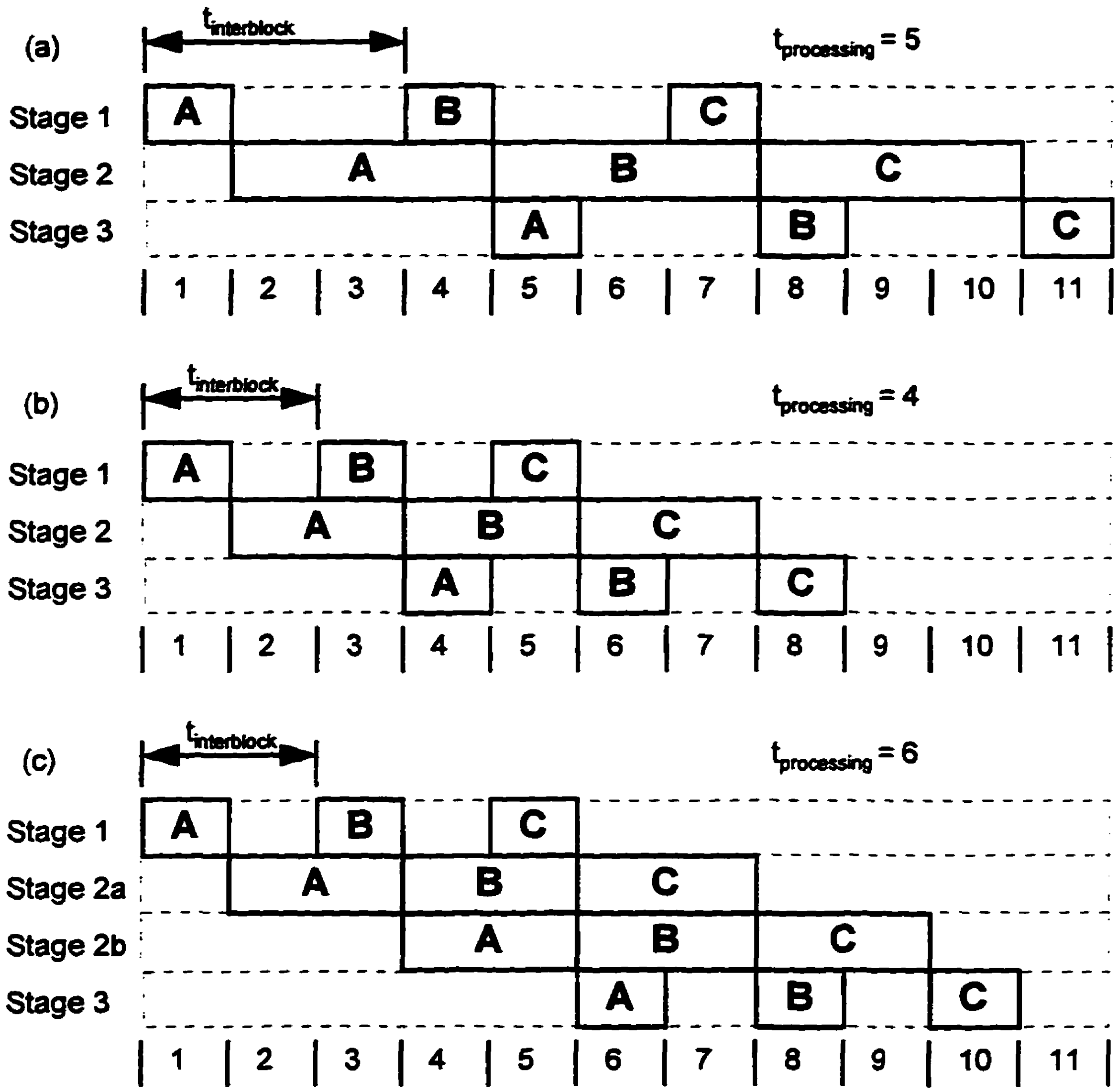


Figure 3.2: Pipeline Design Alternatives

In the first pipeline, Figure 3.2(a), an external delay is required to limit access to the pipeline. In the second pipeline, Figure 3.2(b), the use of faster components reduces the duration of the required external delay (and reduces the processing delay), but the cost of this pipeline is likely higher than the first pipeline because of the use of those faster components. In the third pipeline, Figure 3.2(c), the stage with the largest delay is subdivided into smaller processing elements, which increases the total number of stages in the pipeline, but reduces the duration of the required external delay.

Another approach is to add a FIFO (or FIFOs) to the pipeline. A FIFO allows data to queue until it can be processed by the next component in the pipeline. By using a FIFO in this manner, the requirement for interblocking delay external to the pipeline may be eliminated, but the user of the pipeline must be aware of the potential for overflow (i.e., a FIFO adds delay to the pipeline as necessary, but cannot speed up the operation of the pipeline).

3.5.9.3 OFDM Pipeline Effects

Figure 3.3 and Figure 3.4 show the delay through the fundamental elements of the transmitter and receiver of a COFDM system. The delays shown in the figures are based on the protocol system. In these figures, t_{cycle} is the duration of a clock tick of the transceiver, t_{block} is equal to t_{cycle} multiplied by the number of octets in a block, and t_{slot} is t_{block} plus the guard time required between symbols.

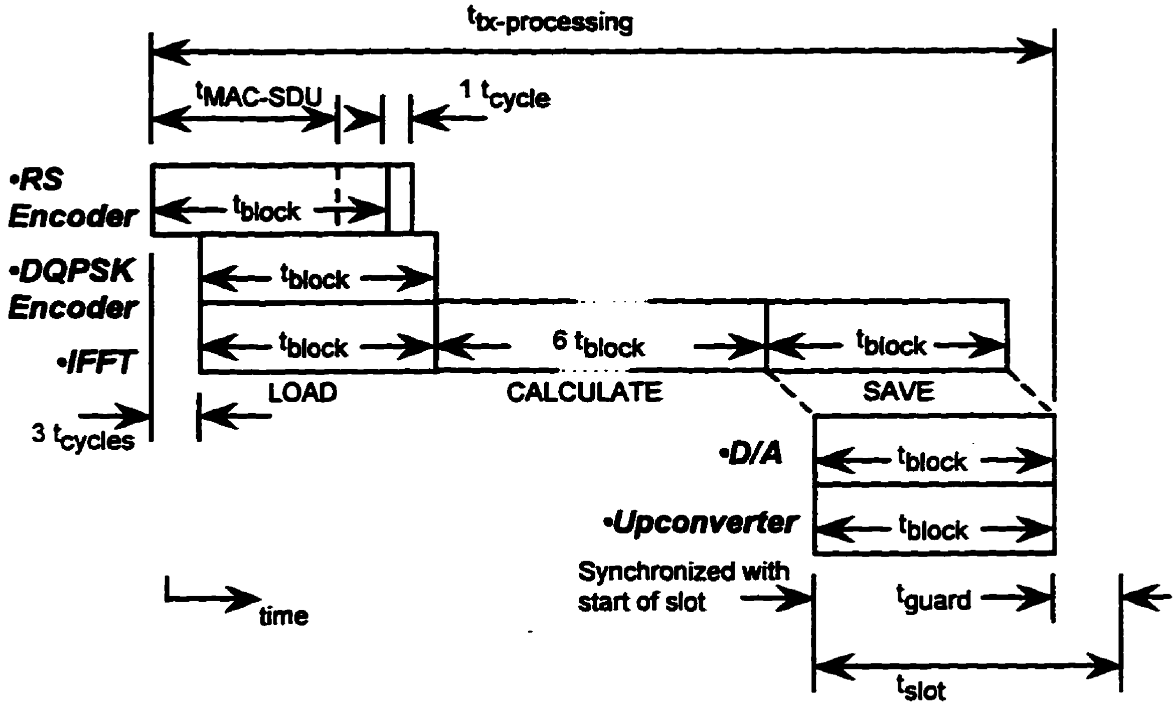


Figure 3.3: OFDM Transmitter Pipeline Timing

In the transmitter (Figure 3.3) the IFFT represents the most significant point of delay. The minimum delay of the IFFT is 1 t_{block} because all of the data must be loaded before the first result may be generated; the delay of the IFFT in the prototype implementation is 8 t_{block}.

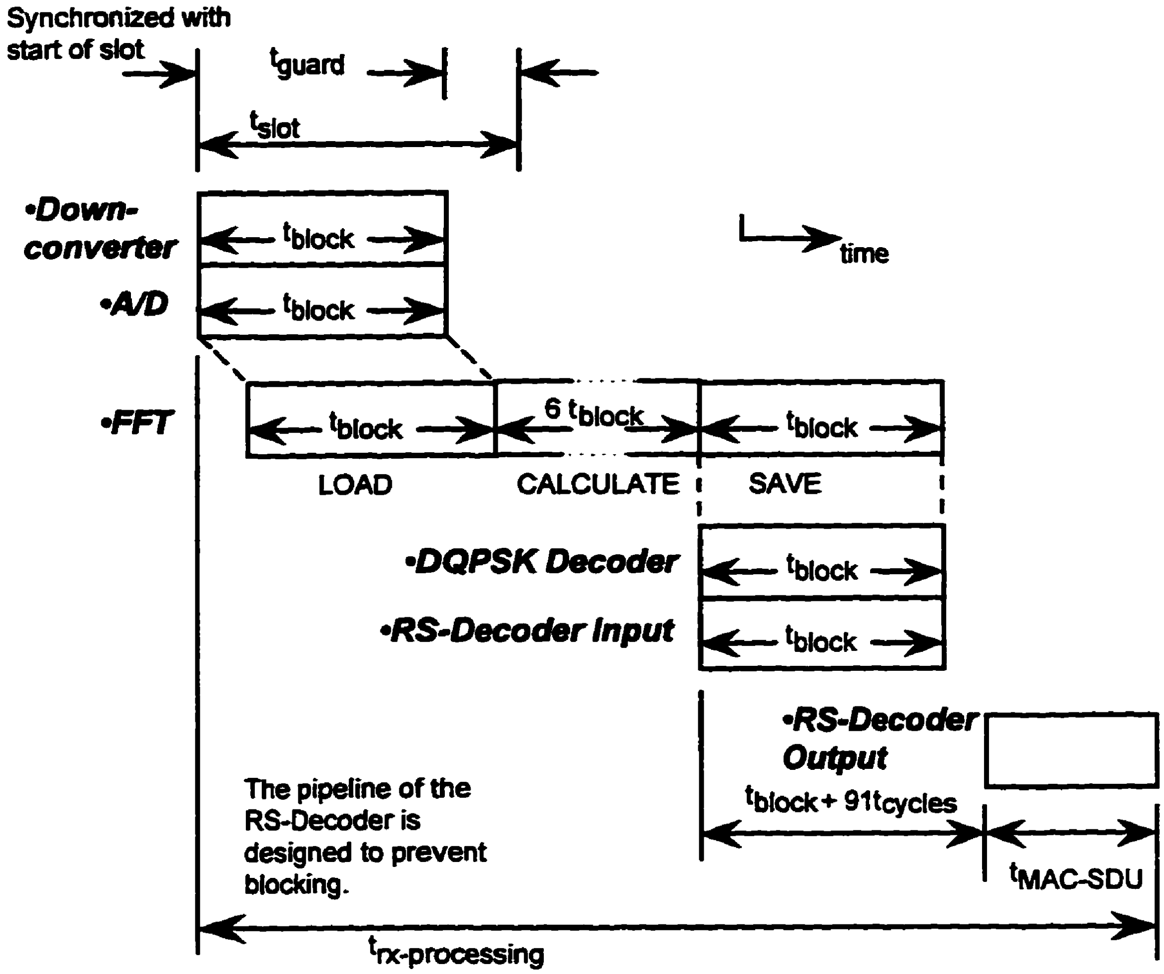


Figure 3.4: OFDM Receiver Pipeline

The FFT of the receiver (Figure 3.4) is the most significant point of delay. The RS-decoder must load an entire block before it can begin decoding.

3.6 The Physical Layer Interface

The interface between the MAC layer and the physical layer is defined by a set of primitives. The primitives that are available to the MAC layer allow the MAC layer to control the operation of the transmit and receive pipelines; and the physical layer has a set of primitives to support the MAC layer control functions, and to pass received messages to the MAC layer. The next section describes the primitives in greater detail.

3.6.1 Primitives

The total set of primitives may be split into three categories:

- transmit primitives
- receive primitives
- state primitives

Transmit primitives relate to the transmit pipeline, and receive primitives relate to the receive pipeline. The effect of a transmit primitive on the communication channel is delayed by the OFDM pipeline until a time in the future; a receive primitive causes an immediate operation on the communication channel, but the result is delayed by the receive pipeline. In controlling the transmit and receive pipelines, the MAC layer must ensure that the transmitter and receiver do not access the communication channel simultaneously. Figure 3.5 demonstrates the effect of the delays in the transmit and receive pipelines on the accesses to the communication channel.

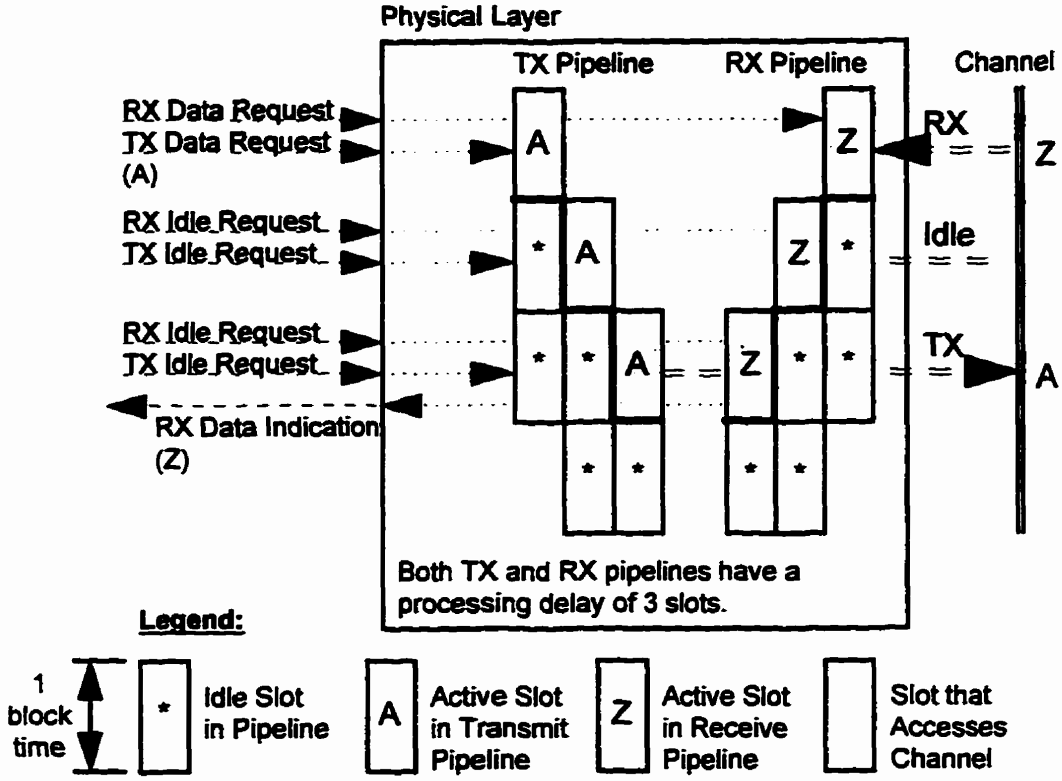


Figure 3.5: Effect of Pipeline Delays on Transmit and Receive Primitives

State primitives are passed by the physical layer to the MAC layer to indicate the current operational state of the physical layer.

The physical layer for a terminal offers the same basic set of primitives as a base-station; however, some differences do exist.

In Table 3.2, the complete set of physical layer primitives is presented.

Table 3.2: MAC-Physical Primitives

Primitive Name	MAC to PHYS	PHYS to MAC	Parameters
PHYS_TX_DATA_REQUEST	✓		• MAC-SDU • antenna (optional)
PHYS_TX_IDLE_REQUEST	✓		• none
PHYS_TX_HEADER_REQUEST *(base-station only)*	✓		• none
PHYS_TX_DATA_CONFIRMATION		✓	• none
PHYS_RX_DATA_REQUEST	✓		• antenna (optional)
PHYS_RX_IDLE_REQUEST	✓		• none
PHYS_RX_DATA_INDICATION		✓	• MAC-SDU • RSSI • timing error (base-station only) • error flag
PHYS_STATE		✓	• synchronized, or not-synchronized

✓ indicates the interfaces on which the primitive is defined.

3.6.1.1 Transmit Primitives

The transmit primitives are used to control the transmit pipeline. Three control primitives are available to the MAC layer: PHYS_TX_IDLE_REQUEST idles the pipeline for one slot (t_{slot}); PHYS_TX_DATA_REQUEST begins the encoding and transmission of one block of data; and PHYS_TX_HEADER_REQUEST, available to base-stations, requests the encoding and transmission of a standard header block. The physical layer responds to any of these requests with a PHYS_TX_DATA_CONFIRMATION that indicates the success or failure of the requested action. If a data field is incorrect, or the pipeline cannot accept the request, then an error value is returned; otherwise, a success is indicated.

The delay between a request being submitted to the physical layer, and the operation being performed on the actual communication channel is the same for all requests.

3.6.1.2 Receive Primitives

The receive primitives control the receive pipeline. Two control primitives are available to the MAC layer: PHYS_RX_DATA_REQUEST makes the receiver active in the current slot; and PHYS_RX_IDLE_REQUEST idles the receiver in the current slot. If the receive pipeline is made active, then after a delay of $t_{rx\text{-}processing}$ when the pipeline has fully processed the information received from the channel, a PHYS_RX_DATA_INDICATION is passed to the MAC layer.

3.6.1.3 State Primitives

The state primitive, PHYS_STATE, is used by the physical layer to inform the MAC layer if the physical layer is able to be used. The physical layer may only be used if synchronization with a base-station has been achieved.

3.7 Summary

This chapter has presented an overview of the COFDM physical layer that forms the base for the wireless access system. This overview included a discussion of the physical layer characteristics significant to the design of the MAC layer. These characteristics are summarized in Table 3.3.

Table 3.3: Summary of Physical Layer Characteristics

Physical Layer Characteristic	COFDM
Data Rate	• Effective block size after FECC is 48 to 55 octets per block. • Block transmission rate is ≥ 500,000 per second.
Error Control Coding	• Fixed amount of FECC per block.
Diversity	• No time diversity is supported by the terminals. • Antenna diversity is used on the receive path at a base-station (and is completely under the control of the physical layer); transmit antenna selection is available to the MAC layer.
Block Error Rate	• Block error probability $< 10^{-9}$
Duplexing	• Time-Division Duplexing (TDD).
Synchronization	• A special header block pattern must be transmitted periodically by a base-station to allow terminals entering a geo-cell to achieve synchronization. • A base-station must transmit at least 20 blocks per second so that terminals in the geo-cell may maintain synchronization with the base-station. • A base station will receive an indication of the timing error associated with a terminal as a byproduct of decoding a received block. A mechanism for correcting the timing error at a terminal must be provided.
Power Amplifier Requirements	• A time equal to the duration of one block must be allowed to elapse between a terminal or base-station transmitting a block and then being able to successfully receive a block. A similar delay is required between a successful reception and a transmission by a terminal or base-station.
Power Control	• A base-station must be able to send power control orders to the individual terminals in a geo-cell.
Pipelining Effects	• Individual base-stations and terminals may have different interblock delay requirements. The lowest interblock delay is zero t_{slot}. The largest interblock delay may be quite large, on the order of hundreds of t_{slot}.

4. THE LOGICAL LINK CONTROL LAYER

4.1 Introduction

This chapter describes the top layer of the wireless access protocol stack: the Logical Link Control (LLC) layer. This chapter is divided into five sections that explain:

- the purpose of the LLC layer;
- the functionality provided by the LLC layer;
- the services offered by the LLC layer to the W-ATM layer;
- the interface between the W-ATM layer and the LLC layer; and
- the interface with the MAC layer.

These sections are then followed by the recommendation of an LLC layer.

4.2 The Purpose of the LLC Layer

The functionality of layer two in the OSI model, the Data Link Control (DLC) layer, is divided into two sublayers in broadcast communication systems: the LLC layer at the top, and the MAC layer at the bottom. The MAC layer is assigned responsibility for managing access to the shared communications link, and the LLC layer assumes responsibility for the other data link control functions. The LLC layer is concerned solely with a station-to-station link, and not with end-to-end issues. A thorough discussion of DLC and LLC protocols can be found in [Freeman], [Stallings], and [Tanenbaum]. Also, [IEEE802.2] is an example of a specific LLC protocol that is in wide-spread use.

Using the OSI model as a basis, the LLC layer must meet the following three requirements.

First, the LLC layer must present a logical interface for the W-ATM layer to use. This logical interface takes the form of Service Access Points (SAPs) that are used by the W-ATM layer to send and receive control and data primitives.

Second, the LLC layer must segment data packets passed from the W-ATM layer at a source SAP into frames for the transmitter, and reassemble frames from the receiver into data packets to be passed through a destination SAP. Thus, the LLC layer offers a facility for the W-ATM layer to use to exchange data between SAPs, and multiplexes the multiple data flows at the higher layer onto a single physical connection.

Third, the particular services offered by the LLC layer to the W-ATM layer may require that the LLC layer implement mechanisms, such as error control, acknowledgements, and flow control, to ensure reliable communications between the two stations (the logical link end-points). The types of services that may be offered by the LLC layer are discussed in detail in a later section of this chapter.

The definition of a LLC layer must present the following information:

- the <u>interface</u> between the W-ATM layer and the LLC layer;
- the specific station-to-station <u>protocol</u> in use; and
- the <u>interface</u> between the LLC layer and the MAC layer, and the associated expectations that the LLC layer has for the MAC layer.

By using a well-designed LLC layer, the "wireless" characteristics of the communication channel may be hidden, and only minimal changes to the ATM layer are required.

4.3 Functionality

This section discusses the functionality that can be provided within the LLC layer. The SAPs available to the W-ATM layer offer access to these functions.

4.3.1 Framing

The LLC layer is responsible for converting a data-stream from the W-ATM layer into discrete frames of data. Each data frame is augmented with control and addressing information useful for the remote LLC entity. A technique for marking the start and end of each frame must be specified. Common solutions to this problem are: explicit size fields in the header, distinctive character flags, start and end bit patterns (with bit stuffing), and physical layer coding violations.

The size of an ATM cell is fixed at 53 bytes, so the use of a fixed size LLC-PDU is feasible. This removes the requirement for explicit start and end flags.

4.3.2 Segmentation-and-Reassembly

In our proposed system, the ATM layer passes complete ATM cells to the LLC layer to be transferred over the wireless link. The characteristics of the MAC layer and physical layer may dictate that each ATM cell be segmented at the transmitter into multiple frames before transmission, and that multiple frames are reassembled by the receiver to form a single ATM cell. This process is referred to as segmentation-and-reassembly. Alternatively, the transmitter may be able to pack several ATM cells into a single frame for transmission, and then the receiver would need to split a frame into individual ATM cells for distribution.

4.3.3 Flow Control

A flow control mechanism is used to prevent a sender from overwhelming a receiver with data. Most flow control mechanisms use the same basic principle: the receiver uses a feedback path to the sender to grant permission for a frame to be sent.

4.3.4 Error Control

The LLC layer may offer a variety of service types to the W-ATM layer. In [IEEE802.2], the LLC specification of connection-oriented service guarantees the network layer that the data will be delivered correctly, and in the proper order. The specification of unacknowledged connectionless service requires the LLC layer to use a best-effort attempt to transfer the data, and, therefore, does not guarantee delivery. To identify frames that have been corrupted by errors, the LLC layer may append a frame checksum sequence (FCS), or forward error correction coding (FECC) information. For example, [Ayanoglu] suggests that in the worst case, three levels of error control coding may be required:

- in the physical layer, over a group of bits (e.g., trellis-coded modulation);
- in the LLC layer, over the contents of a single frame; and
- also in the LLC layer, over multiple frames.

A method is needed to allow a receiver to inform the sender of the successful or unsuccessful reception of each message. The most general solution involves three aspects:

- timers at the sender to force the retransmission of data;
- sequence numbers on each frame to allow the sender and receiver to identify particular frames; and

- acknowledgement (ack) and negative-acknowledgement (nack) messages[1].

An excellent survey of the various protocols that may be used between the sender and receiver to control errors using a frame checksum sequence is presented in [Lin].

Wired-ATM assumes that link-by-link error control is not required because the underlying physical layer characteristics are exceptionally error free. A checksum is used in each ATM header to detect errors in the header (not the entire ATM-cell) which may cause ATM-cells to be routed incorrectly. Nevertheless, the responsibility for error recovery of the data portion has been shifted to the higher protocol layers.

For the wireless ATM system being considered in this thesis, the requirement is for frames to be delivered in the correct order, but a guarantee of delivery is not provided. This approach is consistent with the service guarantees that ATM offers to its higher layers. The low error rate of the wireless physical layer allows the LLC layer to offer error-control services as an optional service that may be selected by the W-ATM layer.

4.3.5 Encryption and Decryption

Encryption and decryption provide security for the data that is transferred over the wireless channel. Not all types of data require the use of a secure transmission facility, so this functionality should be considered selectable. If security features are offered, then the station-to-station LLC signalling must include messages to support authentication, and encryption services.

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[1] A workable error control scheme may be constructed using only acknowledgement messages, rather than a combination of acks and nacks.

4.3.6 Link Management

Link management refers to operations associated with the administration of a link. For connectionless links, the administrative overhead is minimal; however, for connection-oriented links, the process of establishing, maintaining, and releasing connections requires that state information be maintained for the duration of each connection.

A significant question that must be answered is: "can either end of a link initiate a connection?". In some systems, only a single entity, called the primary station, can establish a connection by polling the secondary stations; however, in other systems, both ends are considered equal, and the connection is referred to as balanced.

In the proposed system, link management allows either end to establish a connection.

4.3.7 Capacity Management

This function is a specialized aspect of the link management function. The LLC layer may request that the MAC layer adjust the data rate capacity of the underlying link to meet the current needs of the W-ATM layer.

4.3.8 Priority Messages and Channels

A LLC layer may offer multiple levels of priority for messages passed from the W-ATM layer. Data messages that are submitted for transmission as high-priority may be moved to the head of a transmission queue, and "jump" over any low-priority messages waiting to be sent. Alternatively, the LLC layer may offer a distinct channel that is used for high-priority messages.

The LLC layer for the proposed wireless access system does not need to distinguish different levels of priority for messages on a single channel.

Also, all links that are set up by the LLC layer are considered to be independent, so the W-ATM layer may request a link for high-priority traffic.

4.3.9 Hand-over Support

The LLC layer may be an appropriate layer for controlling some aspects of hand-over (such as link recovery after a hand-over). However, an early assumption of this thesis eliminated the consideration of hand-over by explicitly not considering fully mobile users.

4.3.10 Special Queuing Algorithms

Each distinct traffic link requires a separate queue. The standard queuing discipline for data messages is first-in first-out (FIFO). The W-ATM layer may request access to different types of queuing disciplines at the LLC layer. For example, a traffic source might generate data that is very delay-sensitive, and has an inherent expiry-time. Data messages from such a source might be inserted into a FIFO queue with time-of-expiry support. Only valid messages may be selected from the queue, and any expired messages are deleted automatically (without being sent). Other queuing options, such as last-in first-out (LIFO) and priority queuing, may be appropriate for special types of traffic.

4.4 Services Offered to W-ATM Layer

The LLC layer offers services to the W-ATM layer at Service Access Points (SAPs). Each SAP offers a different set of functionality. In our proposed system, the layer above the LLC layer is a version of ATM, W-ATM, modified to communicate with our LLC layer. With normal ATM, a small set of primitives is sufficient for communicating with a physical layer: PHY_UNITDATA_REQUEST and PHY_UNITDATA_INDICATE [ATMForum]. With W-ATM a larger set of primitives is necessary to communicate sufficient information to the wireless access layers to allow for the control of the wireless links in a manner that is consistent with the traffic contracts.

4.4.1 Service Types

In the OSI model, the number of different service types provided by the LLC layer is dictated by the requirements of the network layer. The service selected by the network layer is influenced by the needs of the transport layer that is ultimately responsible for ensuring end-to-end reliable communications. An alternative view is that the protocol implemented at the transport layer is influenced by the characteristics of the underlying network layer: reliable, or unreliable. If the LLC layer guarantees delivery of data in the correct order and without any errors, then the transport and network layers can be quite simple.

As an example, consider the IEEE LLC layer [IEEE802.2] which makes only three service options available to the network layer:

- unacknowledged connectionless (type 1);
- acknowledged connectionless (type 3); and
- connection-oriented with guaranteed delivery (type 2).

The wide range of possible traffic types in a multimedia system suggests that a broad range of service types should be offered to the W-ATM layer. Every ATM call is connection-oriented, so all the service type may be considered to be connection-oriented. The availability of functionality such as encryption/decryption, ARQ, and additional FECC, should be selectable by the ATM layer. For example, one SAP may offer reliable delivery without encryption/decryption, and another SAP may offer reliable delivery with encryption/decryption. The particular needs of the traffic contract at the W-ATM layer should dictate which SAP is selected.

4.4.2 Circuit, Flow, and Link Identifiers

A significant concern for the W-ATM, LLC, and MAC layers is the identification of particular traffic flows and SAPs. Figure 4.1 shows the interface between the W-ATM layer and the LLC layer.

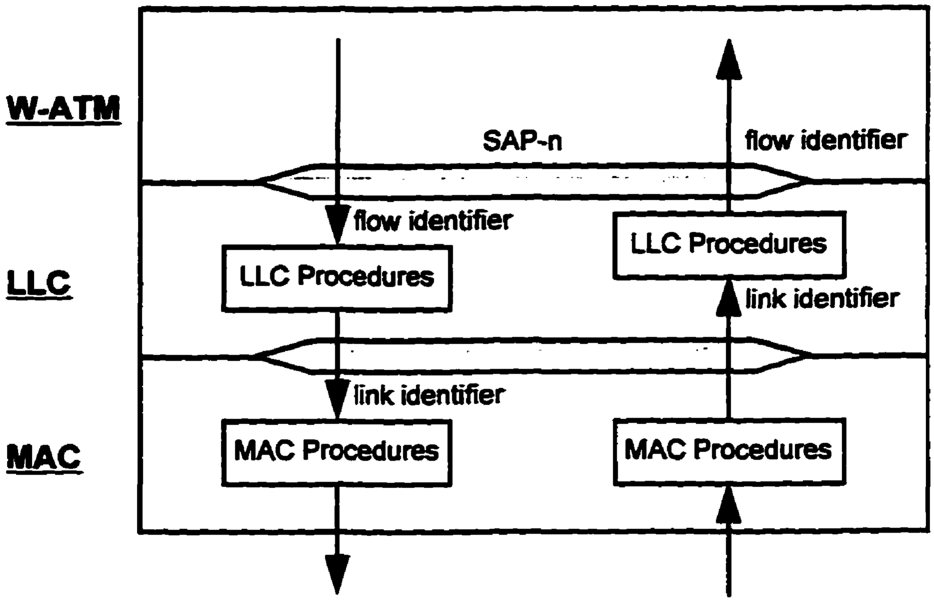

Figure 4.1: Circuit, Flow, and Link Identifiers

The W-ATM layer may have several distinct virtual circuits active concurrently. Each virtual circuit has a unique Virtual Circuit Identifier (VCI). The appropriate VCI is stored in each cell that is transmitted or received by the W-ATM layer. Therefore, the ATM layer can easily associate a cell with a particular virtual circuit.

Each SAP on the interface between the W-ATM layer and the LLC layer has a unique identifier, called a Service Access Point Identifier (SAPI). The values assigned for the SAPIs are assigned consistently across all devices in a system, so that all devices have the same concept of the type of services that are being requested. For example, all terminals and base-stations should consider SAPI 5 to refer to the encryption/decryption SAP.

A SAP may be used by several different W-ATM virtual circuits simultaneously. The LLC layer must be able to distinguish between ATM-cells on the different virtual circuits, because each circuit may have a different connection established on the wireless link. Therefore, during the establishment of a new ATM virtual circuit, a Flow Identifier (flow-id) is created that maps directly to, and from, the VCI. The flow identifier only needs to be unique within a SAP, and must be passed across the interface between the LLC layer and the W-ATM layer with each ATM-cell. A flow-id is used at both ends of a logical link to reference the traffic flow, so the value must be unique at both the base-station and the terminal. The LLC layer uses the flow identifier to cross-reference with a wireless link. The LLC layer may multiplex multiple flows onto a single link if that would not violate the traffic contract of a flow. For example, a single link may be set up by the LLC layer to handle all UBR traffic flows between a terminal and a base-station, but a distinct link is established for each CBR traffic flow.

The LLC layer needs to be able to distinguish between the links that are established over the wireless channel. Each link is assigned a Link Identifier (link-id) by the MAC layer for links originated remotely, and by the LLC layer for links originated locally. A link-id is usable by both the MAC layer and the LLC layer, and is unique within a terminal or base-station. Link-ids do not need to be communicated between terminal and base-station.

4.4.3 Service Primitives

A variety of primitives are required for the interface between the W-ATM layer and the LLC layer. Sets of primitives for managing connections, transferring data, and handling link failures must be provided.

The connection management primitives need to include a group of primitives to handle traffic contracts. During the set up of a virtual circuit, the W-ATM layer needs to provide the LLC layer with information about the traffic characteristics and quality of service requirements of the data that will be passed on the virtual circuit. This information is essential if the LLC layer is to obtain sufficient capacity on the wireless channel. Also, the LLC layer should be informed of changes to the on-going state of all traffic contracts. For example, the link capacity assigned to an ABR traffic source, which uses an end-to-end flow control mechanism to regulate the rate at which ATM-cells are generated by the source, could be adjusted to meet the current needs.

4.5 Services Required from the MAC Layer

The LLC layer requires services from the MAC layer. These services are defined to be independent of the form of the medium access technique, and the nature of the medium [Freeman]. In the next section, the services that are required of the MAC layer are described, and then in the following section, the communication primitives between the LLC layer and the MAC layer are detailed.

4.5.1 MAC Layer Services

The MAC layer is responsible for controlling access to the wireless channel. The LLC layer for our system requires that the MAC layer provide the following capabilities:

- The ability to set up, maintain, and tear-down multiple independent links (also referred to as virtual channels) over the same physical channel. Thus, unlike [IEEE802.2], this LLC-MAC interface is connection-oriented, rather than connectionless.
- The ability to transfer entire LLC-SDUs at one time (rather than an interface that is byte or bit oriented).

- The ability for the LLC layer to specify particular quality of service (QoS) metrics for the MAC layer to use when establishing a new traffic link.
- The ability for the LLC layer to request dynamic changes to the data throughput of individual traffic links. The LLC layer must be able to obtain the current throughput of each traffic link.

4.5.2 Primitives

The capabilities that the MAC layer must provide for the LLC layer suggest the following four groups of primitives:

- connection management primitives;
- data transfer primitives;
- rate adjustment primitives; and
- reset primitives.

The next three subsections contain detailed sets of connection management, data transfer, and rate adjustment primitives that we are proposing.

4.5.2.1 Connection Management Primitives

Connection management primitives are used to set up new connections, and to terminate existing connections between a base-station and a terminal. Either a terminal or a base-station may initiate a new connection, or cancel an existing connection. The list of essential primitives is provided in Table 4.1.

Table 4.1: LLC-MAC Connection Management Primitives

Primitive Name	LLC to MAC	MAC to LLC	Parameters
MAC_CONNECT_REQUEST	✓		• destination MAC address • link-id • link requirements
MAC_CONNECT_CONFIRMATION		✓	• success, or failure • link-id • link characteristics
MAC_CONNECT_INDICATION		✓	• link-id • link characteristics
MAC_DISCONNECT_REQUEST	✓		• link-id
MAC_DISCONNECT_CONFIRMATION		✓	• link-id
MAC_DISCONNECT_INDICATION		✓	• link-id

✓ indicates the interfaces on which the primitive is defined.

4.5.2.1.1 MAC_CONNECT_REQUEST

A connection request is used to request the establishment of a new link between a terminal and a base-station (or vice-versa). A unique link identifier is generated by the LLC layer. The link requirements field of the connect request describes the requirements for the traffic link (e.g., minimum acceptable peak transmit data rate).

4.5.2.1.2 MAC_CONNECT_CONFIRMATION

A connection confirmation primitive indicates the success, or failure of a previous connect request. If a connection has been established, then the link characteristics field specifies the characteristics of the link (e.g., actual peak transmit data rate). However, if a connection attempt has been rejected, then the link characteristics field may specify a set of link requirements that may be acceptable to the system.

4.5.2.1.3 MAC_CONNECT_INDICATION

A connection indication informs the LLC layer that a connection has been initiated by a remote entity. The link characteristics field specifies the characteristics of the link (e.g., actual peak transmit data rate). A unique link identifier is generated by the MAC layer.

4.5.2.1.4 MAC_DISCONNECT_REQUEST

A disconnect request asks the MAC layer to end a traffic connection.

4.5.2.1.5 MAC_DISCONNECT_CONFIRMATION

A disconnect confirmation indicates that a previous disconnect request by the LLC layer has been completed.

4.5.2.1.6 MAC_DISCONNECT_INDICATION

A disconnect indication informs the LLC layer that a traffic connection has been terminated by the remote entity.

4.5.2.2 Data Transfer Primitives

The data transfer primitives are used to exchange data packets between peer LLC layers (a terminal, and a base-station). A connection must be established before transferring data.

Table 4.2: LLC-MAC Data Transfer Primitives

Primitive Name	LLC to MAC	MAC to LLC	Parameters
MAC_DATA_REQUEST	✓		• link-id • LLC-SDU
MAC_DATA_CONFIRMATION		✓	• link-id • success, or failure flag
MAC_DATA_INDICATION		✓	• link-id • LLC-SDU • contents OK flag

✓ indicates the interfaces on which the primitive is defined.

4.5.2.2.1 MAC_DATA_REQUEST

A data request primitive is used to request the transfer of a LLC-SDU to the remote device of a pre-established connection.

4.5.2.2.2 MAC_DATA_CONFIRMATION

A data confirmation primitive indicates the success, or failure, of a previous data request. A success result indicates that an LLC-SDU has been transmitted successfully, but does not indicate that the message has been received successfully (only an explicit acknowledgement from the remote device can do that!). If a failure result is returned, then a problem has arisen that prevents the data from being transmitted. References [IEEE802.2], [IEEE802.3], or [IEEE802.11] provide examples of some failure conditions.

4.5.2.2.3 MAC_DATA_INDICATION

A data indication primitive is used by the MAC layer to pass an LLC-SDU from the MAC layer to the LLC layer.

4.5.2.3 Rate Adjustment Primitives

The following primitives are used to control the capacity of an existing communication path between two LLC layer entities (a terminal and a base-station). These primitives could be extended to control other characteristics of a traffic link, such as jitter.

Table 4.3: LLC-MAC Rate Adjustment Primitives

Primitive Name	LLC to MAC	MAC to LLC	Parameters
MAC_RATE_REQUEST	✓		• link-id • transmit rate request • receive rate request
MAC_RATE_CONFIRMATION		✓	• link-id • success, or failure • transmit data rate • receive data rate
MAC_RATE_INDICATION		✓	• link-id • transmit data rate • receive data rate

✓ indicates the interfaces on which the primitive is defined.

4.5.2.3.1 MAC_RATE_REQUEST

A rate request primitive is used by the LLC layer to request a change in the transmit or receive rate of the specified link.

4.5.2.3.2 MAC_RATE_CONFIRMATION

A rate confirmation primitive indicates the results of a previous rate request.

4.5.2.3.3 MAC_RATE_INDICATION

A rate indication primitive informs the LLC layer of a change in the current capacity of a wireless link.

4.6 The Proposed Modifications

The proposed system can use peer-to-peer messages and protocols that are similar to [IEEE802.2]. Additional fields and messages are required to handle the ARQ schemes, configuration parameters, and encryption/decryption options that may be selected on a per virtual circuit basis. The protocol state machines need to be modified to handle the requirements of setting up, maintaining, and tearing-down individual traffic links.

The LLC-PDU for the proposed scheme includes the following fields in the header portion of each message:

- Service Access Point Identifier (SAPI);
- Flow Identifier; and
- Control Field (encodes the type of message).

Messages that contain W-ATM cells require all three fields; whereas, some messages used for LLC-to-LLC control may need only the control field.

4.7 Summary

This chapter has presented a broad examination of the functionality of the LLC layer, and the MAC and W-ATM interfaces with the LLC layer. The well-known IEEE standard for an LLC layer, [IEEE802.2], has been proposed as a basis for building an LLC layer for the wireless access protocol stack.

In the next chapter, the MAC layer is considered.

5. THE MULTIPLE ACCESS CONTROL LAYER PROTOCOLS

5.1 Introduction

In this chapter, the Multiple Access Control (MAC) layer is discussed in detail. In the next four sections, the following topics are presented:

- a definition of the responsibilities of the MAC layer;
- a precise description of the assumptions;
- a description of the requirements; and
- a presentation of some alternatives from the literature.

5.2 The Purpose of the MAC Layer

The Multiple Access Control (MAC) layer, also known as the Media Access Control layer, is responsible for controlling access to a transmission medium [Shay] [Spragins] [Keiser]. The transmission medium is shared by several devices, so a distributed algorithm is required to control the accesses of these devices to the medium. This algorithm must resolve the following two complications:

- Devices are distributed, so state information must be either explicitly or implicitly shared among these devices; however, the communication channel is the only means for exchanging this information.
- Devices cannot instantaneously know the current status of the other stations in the environment.

The essence of the MAC problem is revealed in Figure 5.1. A simple wired ATM system would have each terminal connected individually to a centralized switch. Terminals could be allowed to transmit at will, and the switch would co-ordinate the servicing of these local queues. However, in a wireless system, the queues are located in the terminals [Bernhard].

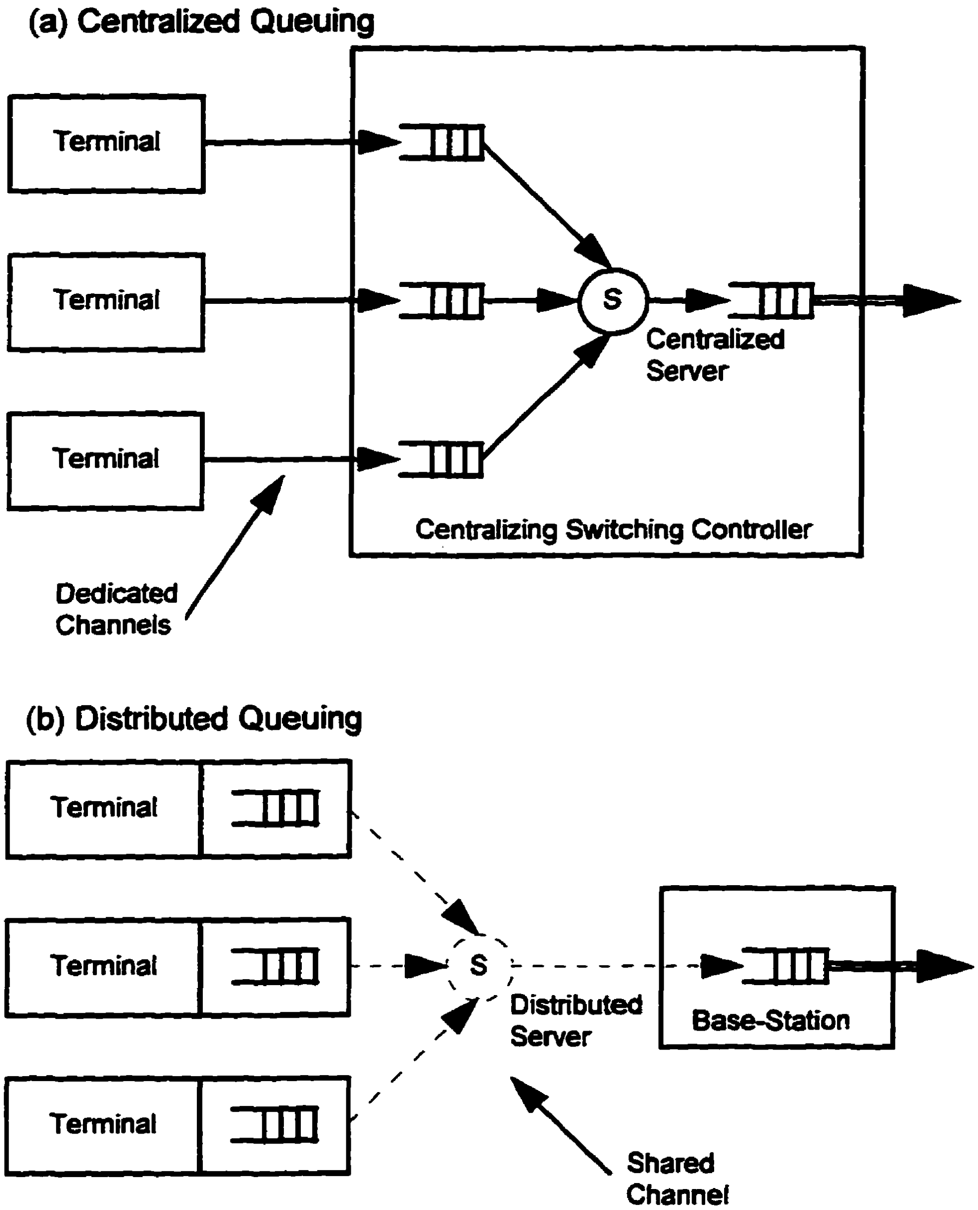

Figure 5.1: Distributed Queuing versus Centralized Queuing

The wireless MAC layers for other wireless LAN products are often assigned additional responsibilities. For example, Hiperlan, a moderate speed

LAN being standardized in Europe, places the responsibility for activities such as encryption/decryption, and address mapping in the MAC layer [Hall]. The IEEE wireless LAN standard [IEEE802.11] is burdened with functionality that might be better suited in the LLC layer, because of a requirement to be compatible with the existing LLC layer [IEEE802.2].

A tremendous wealth of literature exists on MAC algorithms. An excellent overview is presented in [Kurose1], and a comprehensive discussion of the evolution of MAC protocols is presented in [van As].

5.3 Assumptions

In this section, the assumptions that are particular to the MAC layer of our wireless protocol system are identified.

5.3.1 Carrier Sensing

A terminal may monitor the transmission channel prior to attempting a transmission. If the terminal detects the presence of a carrier signal of another terminal on the channel, then the channel is considered busy, but if the carrier signal is not present, then the channel is considered idle. The ability to sense the state of the channel is referred to as 'carrier sensing', or 'listen before talk (LBT)'. MAC algorithms that have carrier sensing available may use the current state of the channel as an input to the decision algorithm. Some MAC algorithms, referred to as p-persistent protocols, transmit only if the channel is currently idle, and the value of a randomly generated number, uniform over [0,1], is below a preassigned probability, p.

In a wired system, the voltage or current on the wire may be monitored to determine the presence or absence of a carrier. In a wireless system, carrier sensing may be possible in some special situations (e.g., mobile terminal and base-station have a line-of-sight transmission path with no hidden terminal problem), but in the proposed system, carrier sensing is not suitable. The decoding delay of the physical layer is much longer than the time to transmit a single packet of data, so the MAC layer cannot be given information about the current state of the channel. This is fundamentally the same as the commonly cited requirement for carrier sensing: the propagation time of a signal must be small in comparison with the time required to transmit a packet. Also, the problem of 'hidden terminals', discussed later, cannot be easily resolved.

5.3.2 Collision Detection

An actively transmitting terminal may have the ability to sample the channel, and determine if the current contents of the channel have been corrupted by a collision with another transmission (or transmissions). This capability is referred to as 'collision detection' or 'listen while talk (LWT)'.

In a wired system, baseband receivers can detect a collision by determining if the voltage levels on the channel are greater than expected for a single transmitter, and broadband receivers can decode the received data and compare with the transmitted data [Stallings]. If a collision is detected, then the transmitter can halt the transmission until a later time. [IEEE802.3] is a well-known example of a wired MAC scheme that employs collision detection.

In a wireless system, collision detection at the transmitter is not possible because in the immediate region of the transmitter, the transmitted signal dominates all other received signals. However, at the intended receiver, the arrival of a corrupted packet may be used as an indication that a collision has occurred (but, the corruption may have been caused by a different event entirely).

5.3.3 Hidden Terminals

The phrase 'hidden terminals' refers to a common situation in which terminals may be located in a geo-cell served by a common base-station, but are unable to detect the transmissions of the others (the seminal work on this problem is presented in [Tobagi]). This problem may arise for a variety of reasons, such as the propagation loss between remotely located terminals, transmission obstacles (e.g., walls) between terminals, or the use of highly directional antennas between terminals and a base-station.

Figure 5.2 shows two situations in which two terminals are effectively hidden from each other. In Figure 5.2(a), both terminals can communicate with the centralized controller (C), but the channel path loss is sufficiently large between the two terminals to prevent the terminals from sensing the transmissions of each other. In Figure 5.2(b), although both terminals can communicate with the centralized controller, the wall between the terminals blocks any transmissions between the terminals.

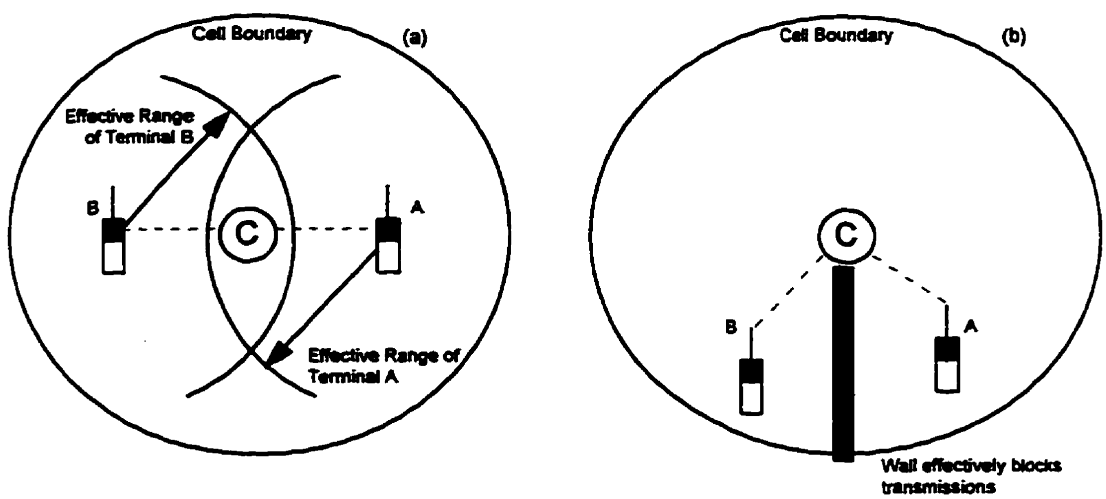

Figure 5.2: Hidden Terminals

The presence of hidden terminals prevents the reliable use of channel sampling techniques, such as carrier sensing and collision detection.

In this thesis, the assumption is that a geo-cell may contain terminals that are hidden from one another.

5.3.4 Capture Effect

In the analysis of MAC algorithms based on the ALOHA scheme, many researchers assume that an FM receiver may track the strongest signal, and, despite the occurrence of a collision between two transmissions, is still able to receive the stronger transmission successfully [Abramson] [Roberts]. This assumption results in a higher (i.e., less pessimistic) estimate of the throughput capacity of an ALOHA MAC scheme. [Chen] agrees that capture may increase throughput, but at the expense of fair access.

If a MAC scheme allows terminals to compete for access to the channel using contention slots[1], then a capture effect may be observed. If a large proportion of the channel accesses are performed in slots that may experience collisions, then the capture effect may result in some terminals (the captured terminals) obtaining an unfair amount of channel capacity. The base-station cannot detect the high level of collisions that are occurring, and thus, cannot execute a centralized back-off strategy to resolve the situation.

One solution to the adverse effect of capture is to use some form of power control to ensure that, at the base-station, the received signal power from each user is nearly equal for all users. The received signal power of a terminal is

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[1] If a protocol allows terminals to compete for access to a wireless channel, then the transmissions of those terminals may collide. The competition for access to the channel is often referred to as contention. Some protocols permit contention to occur only at specific times: contention slots.

affected by the distance from the base-station, and by signal shadowing effects. CDMA has a similar requirement for power-control to resolve the 'near-far' problem [Viterbi].

A second solution is for the MAC layer to avoid collisions by restricting the occurrence of contention situations.

This thesis assumes that collisions are always destructive.

5.3.5 Number of Terminals

The number of terminals in a geo-cell may vary with time. The base-station cannot make any assumptions about the total number of terminals within the geo-cell; however, the MAC layer does have knowledge of the number of active terminals, and the base-station may be aware of the number of registered, but inactive, terminals within the geo-cell (although some of these terminals may be powered-off[2]).

5.3.6 Traffic Characteristics

Many different types of traffic may be carried by the wireless traffic links, so developing general assumptions about the characteristics of the traffic is difficult. However, the wireless access system is intended for ATM traffic, and ATM is connection oriented, so the MAC protocols may be tailored for connection oriented traffic flows and consider QoS on a per link basis.

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2 This statement is correct if terminals do not deregister before powering-down. Some air-interface protocols, such as ETSI CT2, allow terminals to send a deregistration message first.

5.4 Requirements

A list of explicit requirements for the MAC layer is essential. The subsections that follow discuss the particular requirements for the MAC protocol for the proposed wireless ATM system[3].

5.4.1 Interterminal Effects

Ideally, a terminal receives the same quality of service regardless of the number of terminals in the geo-cell. Unfortunately, this ideal situation is rarely achievable. In the next two subsections, the effect of the number of terminals on two key performance characteristics is considered:

- stability (delay); and
- fairness.

Other interterminal effects, such as physical layer interference, exist, but are not considered in this chapter.

5.4.1.1 Stability and Delay

[Stallings] defines delay as "the time interval from when a user node is ready to transmit a packet until when it is successfully received by the central node. This delay is simply the sum of queuing delay, propagation delay, and transmission time." The evaluation of a protocol may consider the mean delay, the maximum and minimum delay, and the variance of the delay (jitter).

[Kurose1] defines stability as "the ability to operate in spite of varying traffic demands and short-term overloading of the network".

Stability and delay are intimately related. An unstable protocol can allow the delay to become infinitely long even though the traffic load is finite.

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[3] [Chen] presents a discussion of the requirements used to design the MAC layer for the IEEE wireless LAN specification [IEEE802.11]. This provides an interesting contrast to the requirements in this thesis.

If ATM traffic is to be carried by our wireless access scheme, then a stable protocol is essential [Falconer1].

5.4.1.2 Fairness

A fair protocol ensures that each host with pending traffic has an equal probability of acquiring the channel [Smulders] [Boggs]. The typical definition of fairness does not require that the stations be granted an equal share of bandwidth, since hosts may use different packet sizes.

A literal interpretation of this definition results in a requirement for no terminal blocking; however, such a requirement would prevent the MAC layer from being able to guarantee traffic contracts. For example, if a base-station is servicing ten terminals with guaranteed CBR traffic contracts using 95% of the channel capacity, and an eleventh terminal makes a request for greater than 5% of the channel capacity, then the request should be rejected. The application in the rejected terminal may be able to alter its resource request to fit in the available capacity, and still meet its requirements.

[Chen] mentions that a contention-based protocol must have a mechanism for resolving unfairness caused by unequal received power at the base-station (i.e., a capture effect occurs that allows a terminal with the greatest received power to dominate the other terminals). This mechanism is essential if signalling and actual data traffic are transmitted using the same access mechanism.

The MAC protocol proposed for the wireless access system in this thesis provides a method for ensuring fair access to signalling functions in the base-station such as registration and call-setup, and to available data transfer capacity.

5.4.2 Data Rate Adaptation

Some applications generate ATM-cells at a non-constant rate (i.e. VBR traffic sources). The ATM layer and the LLC layer must be able to adapt the data rate associated with a traffic link at any time (within the limits established at the beginning of the call). The MAC layer must be able to adjust the data rate of the traffic link in a timely fashion.

5.4.3 Link Setup Time

The time required for a terminal and a base-station to establish a link is an important characteristic of the MAC layer. The link setup time is defined as the time that elapses between the start of the connection process and the successful setup of a link. The setup time for a signalling link may be different from the setup time for a traffic link, and the link setup time may be influenced by which entity (i.e., terminal, or base-station) starts the link setup process.

No quantitative requirement is established in this thesis for link setup times of signalling or traffic links. The MAC protocol should provide configuration parameters that allow the link setup time to be controlled.

5.4.4 Link Blocking Probability[4]

The total capacity of the channel available to the wireless access system is fixed, and is shared amongst many users. Therefore, a link request may be rejected because of insufficient capacity being available, or because the system is too heavily loaded to even begin servicing the link request. The probability that a link request is rejected is referred to as the link blocking

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[4] Link Blocking Probability is also known as Call Blocking Probability.

probability. This probability is affected by the current traffic mix on the channel, and the channel requirements of the traffic request.

A quantitative requirement for link blocking probability is not established by this thesis because of the large range of traffic types that may be carried by the wireless access system. Once a particular application environment has been selected, and the expected traffic mixture ascertained, then the link blocking probability may be computed for that environment.

5.4.5 Distinct Uplink and Downlink Capacities

The data rate of an uplink should be distinct from the data rate of the associated downlink, because applications often have asymmetrical data rate requirements (e.g., file transfer).

5.4.6 Packet Transfer Characteristics

Packets that are transferred on a traffic link must meet two packet transfer requirements:

- packet ordering; and
- duplicate elimination.

5.4.6.1 Packet Ordering

The LLC-SDUs that are transferred on a traffic link must not be reordered by the MAC layer. This does not imply a requirement for reliable transmission, because a lost SDU is better than a misordered SDU.

5.4.6.2 Duplicate Packet Elimination

The design of the physical layer may require that a single base-station has several associated RF signal repeaters [Falconer1] [Leslie]. In such situations, the MAC layer should prevent multiple copies of the same packet from existing on the backbone network, or being sent to a terminal. Two examples are shown in Figure 5.3. In Figure 5.3(a), the transmission of a terminal is received by two repeaters, which results in two duplicate packets being delivered to the base transceiver station (BTS); in Figure 5.3(b), a packet is received by a terminal from two repeaters. This problem may be eliminated by using sequence numbers to detect duplicate packets.

The proposed physical layer of the wireless access system does not employ repeaters, so packets will not be duplicated by that mechanism. The design of the MAC layer must ensure that packets are not duplicated within the MAC layer.

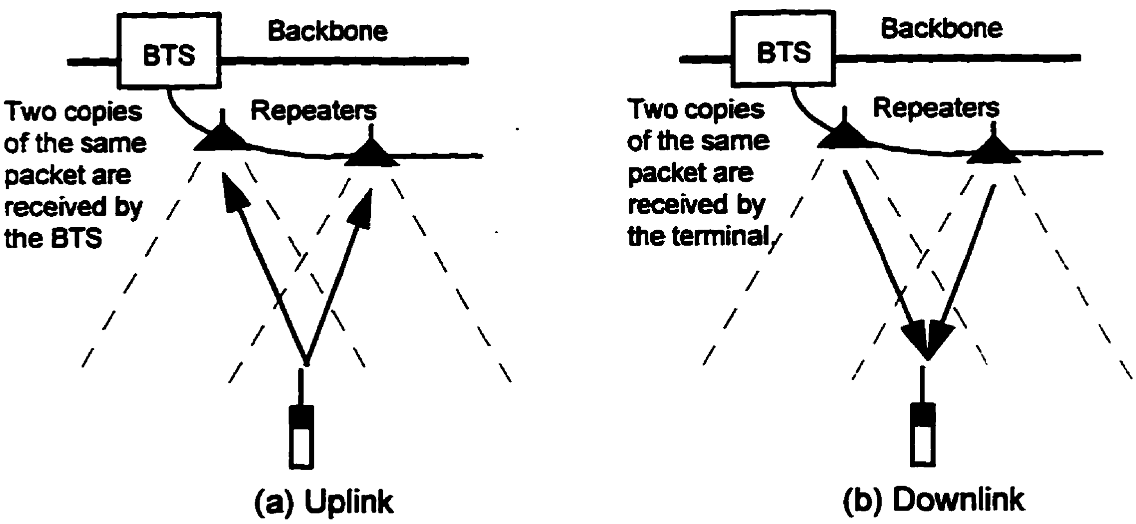

Figure 5.3: Packet Interference

5.4.7 Effective Handling of Physical Layer Restrictions

Chapter 3 outlined the essential characteristics of the physical layer. The impacts of the following three characteristics are discussed briefly:

- pipeline blocking;
- TDD links; and
- physical layer synchronization.

The requirement is for the MAC layer to make effective use of the physical layer given the restrictions of the physical layer.

5.4.7.1 Pipeline Blocking

The requirement for a minimum delay (the minimum interblock delay) between transmit slots, and between receive slots, assigned to each terminal suggests that each terminal needs to be assigned slots interspersed throughout a frame, rather than allocating slots consecutively. By allocating slots evenly throughout a frame, the slot assignment reduces the variance in the transmit delay. A base-station is not aware of the interblock delay associated with a terminal until after a signalling link has been established, and the base-station has received a terminal information message, so the base-station must assign the initial slots for a signalling link as far apart as possible.

5.4.7.2 TDD Links

The use of TDD uplink/downlink pairs results in some delay between information being placed on the uplink, and any corresponding acknowledgements being placed on the downlink. The distribution of uplink and downlink slots in a frame may have undesirable effects on the delay characteristics of traffic links; however, the slot assignment algorithm in a base-station has complete control over the location of uplink and downlink slots in a frame. But, the algorithm must ensure that guard slots are inserted between transmit slots and receive slots.

5.4.7.3 Synchronization

The MAC protocol must ensure that sufficient slots per second are received by each terminal from the base-station to maintain synchronization. Fortunately, terminals are able to maintain synchronization by decoding any OFDM-blocks transmitted by the base-station, so OFDM-blocks carrying paging messages and frame information messages are sufficient for satisfying the synchronization needs of the terminals in a geo-cell.

5.4.8 Terminal Mobility

To support the mobility of terminals, the MAC layer must offer support for registration and paging functions. In the future, the possibility of handover of active calls may be considered.

5.4.9 Throughput Efficiency

[Stallings] defines throughput as the total rate of data being transmitted between stations (also known as the carried load). This parameter, denoted by the letter S, is most often expressed as a fraction of total link capacity, and as a function of the offered load, denoted by the letter G.

If RF spectrum is a scarce resource, then high throughput efficiency is an important, perhaps crucial, requirement [Chen]; however, if RF spectrum is plentiful (as it is in the >20GHz region), then throughput efficiency is not critical. Some researchers suggest that reliability is a more important consideration than high link throughput efficiency [Leslie].

High throughput efficiency is not a requirement.

5.4.10 Asymmetrical Complexity

With a centralized topology, the network elements may be designed to place more complexity in the infrastructure, such as base-stations, and less in the terminals. The benefits of asymmetrical complexity are:

- lower terminal cost (which is significant since the number of terminals is much larger than the number of base-stations);
- longer battery life in the terminals; and
- easier to implement improvements to the resource assignment algorithms (since only the base-stations need to change).

However, by introducing asymmetrical complexity in a system, the total system complexity may be greater than a system with no asymmetry. [Gibbard] presents an example of an asymmetrical approach applied to the physical layer, and [Ayanoglu] provides a logical link layer example.

5.4.11 Reliability and Robustness

[Kurose1] defines reliability as the ability of a protocol to continue to operate despite the failure of a station, and robustness as the insensitivity of a protocol to errors, channel noise, and misinformation. Ideally, a system would be both highly reliable and robust [Leslie].

The need for guaranteed levels of reliability and robustness is dictated by the application environment. Medical and control systems require both high reliability and high robustness; data networks would like high reliability and robustness, but can tolerate some system down time.

The MAC protocol for the wireless access system must be able to handle errors introduced by the communication channel. An implementation of the MAC layer must be undertaken with a goal of producing a highly reliable system.

5.4.12 Services Provided to the LLC Layer

The MAC layer must implement the requirements discussed in the chapter on the LLC layer.

5.5 MAC Protocol Alternatives

This section discusses some of the alternatives for a multiple access control protocol. A brief overview of the classes of multiple access schemes and of the associated general characteristics is presented first. Then, a number of specific schemes for wireless ATM that have appeared in the literature are presented, along with a brief discussion of the suitability of each scheme for our wireless access system.

5.5.1 Overview

As the introduction mentioned, the number of different multiple access control protocols is quite large, but these protocols may be divided into two classes:

- Controlled Access; and
- Contention Based.

Many real-world communication systems use protocols that selectively employ aspects of both classes. For example, the analog cellular telephone standard [EIA-553] uses a contention-based scheme for the signalling channel, but controlled access on the traffic channels. Other protocols exist that dynamically change from contention-based to controlled-access as the offered traffic load increases.

5.5.1.1 Controlled-Access

Protocols that are considered to be controlled-access use some form of terminal ordering to ensure that terminals can access the shared channel without any collisions. Many different approaches are used to assign an order to the terminals. By considering the adaptability of the ordering method, we can subdivide this class into two subgroups:

- Predetermined Allocation; and
- Demand-Adaptive Allocation

5.5.1.1.1 Predetermined Allocation

Algorithms that use a predetermined allocation method assign a fixed channel capacity to a terminal for the duration of its call (i.e., each terminal is granted a set of transmission rights). Pure TDMA is a classic example of a predetermined allocation algorithm.

Predetermined allocation methods are most suitable for applications which generate data at a constant rate, for a long period of time. The availability of a fixed and regular capacity means that the transmission delay is deterministic and constant; however, if an application does not generate data at a constant rate, then the waiting delay may become long at times, and the capacity may be unused at other times. This type of allocation method usually has a hard-limit on the number of active terminals, so blocked terminals receive no service, but existing users are not affected by the arrival of new terminals.

5.5.1.1.2 Demand-Adaptive Allocation

Demand-adaptive allocation schemes assign channel capacity according to the current transmission needs of a terminal, subject to the enforcement of some maximum capacity assignment. Every terminal is periodically offered the opportunity to use the channel. Token-passing, and hub-polling, are examples of common demand-adaptive allocation algorithms.

Demand-adaptive schemes normally assign the channel capacity in a round-robin fashion to all the terminals that have requested access. The waiting time for a terminal is highly dependent on the number of other terminals that may need to access the channel; however, if a terminal has no data to send, then the offer to transmit may be passed to the next station, thereby reducing the idle channel time. If the algorithm restricts the maximum capacity that may be assigned to each terminal, then the waiting delay can be bounded.

5.5.1.2 Contention-Based

Contention-based protocols introduce the possibility of message collisions on a shared channel. These protocols grant a right-of-transmission to a group (known as the enabled group) of one or more stations. If only one member of the group chooses to transmit in the offered time, then the transmission is successful; however, if more than one member of the group chooses to transmit, then none of the transmissions are successful (assuming that no capture effect occurs). Therefore, the crucial element of a contention-based protocol is the technique used to determine the set of terminals in the enabled group. Many different techniques have been applied to the problem of determining membership in the group (e.g., addresses, probability, time-of-last-use). Some of the most well-known protocols are contention-based, including ALOHA, and [IEEE 802.3].

The delay characteristics of contention-based schemes are affected significantly by the offered traffic load. Most common contention-based schemes do not have an upper-bound on the waiting delay. However, unlike controlled-access schemes, contention-based schemes, in general, do not require terminal blocking because a new terminal may be added by reducing the quality of service that all terminals receive (i.e., a trade-off exists between delay and offered load).

5.5.2 Pure TDMA

Pure TDMA schemes use predetermined allocation algorithms, and are not sufficiently flexible to be useful in a MAC protocol for the high-speed wireless access system.

5.5.3 Polling

A polling scheme uses a centralized base-station to periodically poll each of the terminals in a geo-cell. The base-station has control over the order that terminals are polled in, and the frequency of service for each terminal. A terminal must queue data for the uplink channel until it receives a poll request from the base-station. Once granted the uplink channel, a terminal may not hold the channel for longer than a preassigned period. If a terminal does not require the uplink channel, then it returns an indication to the base-station that the channel may be passed on to a different terminal.

In a wireless network, token-ring and token-bus MAC schemes are implemented using polling because the token in those schemes needs to be transferred through the base-station, rather than directly from terminal to terminal, to avoid problems with hidden terminals.

[Mahmoud] suggests the use of a framed, time-division multiple access scheme based on polling in a centralized topology. Registration is supported by providing slotted-ALOHA contention slots. The maximum number of consecutive uplink slots assigned to a terminal is controlled by the base-station using an adaptive algorithm, and is included in the poll request message sent to a terminal on the downlink. An ARQ scheme with both positive and negative acknowledgements is included in the MAC protocol.

For our system, polling is not an attractive solution:

- The minimum interblock delay requirement could result in considerable inefficiency;
- The guard time associated with the TDD transceiver results in an additional overhead for each polling attempt; and
- Complex procedures for controlling the order of polling might be required to ensure that traffic contracts are not violated.

5.5.4 Contention-Based

[Biswas] suggests using Carrier Sense Multiple Access (CSMA) coupled with an acknowledgement scheme at the MAC layer to detect transmission failures. If a transmission failure occurs, and an acknowledgement message is not returned to the terminal, then a backoff algorithm is used to reschedule the transmission until after a delay period.

CSMA-based solutions were rejected for our wireless access system because of the inability of our physical layer to perform carrier sensing. Also, these solutions do not allow for enforcement of traffic contracts.

5.5.5 Reservation

[Raychaudhuri] recommends the use of a "Multiservices Dynamic Reservation (MDR) TDMA" scheme which is an extension of an earlier work on Packet Reservation Multiple Access (PRMA). The proposed scheme uses an over-the-air frame composed of several short duration request slots, and many longer duration message slots each capable of carrying a single modified-ATM-cell. The message slots are divided into two groups: some for CBR traffic, and some for VBR, ABR, and UBR traffic. The request slots are accessed using slotted-ALOHA to request a message slot. CBR message slots are assigned for the duration of a call, and the VBR/ABR/UBR message slots are assigned dynamically.

Some aspects of the reservation-based schemes are attractive for the proposed system. For example, the concept of "reserving" a set of slots for the duration of a call to ensure that a traffic contract can be guaranteed is particularly attractive. We would prefer a more centralized (i.e., asymmetrical) scheme that allows the base-station to control the distribution of slots, and manage the complete set of traffic contracts for the geo-cell.

5.5.6 Dynamically Scheduled

[Smulders] suggests a request/permit mechanism. A terminal requests further channel access by including a request in an uplink message (either alone or piggybacked on an ATM-cell). The request includes the number of cells waiting in the queue at the terminal. The base-station, upon receiving a request, updates its measure of the queue depth at the terminal. If a terminal has at least one cell to transmit, and the transmission of a cell by the terminal would not result in the terminal exceeding its stated peak-cell-rate, then a permit is placed in a single FIFO downlink queue. A terminal transmits an uplink message containing an ATM-cell whenever it receives an appropriately addressed permit.

[Apel] recommends a request/permit mechanism similar to [Smulders].

[Apostolas] proposes a MAC scheme that uses an uplink frame containing many slots. Some slots contain registration subslots that can be accessed by terminals using a slotted-ALOHA protocol. The other slots are contention-free (assigned by the registration process), and are used for carrying data or signalling information from a terminal. The role of each of the uplink slots is broadcast in downlink messages. The scheme uses the Virtual Path Identifier of each ATM-cell to identify particular terminals, and uses the Generic Flow Control (GFC) field of each cell to request particular MAC functions, such as increase bandwidth, decrease bandwidth, or request control channel. The uplink data slots are assigned to terminals using a scheduling algorithm similar to round-robin.

[Vidaller] suggests a TDMA frame divided into subframes with each subframe containing a number of slots capable of holding one ATM-cell per slot. For a CBR or VBR traffic source, the requested bandwidth is assigned for the duration of the call; for ABR traffic, the bandwidth is assigned by the base-station (satellite) on a frame-by-frame basis as a result of receiving petitions from the traffic source. In all cases, the bandwidth is assigned with the goal of grouping slots together as much as possible without violating the delay requirements of the source.

The dynamically scheduled schemes include the attractive concept of a centralized controller to assign and manage the traffic slots for each individual traffic contract. However, the existing proposals in the literature are not suitable for our particular system because of the TDD transceiver.

5.5.7 General Comments on the Literature

With the exception of the proposal in [Biswas], all of the schemes are designed for FDD uplink/downlink channels. Thus, a base-station is able to maintain constant communications with all the terminals in a geo-cell, and, thereby, transmit current control information at all times. Our proposed protocol uses a TDD transceiver.

Some papers do not demonstrate a good understanding of the nature of ATM. For example, some papers suggest that the ATM header can be stored at the base-station, rather than transmitting it with every cell. Unfortunately, the ATM header may contain end-to-end signalling information generated by the AAL layer that is certainly not constant for the duration of a call. In the protocol proposed in this thesis, a new format for the W-ATM cell is suggested, but that format maintains the fields that are essential for end-to-end signalling.

None of the papers cited use realistic traffic models. The conversion of application data into ATM-cells is rarely discussed, and the impact of the AAL process is never considered. One of our recommendations for future work is a more complete investigation of this aspect of ATM system performance.

5.6 Summary

This chapter has presented the assumptions and requirements for the MAC layer of the wireless access protocol. These assumptions and requirements are summarized in Table 5.1 and Table 5.2.

An overview of some proposals in the literature has also been presented in this chapter. In the next chapter, a detailed proposal for a MAC layer is presented.

Table 5.1: Summary of Assumptions for the MAC Layer

Assumption	Section	Summary
Carrier Sensing	§ 5.3.1	• No carrier sensing is possible.
Collision Detection	§ 5.3.2	• No collision detection is possible.
Hidden Terminals	§ 5.3.3	• Hidden terminals may be present in a geo-cell.
Capture Effect	§ 5.3.4	• No capture effect exists; therefore, collisions between transmissions are always destructive.
Number of Terminals	§ 5.3.5	• The number of terminals in a geo-cell is not restricted.
Traffic Characteristics	§ 5.3.6	• A wide range of traffic types may be carried by the MAC layer. Support for per link traffic characteristics must be provided.
Physical Layer Error Control	§ 3.5.4	• The physical layer corrects the majority of communication errors. The effective packet error rate is better than 10^{-9}.

Table 5.2: Summary of Requirements for the MAC Layer

Requirement	Section	Summary
Stability and Delay	§ 5.4.1.1	• The MAC protocol used for transferring data must be stable under load.
Fairness	§ 5.4.1.2	• The MAC protocol must provide fair access to the signalling functions in a base-station, and to the data transfer capacity in a geo-cell.
Data Rate Adaption	§ 5.4.2	• The MAC layer must provide the LLC layer with the ability to change the data rate capacity of a link between a terminal and a base-station.
Link Setup Time	§ 5.4.3	• The MAC protocol must provide configuration parameters that allow the link setup time to be controlled.

Table 5.2: Summary of Requirements for the MAC Layer (cont'd)

Requirement	Section	Summary
Link Blocking Probability	§ 5.4.4	• No quantitative requirement.
Distinct Uplink and Downlink Capacities	§ 5.4.5	• The data rate capacity of an uplink may be different from the data rate capacity of the downlink.
Packet Ordering	§ 5.4.6.1	• The MAC layer must ensure that data packets are delivered to the LLC layer at a receiver in the same order as they were generated by the LLC layer of the transmitter.
Duplicate Packets	§ 5.4.6.2	• The MAC layer must ensure that packets are not duplicated by the MAC layer.
Physical Layer Impact - Minimum Interblock Delay	§ 5.4.7.1	• Transmit and receive actions by terminals and base-stations must be separated by at least the minimum interblock delay.
Physical Layer Impact - Time-Division Duplex Transceiver	§ 5.4.7.2	• The MAC protocol should be designed for a system with a time-division duplex link between terminals and base-stations. Also, a guard time with a length of one OFDM-block must be inserted between a transceiver being used to transmit and then receive.
Physical Layer Impact - Synchronization	§ 5.4.7.3	• A base-station must transmit at least twenty OFDM-blocks per second to allow terminals to retain synchronization, and some of those blocks must be "header blocks" to allow new terminals to become synchronized.
Terminal Mobility	§ 5.4.8	• Registration and paging must be supported so that terminals can roam between geo-cells. • Hand-over is not supported.
Throughput Efficiency	§ 5.4.9	• High throughput efficiency is not a requirement.
Asymmetrical Complexity	§ 5.4.10	• The MAC layer design must be undertaken with the intention of placing as much complexity as possible in the base-stations rather than the terminals.
Robustness	§ 5.4.11	• The MAC protocol must be able to handle errors introduced by the communication channel.

6. THE PROPOSED MULTIPLE ACCESS CONTROL PROTOCOL

6.1 Introduction

The OFDM physical layer requires a MAC layer that employs a Time-Division Multiple Access (TDMA) scheme, and a protocol that satisfies the assumptions and requirements presented in the last chapter.

The proposed MAC layer uses a fixed length over-the-air frame with a well-defined structure. A frame is composed of several slots. Each slot in the frame has the same time duration: one OFDM-block plus a timing guard band as specified in Chapter 3. The large data content of a single OFDM-block and the constraint of a minimum interblock delay suggest that the use of single OFDM-block per time slot is a reasonable choice. Within a frame, several different types of slots are necessary to handle the wide range of functionality required by the MAC protocol.

The subsections that follow present details of the proposed MAC layer:

- the types of time slots used in a frame;
- the structure of a frame;
- the types of data manipulated by the MAC layer;
- the definitions of the messages exchanged between peer MAC entities;
- an explanation of the error control approach; and
- the operation of the MAC protocol.

6.2 Slot Type Definitions

All time slots have the same time duration (i.e., the same data size), and can carry the same amount of user data. Our MAC protocol requires the availability of three different functional classes of slots:

- control slots;
- unscheduled access slots; and
- scheduled access slots.

The terminology "scheduled" and "unscheduled" refers to the association between a slot and a terminal. Scheduled slots are assigned to particular links between one terminal and one base-station, whereas unscheduled slots are not assigned to a link that associates a particular terminal with a base-station. In the proposed MAC protocol, the base-station has complete control over the assignment and reassignment of slots: it schedules slots for particular links.

6.2.1 Control Slots

Slots in the control class are used by a base-station to broadcast information to all the terminals that are synchronized with that base-station. Therefore, only base-stations transmit in a control slot, and all terminals are expected to actively receive the contents of each control slot. The location of control slots in a time frame is constant (for a given base-station) to allow terminals to operate efficiently while in a standby mode.

6.2.2 Unscheduled Access Slots

In a geo-cell, unscheduled access slots are available in two pools: one for terminals, and the other for the base-station. In a control slot, the base-station broadcasts the positions of these slots within each over-the-air frame using a message.

Terminals use these slots to send unscheduled messages to the base-station. A contention algorithm is used by the terminals to select a slot for use. A base-station uses these slots to send unscheduled messages to all idle terminals in the geo-cell; because only a single base-station is present in each geo-cell, a contention algorithm is not required. Thus, the terminals and base-station must listen to all unscheduled access slots for messages from the opposite type of device, but unscheduled access slots may be idle.

Unscheduled access slots have no state information that needs to be maintained by the terminals or base-station between time frames. They are simply available for use as needed.

6.2.3 Scheduled Access Slots

This class contains the majority of the slots in each frame. All scheduled access slots are controlled by the base-station. The initial state of these slots is unassigned. They are held in a single pool of unassigned slots. Unassigned scheduled slots are never used for transmissions, so base-stations and terminals can remain idle during such a slot time.

If a base-station needs to assign slots to a communication link between a terminal and the base-station, then the base-station selects (schedules) slots from the pool of unassigned slots; changes the state of those slots to assigned; places the slots in a pool of assigned slots associated with the link; and informs the terminal of the new scheduled slots. The scheduled slots may be assigned individually for transmissions from a particular terminal to the base-station, or for transmissions from the base-station to a particular terminal. The assigned direction determines the actions of the base-station and the particular terminal. Meanwhile, all other terminals treat assigned scheduled slots the same as unassigned scheduled slots.

A base-station may elect to use a scheduled slot to form a guard band that allows the base-station to switch from transmitting to receiving, or vice versa. These slots are never used for transmitting data, so terminals and the base-station always remain idle. All terminals treat these slots as unassigned scheduled slots.

The state of a scheduled slot at a base-station may be altered by the events listed in Table 6.1. The state-transition diagram for scheduled slots at a base-station is shown in Figure 6.1.

Table 6.1: Scheduled Slot Events at Base-Station

Event	**Summary**
Add	The base-station has assigned the slot to a link; the terminal has not been informed of this change yet.
Delete	The base-station has chosen to remove the slot from a link; the terminal has not been informed of this change yet.
Add Confirmed	The addition of the slot to a link has been confirmed by the terminal.
Delete Confirmed	The deletion of the slot from a link has been confirmed by the terminal.
Change Sent	A message containing the addition or deletion of the slot has been sent to the terminal.
Time-out	A timer has expired, indicating that the terminal has not responded to the addition or deletion order yet.

When a base-station schedules a slot for a terminal, an "add" event changes the state of the slot from "unassigned" to "BS:assigned; MT:not informed" because the terminal has not yet been informed of the new slot. As soon as the base-station sends a slot change order message to the terminal with the new slot information, the "change sent" event results in the slot state being changed to "BS: assigned; MT:?". The base-station does not know if the terminal has received the assignment of the new slot until the base-station receives an acknowledgement from the terminal that results in an "add confirmed" event which changes the state of the slot to "BS:assigned; MT:confirmed".

When a base-station determines that a slot should be deallocated, then a "delete" event changes the state of the slot to "BS:assigned (delete pending); MT:confirmed". The terminal has not been informed of the delete request yet. As soon as a change order deleting the slot is sent to the terminal, a "change sent" event results in the slot state changing to "BS: freeing; MT:? from confirmed". Once the terminal has acknowledged the delete order, the slot state may be changed to "unassigned".

Slot change orders sent by a base-station may be corrupted and lost on the wireless channel, so timers are used to force retransmission of these messages.

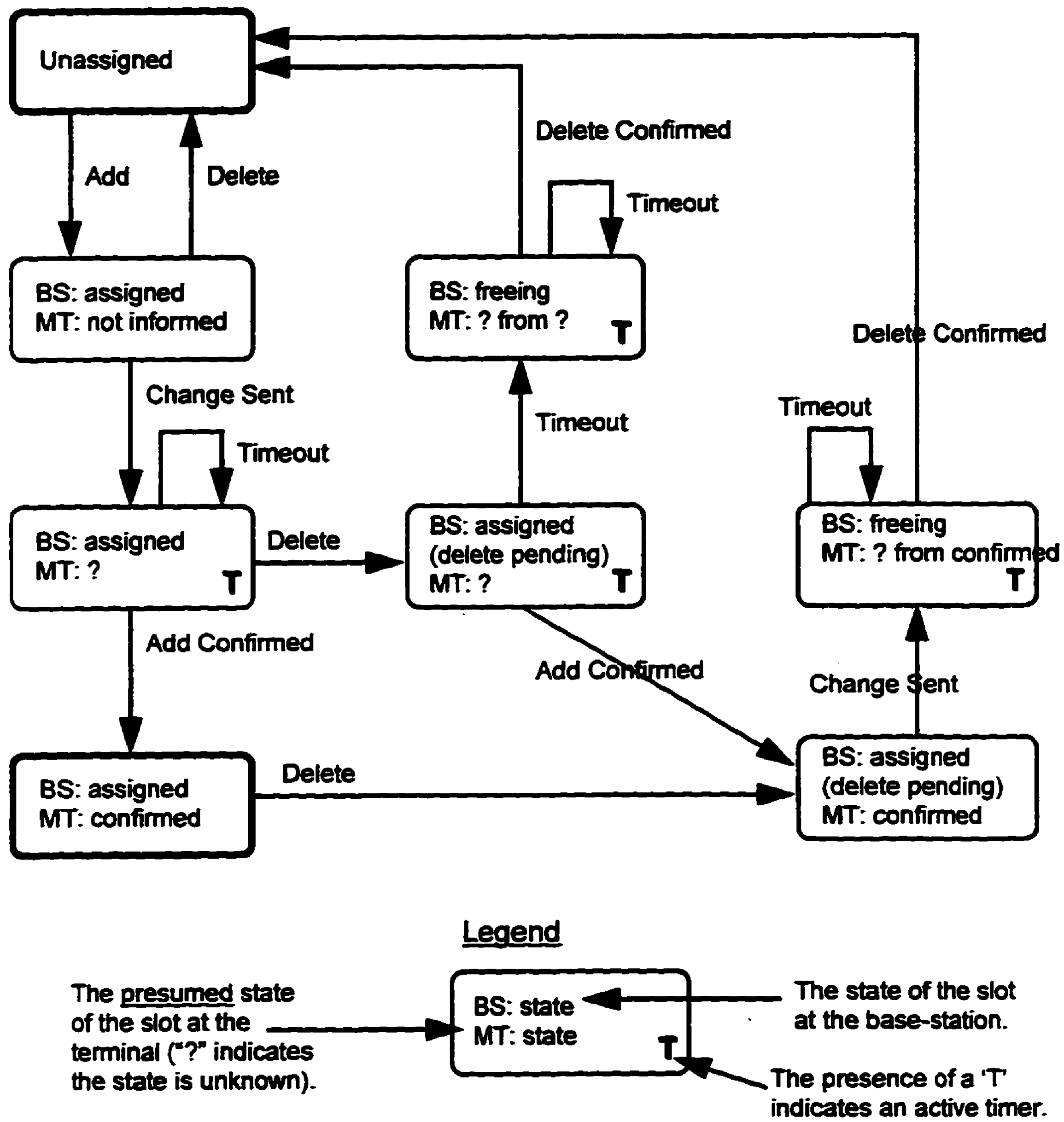

Figure 6.1: State-Transitions of Scheduled Slots at Base-Station

For a terminal, the applicable events are summarized in Table 6.2, and the state-transition diagram is shown in Figure 6.2.

Table 6.2: Scheduled Slot Events at Terminal

Event	Summary
Add	The terminal has received a slot change order containing an add slot command (either receive or transmit) from the base-station.
Delete	The terminal has received a slot change order containing a delete slot command from the base-station.
Delete Confirm	The terminal has sent a message to the base-station confirming the deletion of the slot.

The number of slot states at a terminal is lower than at a base-station, but, unlike a base-station, a terminal must distinguish between transmit slots (terminal to base-station) and receive slots (base-station to terminal). Transmit slots cannot be deleted until after an acknowledgement confirming the change order is sent to the base-station.

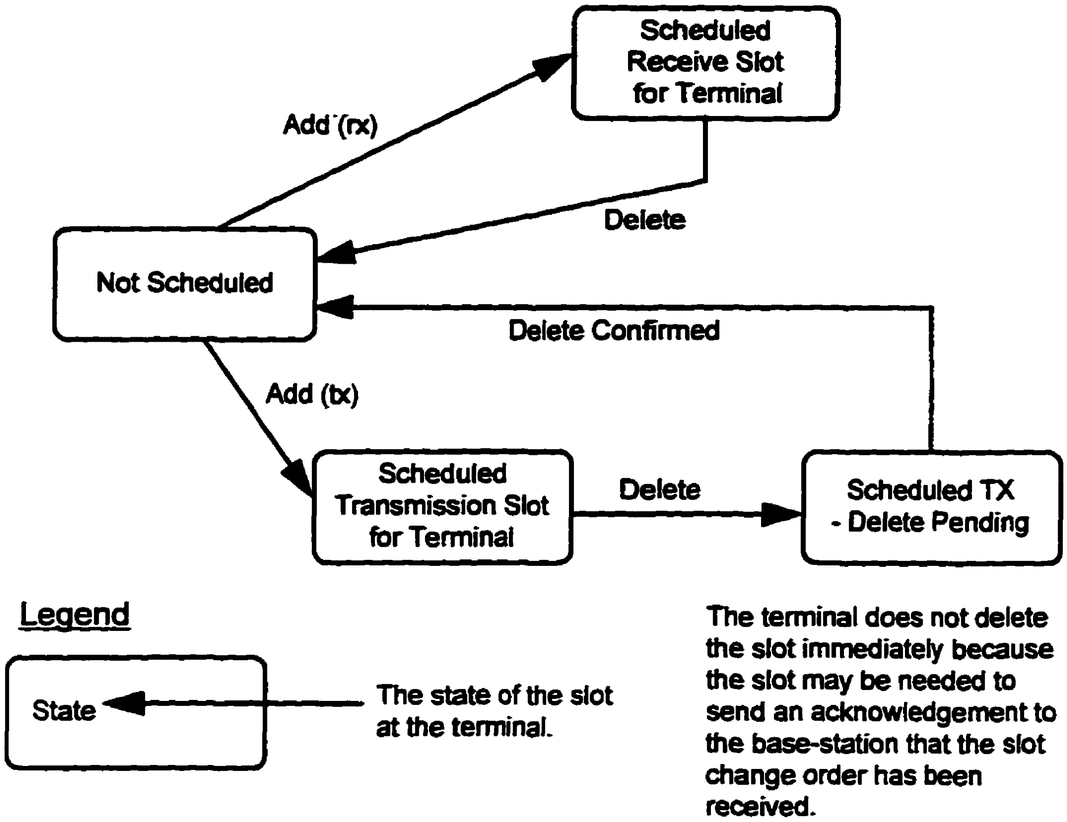

Figure 6.2: State-Transitions of Scheduled Slots at Terminal

6.3 Frame Definition

Each base-station establishes a frame length for its geo-cell, and broadcasts the frame length at regular intervals as part of an information message in a control slot. The frame length remains constant within that geo-cell until the base-station is taken out of service.

Each slot in a frame has an identifier that unambiguously identifies the location of that slot in the frame for both terminals and the controlling base-station.

A frame may be configured in many different ways, but is subject to the following restrictions:

- the first slot of a frame must be a control slot (for transmission of a header block);
- the second slot of a frame must be a control slot (for transmission of a base-station information message);
- the minimum frame length is eight time slots (two control slots, one unscheduled access slot for the terminals, one unscheduled access slot for the base-station, two scheduled access slots, and two guard slots); and
- the maximum frame length may be many thousands of time slots (one parameter that restricts the maximum length is the size of the field used to represent a slot identifier).

Figure 6.3(a) presents a sample frame format for an idle system. A frame length of 22 slots has been selected for the geo-cell. Slot #3 has been configured for unscheduled transmissions (e.g., paging) from the base-station, and slot #14 has been configured for unscheduled transmissions (e.g., originations) from terminals.

Figure 6.3(b) shows the same frame in a lightly loaded geo-cell. Slots #13 and #22 have been reserved by the base-station to act as guard-bands between the transmit and receive slots. Slots #5-#7 and #15-#17 have been assigned to links between the base-station, and one or more active terminals.

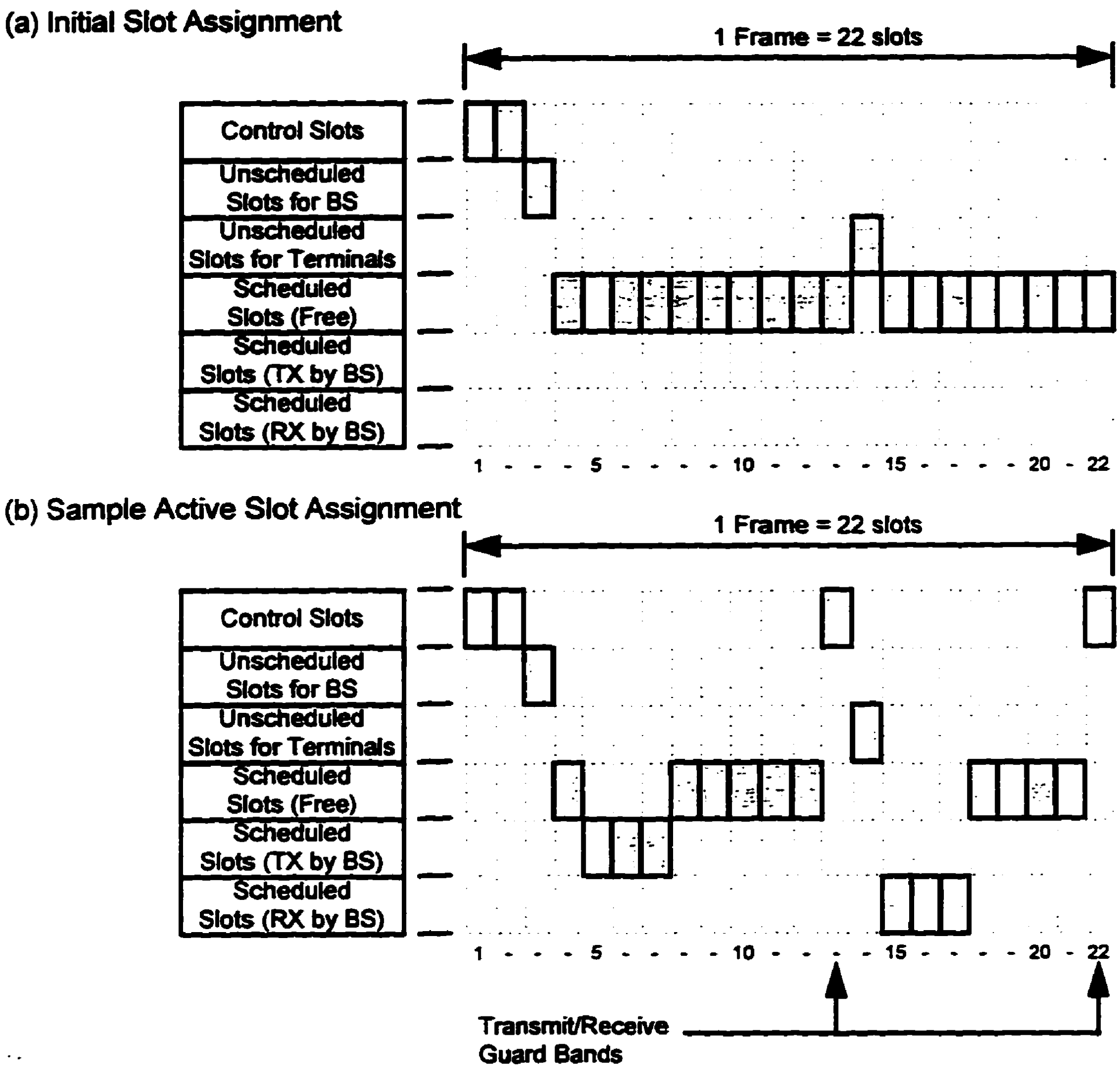

Figure 6.3: Sample Frame Formats

6.4 MAC Layer Data Entities

The MAC layer uses a number of different types of data entities. Some data types are used only within a single MAC layer instance, and others are exchanged between peer MAC layer instances. The subsections that follow describe some of the most important data types.

6.4.1 Device Identifier

All terminals and base-stations are assigned individual and unique device identifiers. These identifiers are commonly referred to as MAC addresses. Any transmitted messages that do not have an implicit source device and/or destination device must include the MAC address of the source and/or destination.

6.4.2 Sequence Numbers

The MAC protocol uses sequence numbers with a subset of the messages that are transmitted between peer MAC layers. The sequence numbers are used to detect the loss of messages that are critical to the proper operation of the MAC layer. A retransmission and acknowledgement algorithm is used between peer entities to overcome transmission errors (discussed in Section 6.6).

Each message transmitted from a terminal to base-station (on an uplink) contains one or two sequence numbers:

- D(RX) is the sequence number of the message received and successfully decoded most recently by the terminal on the downlink; and
- U(TX) is the sequence number of the uplink message.

D(RX) is present in all messages, and U(TX) is present only in messages that should be acknowledged by the base-station.

Messages from a base-station to a terminal (transmitted on a downlink) may also contain one or two sequence numbers:

- U(RX) is the sequence number of the message received and successfully decoded most recently from the terminal; and
- D(TX) is the sequence number of the downlink message.

U(RX) is included in all messages, and D(TX) is included only in messages that must be acknowledged by the terminal.

6.4.3 Time Slot Identifiers

Each slot in a frame has a unique identifier that may be used by both terminals and base-stations.

6.4.4 Slot Change Orders

Slot change orders are sent by a base-station to a terminal to change the list of slots associated with a traffic link, or a signalling link. An order may request that the terminal perform one of three actions: (a) add the accompanying list of slots; (b) delete the accompanying list of slots; or (c) delete all slots.

6.4.5 LLC-Service Data Unit

An LLC-SDU is the unit of data passed from the LLC layer to the MAC layer for transmission, or by the MAC layer to the LLC layer after reception. The contents of an LLC-SDU are not accessible by the MAC layer.

6.4.6 Rate Request

The transmission rate of a traffic link is expressed in data packets per frame. A terminal may request that the current transmission rate of a downlink or an uplink be changed. A base-station may change the transmission rate of a downlink or an uplink without consulting the terminal because the base-station controls the allocation of scheduled access slots.

6.4.7 Link Identifier

A terminal may have multiple active over-the-air links with a base-station. Each link has a group of logically related slots identified by a link identifier. The values used for link identifiers must be unique to a terminal, but do not need to be unique among the set of all terminals associated with a base-station.

6.4.8 Link Type

Two types of links exist: signalling links and traffic links. A signalling link is established between a terminal and a base-station to carry link-setup and link-management messages. Multiple individual traffic links may be established to carry distinct traffic flows between a terminal and a base-station.

6.5 MAC-to-MAC Messages

The operation of the MAC protocol requires that messages be exchanged between terminals and the base-station that controls the geo-cell containing the terminals. All messages are sent to, or received from, a base-station; no terminal to terminal messages are permitted.

Table 6.3 contains a summary of the messages that may be exchanged between the MAC entity in a terminal, and the MAC entity in the base station servicing the terminal. After the table, an explanation of the messages is presented.

Table 6.3: MAC-MAC Messages

Message Name	Required Slot Type	BS to MT	MT to BS	Ack'd?	Parameters
Link Request	Unscheduled		✓	yes	• device identifier • sequence numbers
Link Grant / Link Poll[1]	Unscheduled	✓		yes	• grant, or poll flag • accepted, or rejected flag • device identifier • uplink slot change order • downlink slot change order • sequence numbers
Link Modification Request	Scheduled		✓	yes	• uplink rate request • downlink rate request • sequence numbers • disconnect request flag • link identifier
Link Modification Response / Link Modification Order	Scheduled	✓		yes	• response, or order flag • uplink slot change order • downlink slot change order • sequence numbers • link identifier
Data Send - Terminal	Scheduled		✓	no	• LLC-SDU • sequence numbers
Data Send - Base Station	Scheduled	✓		no	• LLC-SDU • sequence numbers
Base-Station Information	Control	✓		no	• blocked, or not-blocked flag • list of unscheduled-to-BS slots ids • list of unscheduled-to-TERM slots ids • list of header slot ids (1 per frame) • contention access algorithm and parameters • device identifier • frame length

[1]The base-station may choose to place multiple link grant/link poll messages in a single unscheduled slot. This may result in an improvement in the performance of the protocol, but requires that an additional field be added to the message to point to the next link grant/link poll in the slot.

Table 6.3: MAC-MAC Messages (cont'd)

Message Name	Required Slot Type	BS to MT	MT to BS	Ack'd?	Parameters
Terminal Information	Scheduled		✓	yes	• physical layer characteristics • sequence numbers
Idle	Scheduled	✓	✓	no	• sequence numbers

6.5.1 Link Request

A *Link Request* message is used by a terminal to request that a base-station establish a bi-directional signalling link between the terminal and the base-station.

6.5.2 Link Grant and Link Poll

A *Link Grant* is used by a base-station to assign the initial signalling slots to a terminal in response to a *Link Request*. A *Link Poll* is used to establish a signalling link if the link setup is being initiated by the base-station.

6.5.3 Link Modification Request

A *Link Modification Request* is used by a terminal to request the creation of a new traffic link, a modification in the current capacity of an existing traffic link, or the termination of an existing signalling or traffic link.

6.5.4 Link Modification Response and Link Modification Order

A *Link Modification Response* is used by a base-station in response to a *Link Modification Request* to supply a list of changes to the current list of scheduled slots associated with a link.

A *Link Modification Order* is similar to a *Link Modification Response*, except that it is generated autonomously by the base-station, and not as the (direct) result of a message from the terminal.

6.5.5 Data Send

Data Send messages are used to transfer LLC-SDUs bidirectionally between a terminal and a base-station.

6.5.6 Base-Station Information

Base-Station Information messages are broadcast by a base-station to all terminal that are synchronized with the base-station. A message is generated once per frame, and is used to convey general information particular to that base-station.

6.5.7 Terminal Information

A *Terminal Information* message is used by a terminal to respond to a *Link Grant* or a *Link Poll*. It contains information about the specific characteristics of the terminal, such as the minimum interblock delay.

6.5.8 Idle

An *Idle* message is transmitted in a scheduled slot if no other information is available to be sent.

6.6 MAC Protocol Robustness

The messages that are exchanged between peer MAC entities are often crucial to the correct operation of the MAC layer protocol. For example, *Link Grant*, *Link Modification Response*, and *Link Modification Order* messages transfer slot assignments that must be received correctly for the traffic and signalling links to operate properly. Some messages, such as the *Data Send* messages used to transfer LLC-SDUs, are not critical to the correct operation of the MAC layer, and are not offered guaranteed delivery by the MAC layer because the higher layer protocols are assumed to be handling errors. The MAC protocol uses a combination of sequence numbers and retransmission timers to ensure the correct operation of the MAC protocol in an environment that may introduce errors into messages transmitted over the transmission channel.

6.6.1 Sequence Number Handling

Each message sent to a peer MAC entity includes a pair of sequence number fields. The first field is used by the transmitter to identify the enclosing message if the recipient should acknowledge the reception of the message. The transmitter selects a value for the identifier by computing the next available number from a windowed set of sequence numbers[2]. The second field contains the value of the message identifier received most recently from the intended recipient of the message, and serves as an acknowledgement of the message that used that identifier.

When a message that needs to be acknowledged is transmitted, a retransmission timer is started. If a message is lost (most likely corrupted during transmission), then the transmitting entity will not receive an acknowledgement and the retransmission timer will expire. An algorithm is used with the windowed set of sequence numbers to ensure retransmission of lost messages. Our design incorporates Go-Back-N [Tanenbaum]. With this algorithm, the expiry of a retransmission timer results in the retransmission of the message associated with the timer, and in the re-evaluation and retransmission of all messages that were sent after that message.

At the receiver, the arrival of a message with an invalid message identifier (i.e., not the next consecutive sequence number), results in the deletion

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[2] With a windowed set of sequence numbers, the range of sequence numbers is larger than the maximum size of the window. The maximum size of the window is limited, and the extent of the window is adjusted as messages are transmitted and acknowledgements are received. Only sequence numbers that lie within the window are valid.

of that message if the message needs to be acknowledged. Messages that are not to be acknowledged do not include a message identifier, and are always accepted if they are successfully decoded. Unacknowledged messages always include the second of the sequence number fields: the acknowledgement field.

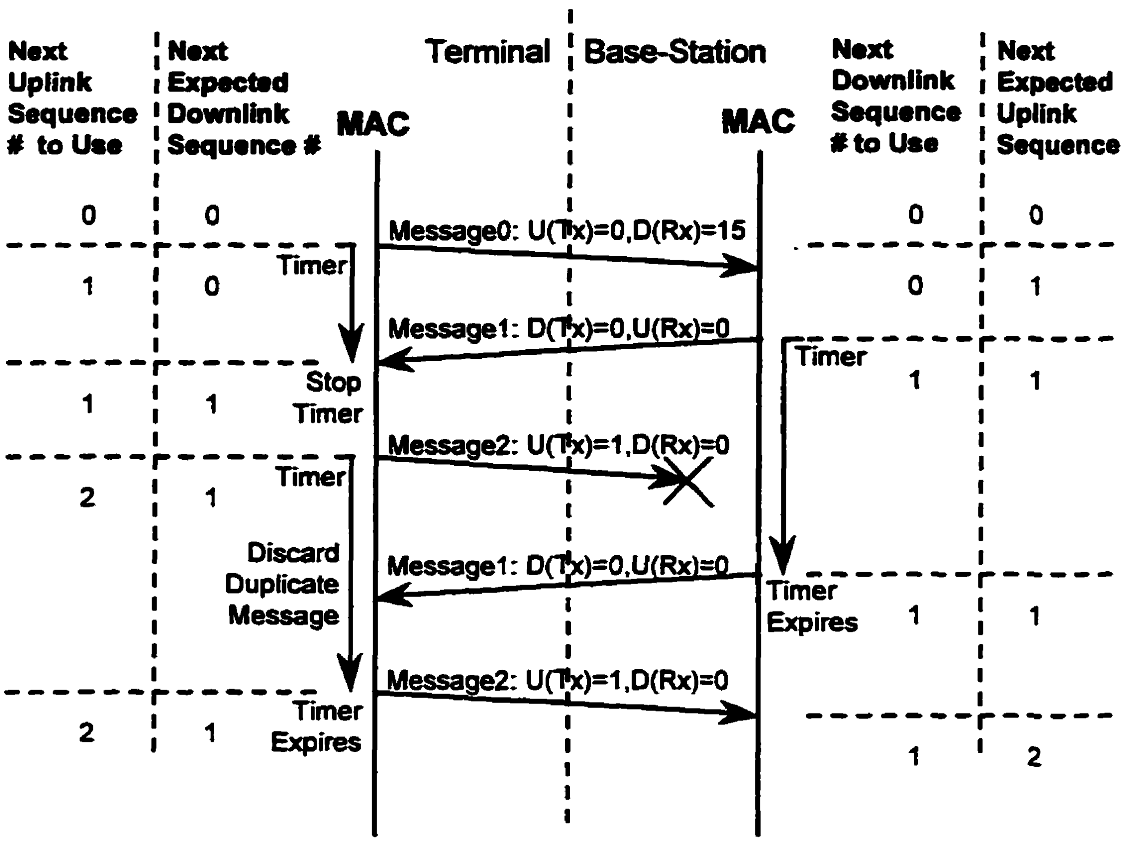
When a message is successfully acknowledged by the intended recipient, then that message may be deleted from the local buffer and the sequence number window may be advanced appropriately. The same acknowledgement scheme is used in a symmetrical fashion on both the uplink and downlink between a terminal and a base-station.

A selective retransmission algorithm may be suitable for this application, especially since the probability of a message being lost is quite low. However, the effect of the TDD transmission channel may be to render the algorithm only as effective as a Go-Back-N approach, but at the expense of greater buffering requirements and a smaller effective window size for the same field size.

A MAC entity needs to maintain only one set of sequence numbers for each active signalling link, rather than one for each link. The messages transferred over the traffic links carry acknowledgements, but do not need to be acknowledged, so a single set of sequence numbers is satisfactory.

In Figure 6.4, an example showing the operation of the sequence number algorithm is presented. In this example, a base-station and a terminal are exchanging messages. A message, Message2 from the terminal to the base-station is corrupted. This results in the loss of the acknowledgement for an earlier message from the base-station, Message1. The base-station retransmits this message upon expiry of the retransmission timer, and the terminal deletes the message because it is outside the valid sequence number window.

Meanwhile, at the terminal the timer associated with the corrupted message expires, and Message2 is then delivered successfully.



Note: This example assumes that sequence numbers can range from 0 to 15. Therefore, the value of D(Rx) associated with Message0 is 15, because the next valid sequence number that may be used by the base-station is 0 (and, the most recently used sequence number was 15).

Figure 6.4: Example of Sequence Number Operations

The sequence numbers are initialized during the establishment of the signalling link. If a terminal generates a *Link Request* message then the terminal uses zeroes as the initial values for U(TX) and D(RX), and the base-station initializes U(RX) and D(TX) to zero upon receiving the *Link Request*. If the base-station begins the link setup process, then U(RX) and D(TX) are set to zero before sending the *Link Poll*. If a terminal and base-station begin the link setup process simultaneously, then the base-station ignores the *Link Request* message from the terminal, and the terminal resets its sequence numbers after receiving the *Link Poll* message.[3]

The size of the sequence number window must be chosen carefully. If the valid range of sequence numbers is 0 to MaxSeq, then with a Go-Back-N algorithm at most MaxSeq messages may be outstanding at once, and with Selective Retransmission at most (MaxSeq+1)/2 messages. With a TDD channel, the mean time between a message being sent and the corresponding acknowledgement being received is on the order of one half of the frame time. Also, the assignment of slots may result in acknowledgements arriving in bursts, so a large window size is necessary to minimize blocking of transmissions. Fortunately, the number of acknowledged messages should be small, in comparison to the number of data messages, so a small size, such as MaxSeq equal to 15, may be acceptable.

6.6.2 Message Retransmission Timers

The retransmission algorithm depends on the use of timers to indicate that messages have not been acknowledged within an acceptable period of time. Each message that needs to be acknowledged must have an associated retransmission timer started when the message is passed to the physical layer for transmission. The duration of a timer is determined from: (a) the maximum time until a response could be received, (b) the minimum time until a response could be received, (c) the current number of slots assigned to the link (which may result in a decrease in the expected time until an acknowledgement), and (d) the number of outstanding messages.

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[3] This is possible, because the operation of the signalling link is the same regardless of which entity succeeds in setting up the link.

6.7 Message Flow Diagrams

The purpose of the MAC protocol is to set up and manage signalling and traffic links between terminals and the base-station in a geo-cell. A key concept of the proposed MAC protocol is the use of a signalling link for establishing and controlling multiple traffic links. In Figure 6.5, the basic flows of information through the MAC layer, and the significant components of the MAC layer are shown. Appendix A presents detailed state-transition tables and diagrams.

In the subsections that follow, the operation of the MAC protocol is illustrated using a number of examples. In each example, the sequence of messages associated with a particular situation is shown in a message sequence chart (also known as an event diagram). To avoid overcomplicating the diagrams, the mapping of messages onto particular types of slots is not shown.

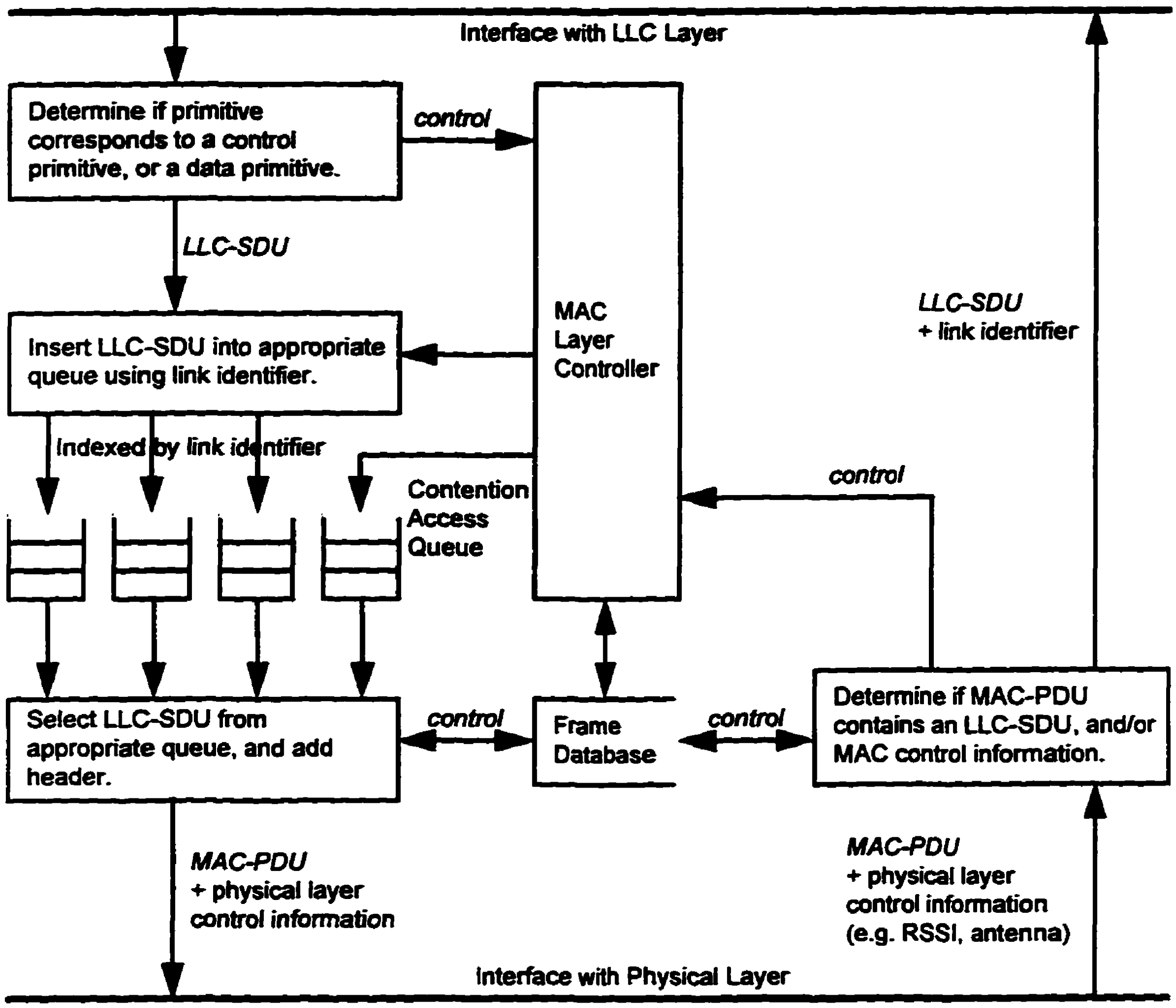

Figure 6.5: Basic MAC Layer Operation

6.7.1 Signalling Link Setup by Terminal

An idle terminal requires a signalling link to set up a traffic call. The large variety of possible applications for terminals suggests that the stimulus for setting up a signalling link should be configurable. For example, some terminals may establish signalling links when the first traffic link needs to be set up (i.e., when a MAC_CONNECT_REQUEST primitive is received from the LLC layer); others may establish signalling links when synchronization with a base-station is achieved. Similarly, the mechanism used to initiate a signalling link tear-down should be configurable.

Regardless of the event that causes a signalling link to be required, the same algorithm is used to establish the link. Figure 6.6 shows the sequence of messages, and the associated timers that are required to reliably set up a signalling link.

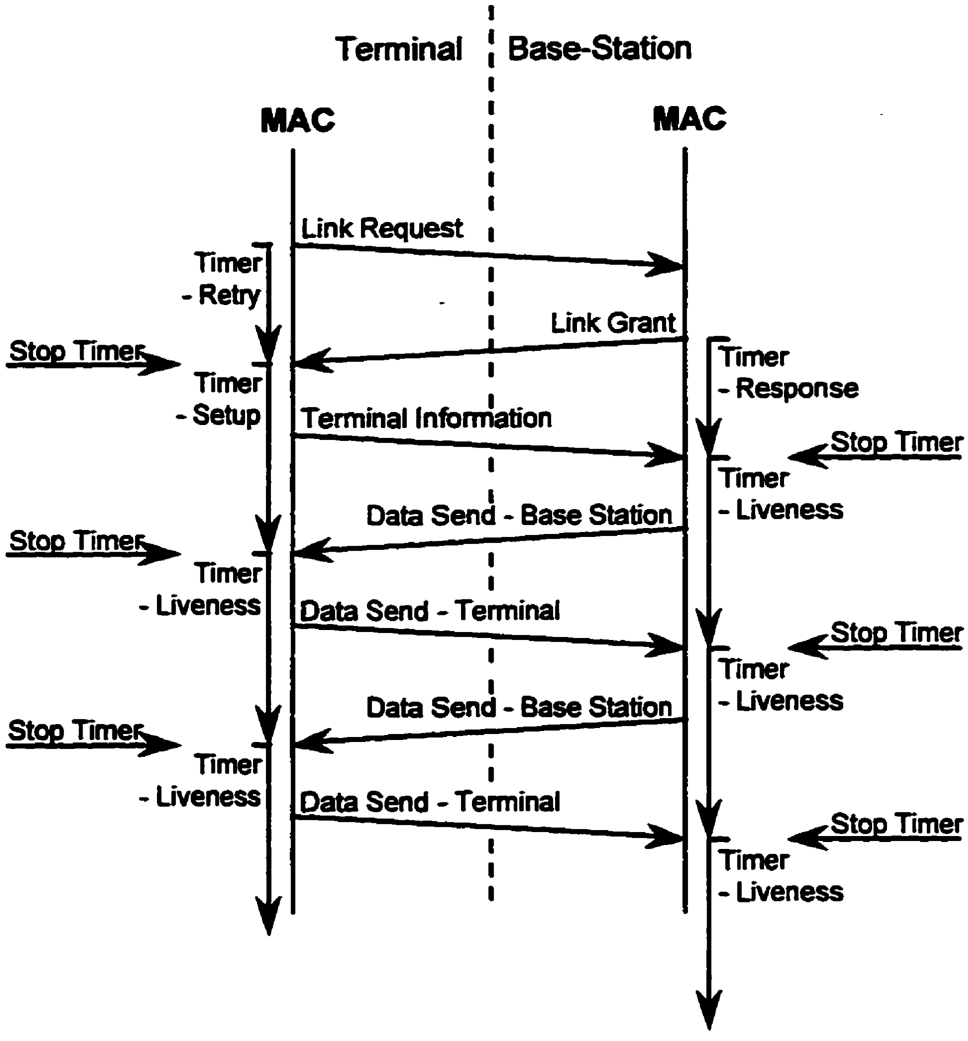

Figure 6.6: Signalling Link Setup at Request of a Terminal

The *Link Request* message may be subject to collisions with *Link Request* messages generated by other terminals in the geo-cell. If the *Link Request* message is received successfully by the base-station, then the base-station enqueues a *Link Grant* message for transmission to the terminal in the next available slot. The *Link Grant* message contains the assignment of slots for the signalling link. After receiving the *Link Grant* message, the terminal transmits a *Terminal Information* message to provide the base-station with the essential physical layer characteristics, such as the minimum interblock delay, which are required for assigning further slots to the terminal.

If the *Link Request* message of a terminal collides with other *Link Request* messages, or is corrupted by the wireless channel, then a retransmission mechanism is used. After sending a *Link Request* message, a terminal starts a retry timer. If a link is not set up before this timer expires, then a new *Link Request* is generated, and a new retry timer is started. The duration of the timer is randomly selected from a window of values that grows exponentially with each successive attempt. For example, the first window may extend from 1 to 10 slots; the second window may extend from 1 to 20 slots; and so on. The exponential growth of the window size is necessary to handle heavy traffic load (as in [IEEE802.3]). Once a link is set up successfully, or the maximum number of permitted attempts has been made, the window size is returned to its initial value.

In Figure 6.7, the handling of a *Link Request* collision is shown.

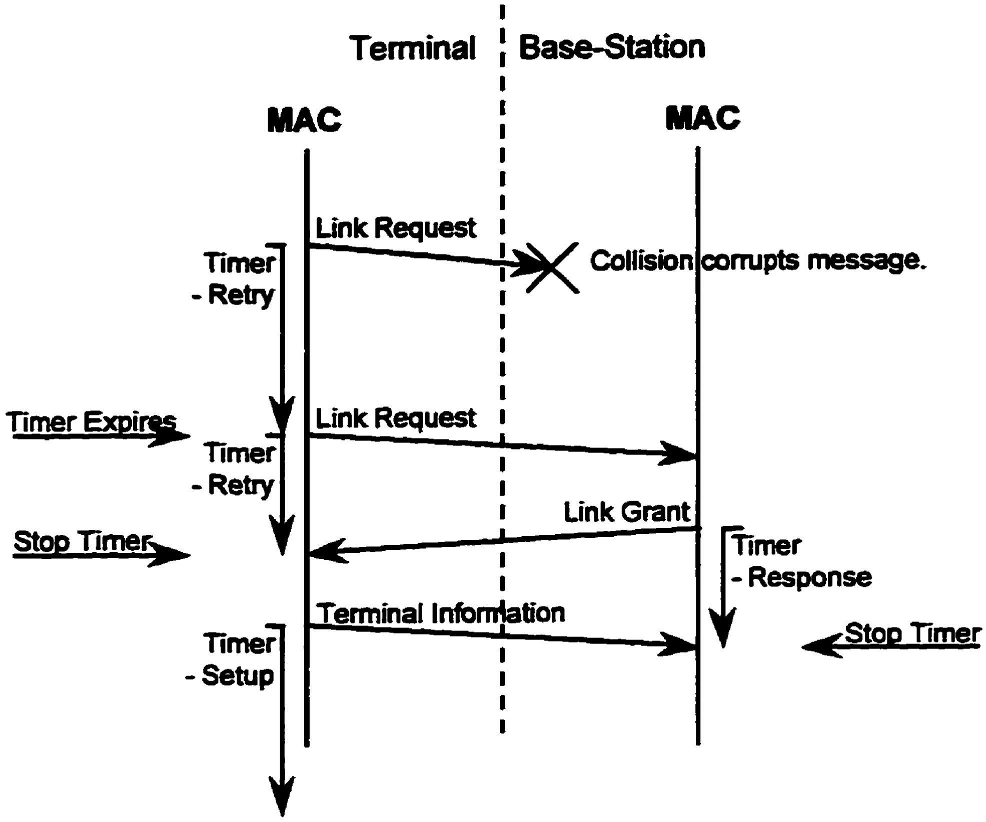

Figure 6.7: Effect of a Collision on a Link Request Message

6.7.2 Signalling Link Setup by Base-Station

The process of setting up a signalling link may be initiated by a base-station after receiving a MAC_CONNECT_REQUEST primitive from the LLC layer. The steps required to establish a signalling link in this direction are similar to those used in the other direction, but the process is significantly more reliable because of the absence of any potential for collisions. A successful link set up process is shown in Figure 6.8.

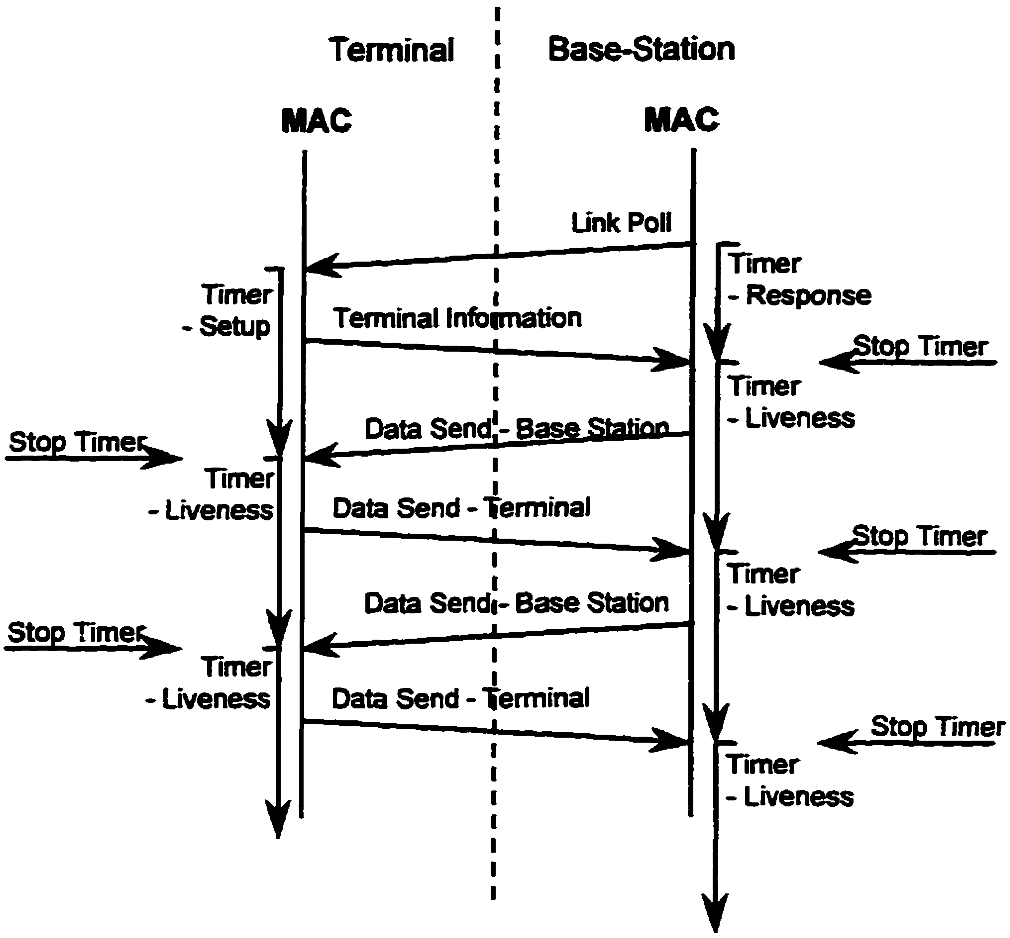

Figure 6.8: Signalling Link Setup at Request of a Base Station

Although the process of setting up a link from the base-station is much more reliable, retransmissions are still required to handle the possibility of message corruption. And, of course, the base-station will be unable to reach a terminal that is powered-down, or that has moved to a new geo-cell without informing the location manager for the network. Figure 6.9 shows the sequence of events associated with the failure of the base-station to communicate with a terminal. The number of attempts by the base-station to contact a terminal should be a configurable parameter.

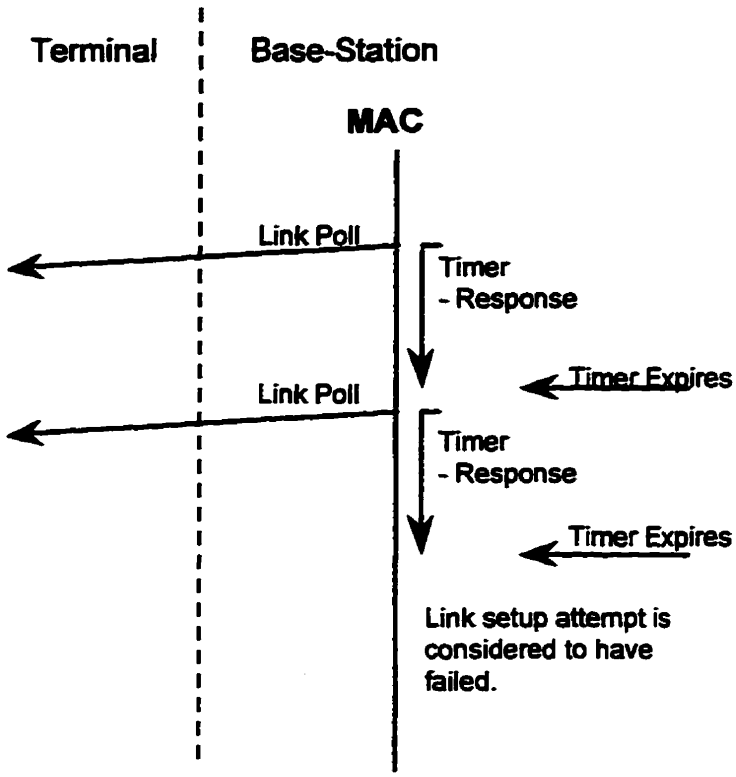

Figure 6.9: Base-Station Fails to Set Up Link with Terminal

A base-station may attempt to set up a link to a terminal at the same time as that terminal attempts to contact the base-station. Figure 6.10 shows the handling of such a situation. The attempt by the base-station has a higher probability of success (because of the absence of collisions) than the attempt by the terminal, so the *Link Request* of the terminal is ignored by the base-station. The characteristics of a signalling link are independent of the entity that initiated the setup process.

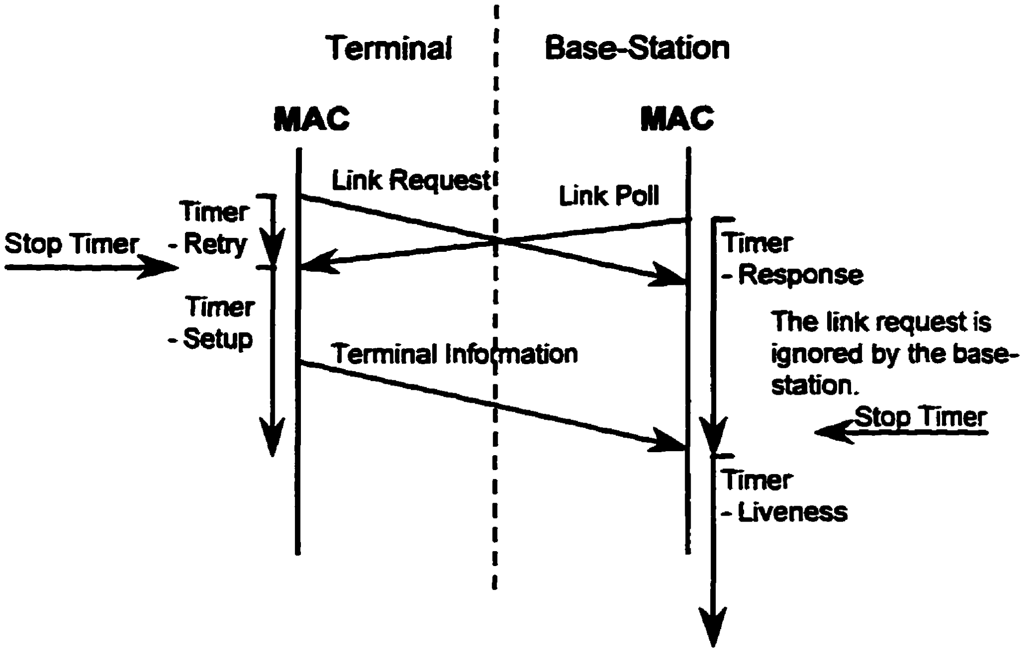

Figure 6.10: Signalling Link Setup with Simultaneous Requests

6.7.3 Traffic Link Setup and Capacity Modification by Terminal

A *Link Modification Request* message is used by a terminal to request the establishment of a new traffic link, or to modify the link rate currently associated with a particular traffic link. Figure 6.11 shows the request-response message sequence.

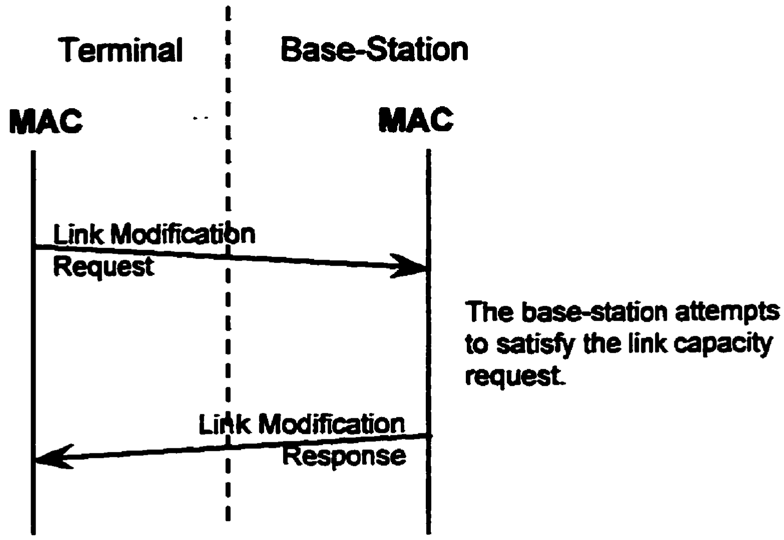

Figure 6.11: Link Capacity Modification by Terminal

The base-station responds to the *Link Modification Request* with a *Link Modification Response* message that indicates the outcome of the request. Many results are possible, such as:

- a new traffic link is set up (with a capacity in the requested range);
- a request for a new traffic link is rejected (because of insufficient capacity being available);
- the transmit and/or receive data rate of an existing traffic link is modified; or
- a modification request for an existing traffic link is rejected.

6.7.4 Traffic Link Setup and Capacity Modification by Base-Station

A base-station may unilaterally modify the capacity of an existing traffic link. A single message is used to inform the terminal of the change (Figure 6.12). The same message is used to establish a new traffic link.

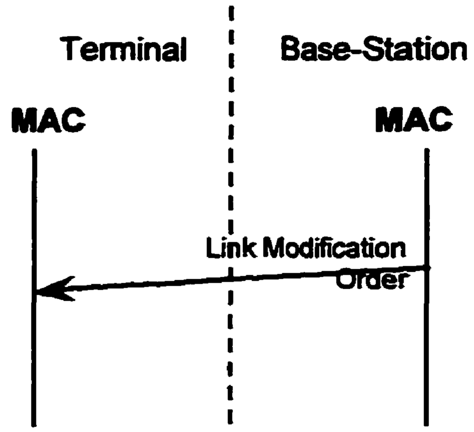

Figure 6.12: Capacity Modification by Base Station

6.7.5 Traffic Link Termination

A traffic link may be ended at the request of either the terminal or the base-station. A base-station terminates a link by sending a *Link Modification Order* to the terminal with a delete order for all of the slots associated with the link; a terminal may terminate a link by sending a *Link Modification Request* to the base-station, and the base-station will then respond with a *Link Modification Response* that deletes all of the slots associated with the traffic link.

Alternatively, a traffic link may be terminated if a loss of connectivity is detected between the terminal and base-station by either MAC entity. Each traffic link has an associated 'liveness timer'. If a message is received successfully from the other MAC entity, then the timer is restarted; however, if the timer expires, then a link error is recorded and the liveness timer is restarted. If several (a configurable number) consecutive link errors are recorded, then the traffic link is considered to have failed. The duration of the liveness timer associated with a traffic link is equal to the time until the next message is scheduled to be received from the other MAC entity on that link.

6.7.6 Signalling Link Termination

A number of different configuration options should exist for controlling the termination of a signalling link. Some terminals may want to eliminate the signalling link when the last traffic link is terminated; other terminals may want to wait for a period of time before terminating the signalling link in case a new traffic link is required shortly thereafter.

The process of terminating a signalling link is identical to the process used for terminating a traffic link (including the possibility of a connectivity failure). If a signalling link is terminated, and the terminal still has active traffic links, then the traffic links are automatically terminated using the algorithm for link connectivity failure.

6.7.7 Data Transfer

When a LLC-SDU is passed from the LLC layer (using a MAC_DATA_REQUEST primitive), the MAC layer enqueues a data message for transmission in a slot associated with the traffic link specified with the LLC-SDU. A MAC_DATA_CONFIRMATION primitive is returned to the LLC layer once the data message is transmitted (the link-id allows the LLC layer to associate the confirmation with a particular link).

When the MAC layer receives a *Data Send* message, containing a LLC-SDU, from the physical layer, the MAC layer can cross-reference the slot with a link identifier before passing the LLC-SDU up to the LLC layer.

6.8 Summary

This chapter has presented detailed information about the MAC protocol that we are proposing for our wireless access system. The central concept of this protocol is the use of two different types of links between terminals and a base-station: signalling links for transferring control information between the MAC layer in a terminal and the MAC layer in a base-station, and traffic links for transferring the traffic generated by the higher layers. The set up, control, usage, and termination of these links in a TDMA frame were discussed in some detail.

A preliminary software simulation environment was developed to determine some of the operational characteristics of the MAC layer in a single geo-cell with one base-station and a variable number of terminals. This software was used to test the operation of the proposed MAC layer in a few different situations, and would be a useful starting point for further research.

In the next chapter, the overall conclusions of this thesis and some recommendations for future work are discussed.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Summary

This final chapter summarizes the conclusions of this thesis, and recommends topics for future research work.

7.2 Conclusions

The main contributions of this thesis are summarized as follows:

- a formulation of ideas on multiple access protocols that exploits a centralized system architecture to allow for the enforcement of ATM traffic contracts;
- a proposal of an LLC protocol (adapted from the IEEE 802.2 protocol for wired local area networks) that provides the required communication services for the wireless ATM protocol layer; and
- the development of message flow charts and state diagrams for the proposed MAC protocol which can be directly used for building a prototype wireless ATM network.

The proposed data link protocols for the MAC and LLC sublayers have addressed the problem of providing a wireless transmission system for ATM cells. These protocols provide support for traffic contracts, and provide functionality that may be used to limit the adverse effects of the wireless channel.

The MAC layer offers a highly centralized approach for scheduling transmission slots to particular traffic links. This approach allows for considerable flexibility in controlling and changing the scheduling algorithm because the wireless terminals are effectively independent of the particular slot assignment algorithm. New algorithms may be introduced without introducing changes in the wireless terminals, and existing algorithms may be adjusted to provide different performance.

The LLC layer offers a wide range of functionality to the W-ATM layer. The complexity of the LLC layer is determined by the amount of functionality that the LLC layer must provide. For example, if only link management functionality is required, then the LLC layer is quite simple, but if the W-ATM layer also requires encryption/decryption functionality in the LLC layer, then the LLC layer complexity increases considerably. A base-station needs to implement the complete range of services, but a terminal should implement only the subset of services appropriate for its particular application.

7.3 Recommendations for Future Work

This thesis has proposed MAC and LLC protocols for a wireless ATM network. An evaluation of the performance characteristics of the proposed MAC and LLC protocols is therefore the necessary next step. Particular problems that are worthy of investigation are the following:

- transmission delay characteristics (of ATM-cells);
- throughput efficiency;
- call blocking probability;
- signalling link establishment delay, and the effect of the particular type of contention resolution protocol used by the terminals; and
- sensitivity of performance characteristics to the partitioning by the MAC layer of slots into scheduled and unscheduled groups.

The proposed MAC layer uses a Go-Back-N algorithm to handle retransmission of packets. An investigation of the impact on performance characteristics of the alternative, Selective Repeat, should be performed.

The work in this thesis should be extended by considering the problems associated with supporting terminal mobility. For example, the management of virtual circuits to mobile terminals during handovers should be explored.

The interactions between the data link layers and the control plane of ATM should be investigated. Aspects such as call admission control, traffic contracts, and quality of service should be investigated in more detail.

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APPENDIX A

Control of Signalling Link

The states of a signalling link are shown in Figure A.1 for a base-station and in Figure A.2 for a terminal. Information about the handling of particular events is not shown in the figures, although the state transition paths are shown. Detailed state-transition tables are provided in Table A.1 for a base-station, and in Table A.2 for a terminal.

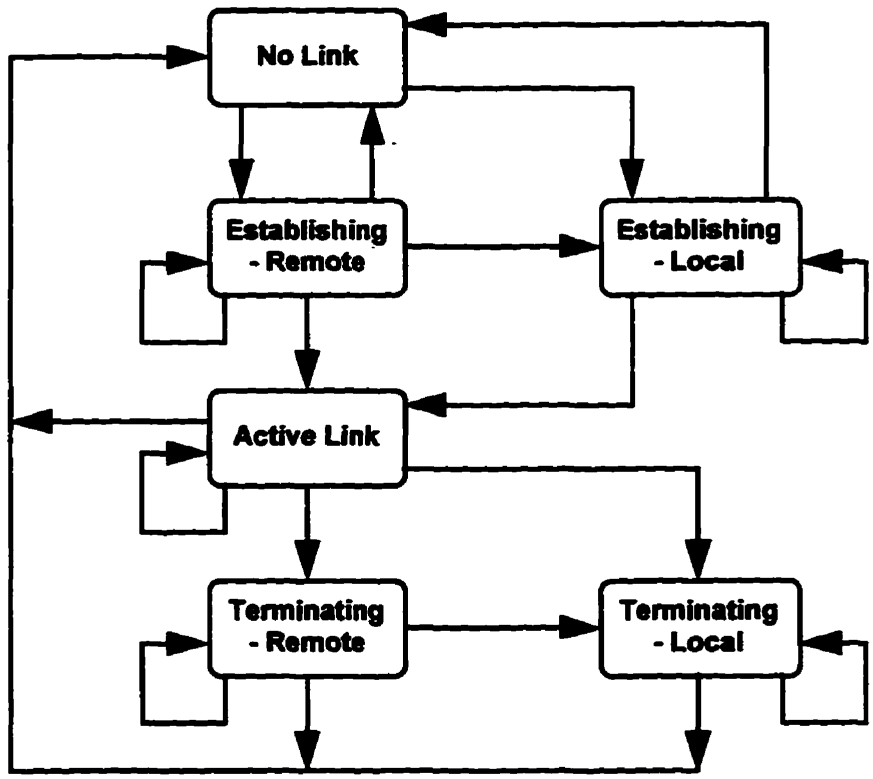

Figure A.1: Signalling Link State-Transition Diagram for Base-Station

Table A.1: State Transitions at Base-Station for Signalling Link

Event	Source	Actions	Next State
(1) No Link			
MAC_CONNECT_REQUEST	LLC	• enqueue *Link Poll* • set retry counter to maximum value • start timer (response) • assign preliminary TX and RX slots	⇒ (2b) Establishing Link (Initiated by Local)
Link Request	terminal MAC	• enqueue *Link Grant* • set retry counter to maximum value • start timer (response) • assign preliminary TX and RX slots	⇒ (2a) Establishing Link (Initiated by Remote)
(2a) Establishing Link (Initiated by Remote)			
MAC_CONNECT_REQUEST	LLC	• reset retry counter to maximum value	⇒ (2b) Establishing Link (Initiated by Local)
Timer Expiry (response timer) and retry = 0	local MAC	• free TX and RX slots	⇒ (1) No Link
Timer Expiry (response timer) and retry > 0	local MAC	• decrement retry counter • enqueue *Link Grant* • start timer (response)	⇒ No Change
Any type of message received from the terminal in a scheduled RX slot (acknowledges the TX and RX slots).	terminal MAC	• start timer (liveness) • stop timer (response) • MAC_CONNECT_INDICATION	⇒ (3) Active Link

Table A.1: State Transitions at Base-Station for Signalling Link (cont'd)

Event	Source	Actions	Next State
(2b) Establishing Link (Initiated by Local)			
Timer Expiry (response timer) and retry = 0	local MAC	• MAC_CONNECT_CONFIRMATION (failed) • free TX and RX slots	⇒ (1) No Link
Timer Expiry (response timer) and retry > 0	local MAC	• decrement retry counter • enqueue *Link Poll* • start timer (response)	⇒ No Change
Any type of message received from the terminal in a scheduled RX slot (acknowledges the TX and RX slots).	terminal MAC	• start timer (liveness) • stop timer (response) • MAC_CONNECT_CONFIRMATION (succeeded)	⇒ (3) Active Link
Link Request	terminal MAC	• reset retry counter to maximum value	⇒ No Change
(3) Active Link			
Timer Expiry (liveness timer)	local MAC	• free TX and RX slots	⇒ (1) No Link
Any type of message received from the terminal in a scheduled RX slot.	terminal MAC	• restart timer (liveness)	⇒ No Change
Link Modification Request that requests the termination of the link.	terminal MAC	• enqueue *Link Modification Response* that deletes all scheduled TX and RX slots	⇒ (4a) Terminating Link (Initiated by Remote)
MAC_DISCONNECT_REQUEST	LLC	• enqueue *Link Modification Order* that deletes all scheduled TX and RX slots	⇒ (4b) Terminating Link (Initiated by Local)

Table A.1: State Transitions at Base-Station for Signalling Link (cont'd)

Event	Source	Actions	Next State
(4a) Terminating Link (Initiated by Remote)			
All slots associated with the session released by base-station. [a]	local MAC	• MAC_DISCONNECT_INDICATION • stop timer (liveness)	⇒ (1) No Link
Any type of message received from the terminal in a scheduled RX slot.	terminal MAC	• restart timer (liveness)	⇒ No Change
MAC_DISCONNECT_REQUEST	LLC	• no actions required	⇒ (4b) Terminating Link (Initiated by Local)
Timer Expiry (liveness timer)	local MAC	• free TX and RX slots	⇒ (1) No Link
(4b) Terminating Link (Initiated by Local)			
All slots associated with the session released by base-station. [a]	local MAC	• MAC_DISCONNECT_CONFIRMATION • stop timer (liveness)	⇒ (1) No Link
Any type of message received from the terminal in a scheduled RX slot.	terminal MAC	• restart timer (liveness)	⇒ No Change
Timer Expiry (liveness timer)	local MAC	• free TX and RX slots	⇒ (1) No Link

<u>*Notes:*</u>

([a]) When the base-station receives an acknowledgement for the message that deleted the slots, it will consider the signalling link to be terminated.

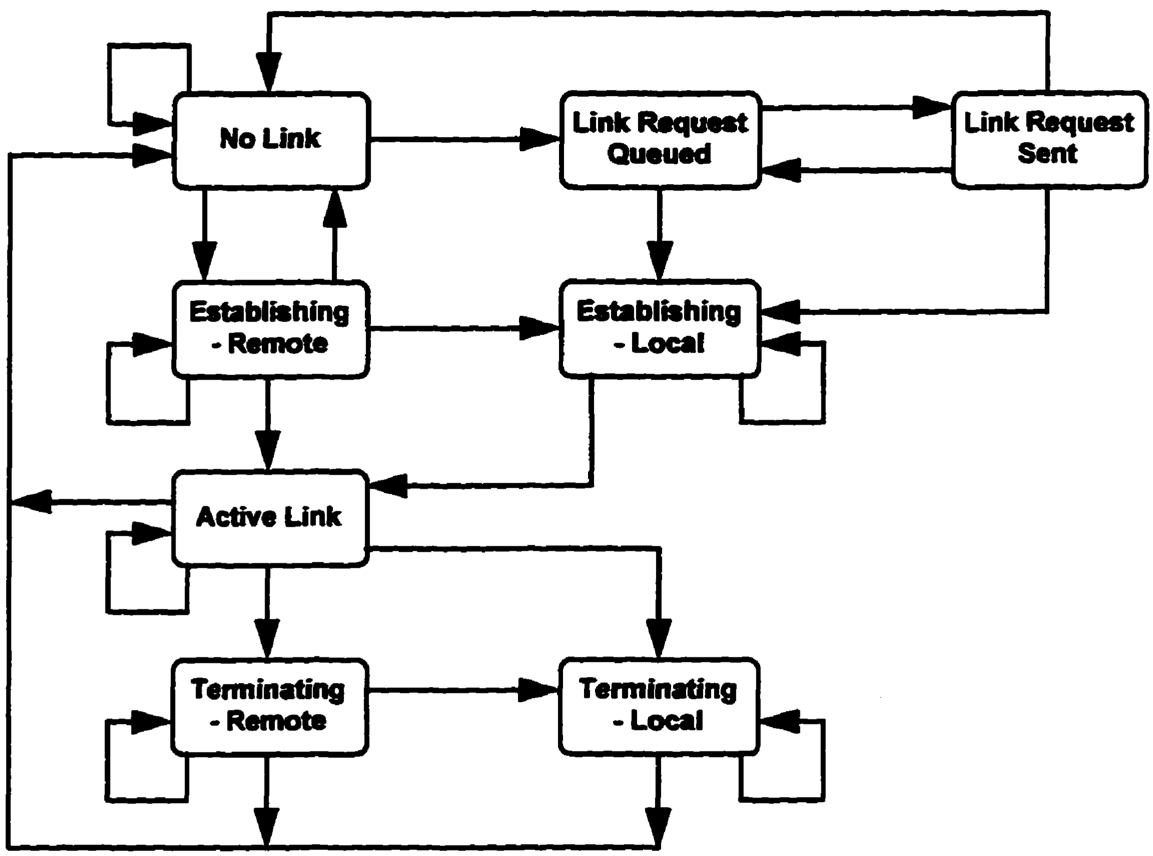

Figure A.2: Signalling Link State-Transition Diagram for Terminal

Table A.2: State Transitions at Terminal for Signalling Link

Event	Source	Actions	Next State
(1) No Link			
Link Grant (accepted), or *Link Grant* (rejected)	base-station MAC	• no actions required	⇒ No Change
MAC_CONNECT_REQUEST	LLC	• enqueue *Link Request* • set access counter to maximum value • select access slot	⇒ (5) Link Request Queued
Link Poll	base-station MAC	• update TX and RX slot states • start timer (link-confirm)	⇒ (2a) Establishing Link (Initiated by Remote)
(2a) Establishing Link (Initiated by Remote)			
Link Poll	base-station MAC	• restart timer (link-confirm) • free original list of TX and RX slots • update TX and RX slot states	⇒ No Change
Timer Expiry (link-confirm timer)	local MAC	• free TX and RX slots	⇒ (1) No Link
MAC_CONNECT_REQUEST	LLC	• no actions required	⇒ (2b) Establishing Link (Initiated by Local)
Any type of message received from the base-station in a scheduled RX slot (acknowledges the TX and RX slots).	base-station MAC	• stop timer (link-confirm) • start timer (liveness) • MAC_CONNECT_INDICATION	⇒ (3) Active Link

Table A.2: State Transitions at Terminal for Signalling Link (cont'd)

Event	Source	Actions	Next State
(2b) Establishing Link (Initiated by Local)			
Link Poll, or *Link Grant* (accepted)	base-station MAC	• restart timer (link-confirm) • free original list of TX and RX slots • update slot states	⇒ No Change
Any type of message received from the base-station in a scheduled RX slot (acknowledges the TX and RX slots).	base-station MAC	• stop timer (link-confirm) • start timer (liveness) • MAC_CONNECT_CONFIRMATION (succeeded)	⇒ (3) Active Link
Timer Expiry (link-confirm timer)	local MAC	• free TX and RX slots • MAC_CONNECT_CONFIRMATION (failed)	⇒ (1) No Link
(3) Active Link			
Any type of message received from the base-station in a scheduled RX slot.	base-station MAC	• restart timer (liveness)	⇒ No Change
Timer Expiry (liveness timer)	local MAC	• free TX and RX slots	⇒ (1) No Link
Link Modification Order that deletes all the TX and RX slots.	base-station MAC	• no actions required [a]	⇒ (4a) Terminating Link (Initiated by Remote)
MAC_DISCONNECT_REQUEST	LLC	• enqueue *Link Modification Request* to delete all TX and RX slots	⇒ (4b) Terminating Link (Initiated by Local)

Table A.2: State Transitions at Terminal for Signalling Link (cont'd)

Event	Source	Actions	Next State
(4a) Terminating Link (Initiated by Remote)			
All slots associated with the session have been released.	local MAC	• MAC_DISCONNECT_INDICATION • stop timer (liveness)	⇒ (1) No Link
MAC_DISCONNECT_REQUEST	LLC	• no actions required	⇒ (4b) Terminating Link (Initiated by Local)
Any type of message received from the base-station in a scheduled RX slot.	local MAC	• restart timer (liveness)	⇒ No Change
Timer Expiry (liveness timer)	local MAC	• free TX and RX slots	⇒ (1) No Link
(4b) Terminating Link (Initiated by Local)			
All slots associated with the session have been released.	local MAC	• MAC_DISCONNECT_CONFIRMATION • stop timer (liveness)	⇒ (1) No Link
Any type of message received from the base-station in a scheduled RX slot.	local MAC	• restart timer (liveness)	⇒ No Change
(5) Link Request Queued			
Link Poll, or *Link Grant* (accepted)	base-station MAC	• update slot states • start timer (link confirm)	⇒ (2b) Establishing Link (Initiated by Local)
Previously enqueued *Link Request* transmitted in access slot.	local MAC	• decrement access counter • start timer (access)	⇒ (6) Link Request Sent

Table A.2: State Transitions at Terminal for Signalling Link (cont'd)

Event	Source	Actions	Next State
(6) Link Request Sent			
Timer Expiry (access timer) and access counter = 0	local MAC	• MAC_CONNECT_CONFIRMATION (failed)	⇒ (1) No Link
Timer Expiry (access timer) and access counter > 0	local MAC	• enqueue *Link Request* • select access slot	⇒ (5) Link Request Queued
Link Grant (rejected)	base-station MAC	• stop timer (access) • MAC_CONNECT_CONFIRMATION (failed)	⇒ (1) No Link
Link Poll, or *Link Grant* (accepted)	base-station MAC	• stop timer (access) • update slot states • start timer (link-confirm)	⇒ (2b) Establishing Link (Initiated by Local)

Notes:

([a]) *If the base-station deletes all the slots, then the terminal will consider the signalling link to be terminated when the terminal sends an acknowledgement to the base-station for the message that deleted the slots.*