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A hybrid Multilayer Error Control Technique for Multihop ATM Networks

Hui Yang

A Thesis

In

The Department

Of

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ABSTRACT

A hybrid Multilayer Error Control Technique for Multihop ATM Networks

Hui Yang

There has been a great interest lately in the utilization of the ATM technology for networks. Especially in recent year, wireless ATM has emerged. Since the wireless links are characterized by higher, time-varying error rates and burstier error patterns in comparison with the fiber-based links fro which ATM was designed. The mean time error checking and correction get more and more important and necessary.

In this work, a new multilayer error control technique is presented and analyzed for ATM networks. While standard Go-Back-N ARQ technique is applied end to end, a new lost-cell concealment technique cooperates below as a forward error correction mechanism that also operates end to end. As the cell travels the inter-network enroute to the destination ATM user node interface (UNI), the CRC is checked and the cell is dropped or passed to the next ATM hop accordingly.

The error detection and correction techniques above are applicable to connection oriented traffic, however in this work we deal with the connectionless case. The choice of one of these alternatives has its implication on the CRC regeneration at each ATM Network Node Interface (NNI). In this work we present the hierarchy of the error control technique above, and analyze the end to end user performance in terms of net throughput and reliability. In the process we investigate the interactive effects of the channel and ATM signaling parameters on the system performance, with particular emphasis on the design of the error control scheme.

ACKNOWLEDGMENTS

I would like to express my profound gratitude to my supervisor Dr. A.K. Elhakeem, for providing the guidance and encouragement that made this work possible. He has always been available to advise and direct me throughout the course of this work. Also he has a great tolerance to contribute his time, effort to the work presented in this thesis.

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Most of all, I would like to thank my family and friends for their help, advice and encouragement.

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Content List of Symbol

AAL	ATM Adaptation Layer
ABR	Available Bit Rate
ACK	Acknowledges
ARQ	Automatic Repeat Request
ATM	Asynchronous Transfer Mode
BCH	Bose-Chaudhuri-Hocquenghem
BER	Bit Error Ratio
B-ISDN	Broadband Integrated Service Digital Networks
BOM	Beginning of the Message
CBR	Constant Bit Rate
CL	connectionless
CLD	Cell-Loss-Detection
CLD-P	CLD Parity
CLNAP	Connectionless Network Access Protocol
CLNIP	Connectionless Network Interface Protocol
CLP	Cell Loss Priority
CLS	Connectionless server
CLSF	Connectionless Service Function
CO	connection-oriented
CPCS	Common Part Convergence Sublayer

CRC	Cyclic Redundancy Check
CRPs	Cell Recognition Patterns
CS	Convergence Sublayer
DLC	Data Link Control
FEC	Forward Error Correction
GBN	Go-Back-N
GFC	Generic Flow Control
HEC	Header Error Check
IP	Internet Protocol
ITU	International Telecommunication Union
ITU-T	International Telecommunication Union-Telecommunication
LAN	Local Area Network
LANE	LAN Emulation
LLC	Logical link layer
MAC	Medium Access Control
MAN	Metro Area Network
MID	Multiplexing Identifier
MPOA	Multi-Protocol Over ATM
NICs	Network Interface Cards
NNI	Network-to Network Interface
OAM	Operation, Administration and Maintenance
PCN	Personal Communication Networks
PDU	Protocol Data Units

PL	Physical Layer
PM	Physical Medium
PMD	Physical Medium Dependent
PRM	Protocol Reference Model
PT	Payload Type
QoS	Quality of Service
Res	Reserved
RS	Reed-Solomon
SAP	Service Access Point
SAR	Segmentation and Re-assembly
SC	Segment counter
SDU	Service Data Unit
SN	Sequence Number
SONET	Synchronous Optical Network
SR	Selective Repeat
SSCS	Service Specific Convergence Sublayer
ST	Sequence Type
SW	Stop and Wait
TC	Transmission Convergence
TPDU	Transport Protocol Data Units
UBR	Unspecified Bit Rate
UNI	User-to-Network Interface
VBR	Variable Bit Rate

VCC	Virtual Channel Connection
VCI	Virtual Channel Identifier
VPI	Virtual Path Identifier
WAN	Wide Area Network
WATM	Wireless ATM

Chapter 1

Introduction

1.1 ATM

Asynchronous Transfer Mode (ATM) is based on asynchronous time division multiplexing and the use of fixed length cells. Each cell consists of a header and an information field. The cell header is used to identify cells belonging to the same virtual channel within the asynchronous time division multiplex. It is also used to carry out the appropriate cell-routing functions. The ATM cell information field is transparently routed throughout the ATM network.

There has been a great interest lately in the utilization of the ATM technology for both wire and wireless networks, and before its own implementation it has been adapted as the platform for Broadband Integrated Service Digital Networks (B-ISDN). The ATM standard is designed to efficiently support high-speed digital voice and data communications.

An ATM network consists of ATM switches that are connected to each using an interface called Network-Node Interface (NNI). ATM is a connection-oriented protocol.

1.2 Broadband ISDN

The international Telecommunication Union (ITU) – Telecommunication standardization Sector (ITU-T), formerly known as the CCITT, describes the Broadband Integrated Services Digital Network (B-ISDN) as a network built on the concepts of the ISDN model, and as a network which is implemented using ATM and Synchronous Optical Network (SONET) technologies. The ITU-T presents these two technologies as complementary technologies. ATM switches can act as the UNI with the user's Customer Premise Equipment. As a result, the user can deploy a wide variety of services at an ATM node that relays the traffic to SONET ports or local UNI ports. Therefore, SONET and ATM form an alliance for B-ISDN where SONET provides the transport, operations and maintenance services, while ATM provides direct services to the users.

1.3 ATM Traffic Classes

Traffic is classified into four different classes in ATM. Figure 1 illustrates the relationship of each class in terms of timing, Bit-rate and connection mode requirements. The four classes of ATM traffic are [1]':

<table>
<tr><th>Class A</th><th>Class B</th><th>Class C</th><th>Class D</th></tr>
<tr><td colspan="2">Timing required</td><td colspan="2">Timing not required</td></tr>
<tr><td>Constant rate</td><td colspan="3">Variable rate</td></tr>
<tr><td colspan="3">Connection-oriented</td><td>Connectionless</td></tr>
</table>

Figure 1.1: Traffic Classes

Class A: Constant Bit Rate (CBR) traffic such as telephony, circuit emulation of narrow-band ISDN services and video conferencing.

Class B: Variable Bit Rate (VBR) is divided into two categories depending on sensitivity to cell delay variations.

Class C: Available Bit Rate (ABR) traffic that constitute most of the remaining bandwidth and is used for normal data traffic such as file transfer. Applications using this class require fair access to this bandwidth with a minimum of cell loss.

Class D: unspecified Bit Rate (UBR) traffic is intended for applications and services that use what is left of the bandwidth and insensitive to cell delay or loss.

1.4 Connectionless Service

With a connectionless data transmission service, no connection is established between the source system and the destination system. Each packet transmitted is sent from a source system to a destination system independently of all others without requiring that a connection first be established between them. A connectionless service is sometimes called data gram service.

With a connectionless data delivery service, one message at a time is exchanged between a source and destination system. A connectionless service provides a best-efforts delivery service in which a message might be lost, duplicated, or delivered out of sequence with respect to other messages. With a connectionless Data Link layer service, no two messages are related in any way, no sequence checking is performed, and no acknowledgments are sent. Any mechanisms for error handling must be implemented in the higher layers.

A typical LAN data link provides a data gram delivery service. Some type of ATM data links also provide a connectionless data delivery service.

The ATM standards for the ATM adaptation layer class D service is intended to provide the type of data transfer service associated with computer networks that have a connectionless style of operation, such as a typical local area network. Class D service also can be used in place of service provided by a connectionless wide area network.

With class D service, the information to be carried through the ATM network takes the form of varying-size packets that many have a variable arrival rate. Class D service does not require that a connection be established between the sending and receiving ATM user software. Each packet, the source ATM user software sends into the network must contain full source and destination network addresses and is transmitted independently of any other packets. Each packet can be sent to a single specified receiver, or it can be multicast to multiple receiving users.

1.5 The Connectionless Server Approach

The connectionless server (CLS) approach to provide LAN-like service.

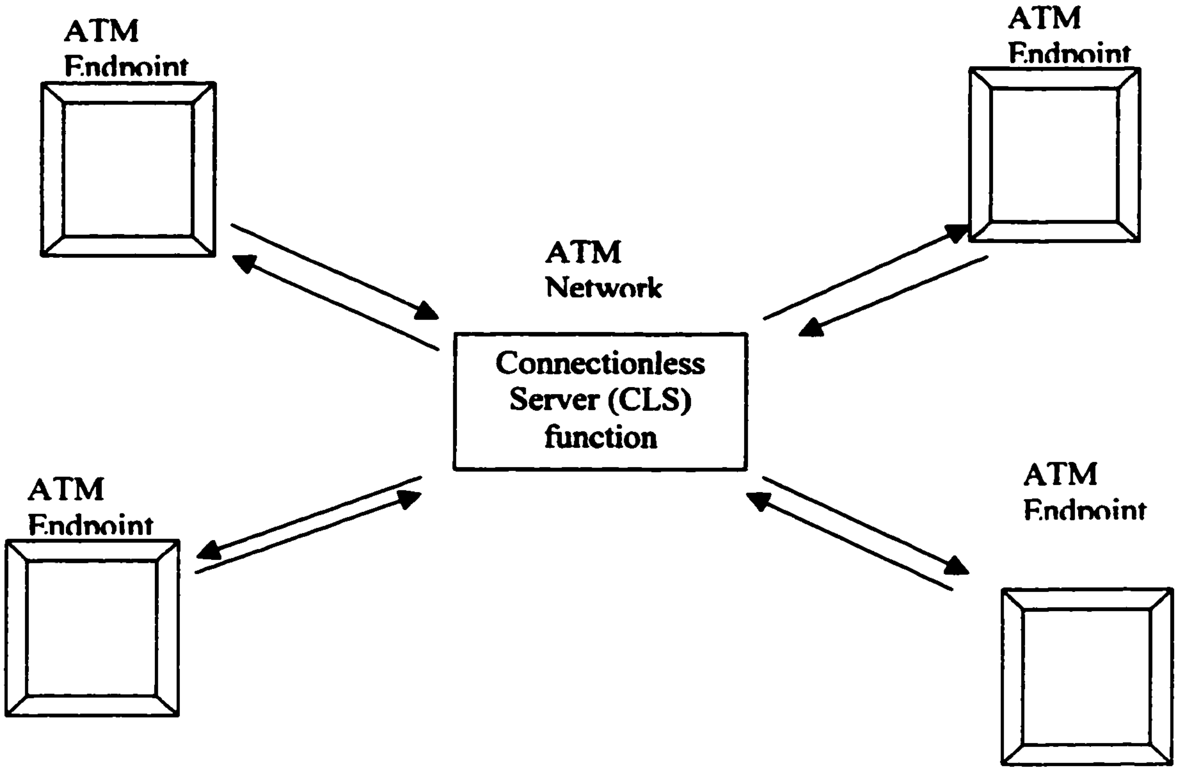


Figure 1.2: The connectionless server (CLS) with LAN-like service

When a connectionless server (CLS) function is used to provide LAN connectivity, each LAN user implements an ATM endpoint that has a direct virtual channel connection (VCC) to the connectionless server.

1.6 LAN (Local Area Network Technology)

As WANs have expanded in scope, organizations have also expanded their use of personal computers and individual workstations to support the computer needs of users throughout the organization. As the use of small computers has grown, a need also has grown for these computer systems to communicate--- with each other and with the larger, centralized data processing facilities the organization maintains.

Small computers are often initially used in a stand-lone manner to support applications local in nature.

The type of networks users of small computers often begin using for such purposes are called local area networks (LAN). LAN provides a means for meeting the requirement for high-speed, relatively short-distance communication among intelligent devices.

The majority of LANs in use today are used to interconnect personal computers and workstations. Some of the machines in a LAN are often called servers, to which the machines of individual computers share access.

On a LAN data link it is necessary to assign a unique station address to each of the network interface cards (NICs)on the data link. Station addresses are used to identify the source and destination of each frame transmitted over the LAN. A LAN NIC's station address is often called its MAC address because it is typically the Medium Access Control (MAC) sublayer of the Data link layer that processes station addresses.

1.7 Error-Detection Mechanisms

The AAL-3/4 protocol provides for several types of error checking to help ensure that no uncorrected errors occur during transmission. The following are error-handling mechanisms applied to each individual cell the SAR sublayer passes down to the ATM layer for transmission [4].

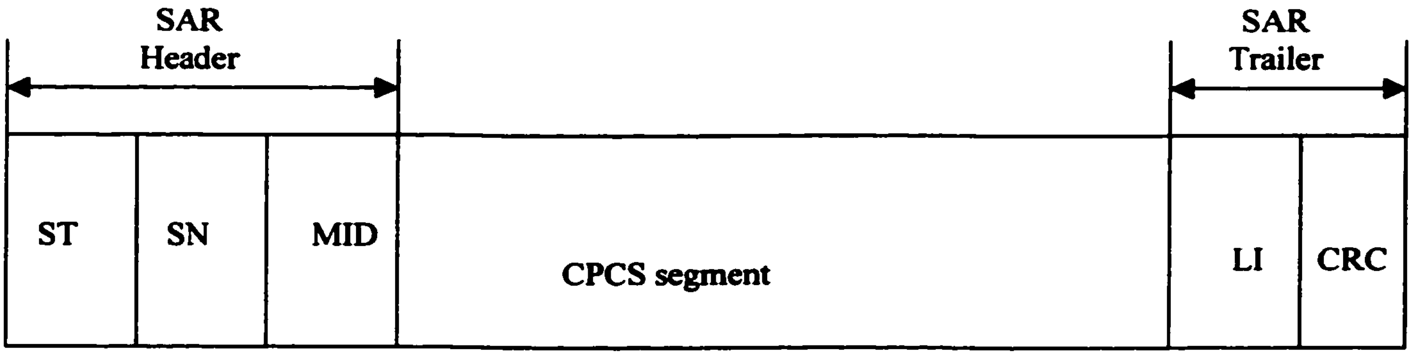


Figure 1.3: Error – detection Mechanism

- A CRC check is made to detect cells that have been corrupted during transmission
- A Sequence Number (SN) field is used to detect lost or miss inserted cells
- Multiplexing Identifier (MID) and Sequence Type (ST) fields are used to ensure that cells are properly reassembled into a CRC-PDU.
- A Header Error Check field is used to detect errors in the cell header

1.8 Scope of Thesis

In this thesis, Chapter 1 provides a brief overview of the ATM in the B-ISDN model. This is followed by describing the ATM traffic classes and their relationship with respect to connection model and connectionless server approach. LAN concept is also introduced and discussed. Finally, the error-detection mechanisms are presented.

Chapter 2 presents Asynchronous Transfer Mode (ATM). In this chapter we describe the ATM structure, relationship of B-ISDN and ATM, why ATM becomes more and more useful in nowadays telecommunication networks, what is the role of ATM in LAN, and networks management.

Chapter 3 present wireless ATM and associated FEC techniques. First, it introduces wireless ATM (WATM) networks, and wireless networks control. Then it presents error control schemes for networks and code shortening, puncturing and selection, third by it introduces packet transmitting methods including ARQ, stop and wait, and Go-Back-N methods. Finally it presents the error control for wireless ATM.

Chapter 4 is the key chapter of this thesis. Which presents and analyzes: A Hybrid Multilayer Error Control Technique for Multihop ATM networks.

Chapter 2

Asynchronous Transfer Mode

2.1 Introduction

Asynchronous Transfer Mode (ATM) provides high- speeds with low-delay switching and multiplexing network to properly transport all types of applications such as: voice, video, and data. It is the technology of choice to achieve universal networking. It is the transport mode of choice of B-ISDN (Broadband Integrated Services Digital Network), in which user information is transmitted between communicating entities using fixed-size packets, referred to as ATM cells. ATM segments and multiplexes traffic into fixed length packets called cells. Each cell has a header containing a virtual circuit identifier that is used to relay traffic through high-speed switches in the network. ATM does not provide any error detection or retransmissions on the cell payload, since it assumes a reliable end-to-end network. ATM is a compromise that allows the integration of different services with different characteristics and requirements.

In this chapter, we present the ATM standard. We start with the ATM cell structure, and we discuss the use and the value of each field of the ATM cell.

2.2 The ATM Cell

Some of the design objectives used to define ATM include integrating multimedia traffic, minimizing the switching complexity, the processing needed at intermediate nodes, the buffer management complexity, and the buffering needed at intermediate nodes mainly to keep up with the high-speed transmission links in the network. These design objectives are met at high transmission speeds by keeping the fundamental unit of ATM transmission---the ATM cell---short and fixed in length. More technically, the ATM framework is a connection-oriented packet switching technology that segments application data frames into 48-byte-long cell payloads, add the associated 5-byte header, transfers these cells through the ATM network, and assembles the cell payloads at their destination to reconstitute the original user data frames [4].

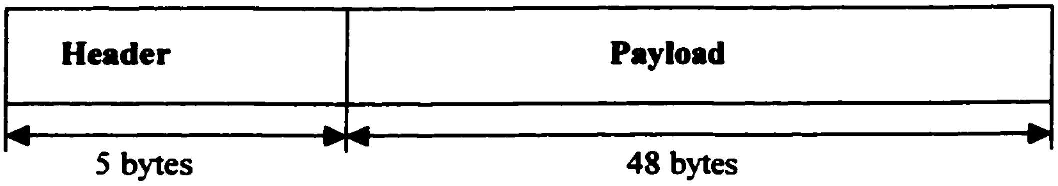


Figure 2.1 ATM Cell Structure

Characterizing ATM as asynchronous indicates that cells may occur at irregular times that are determined by the nature of applications rather than the framing structure of the transmission system [1][2][3].

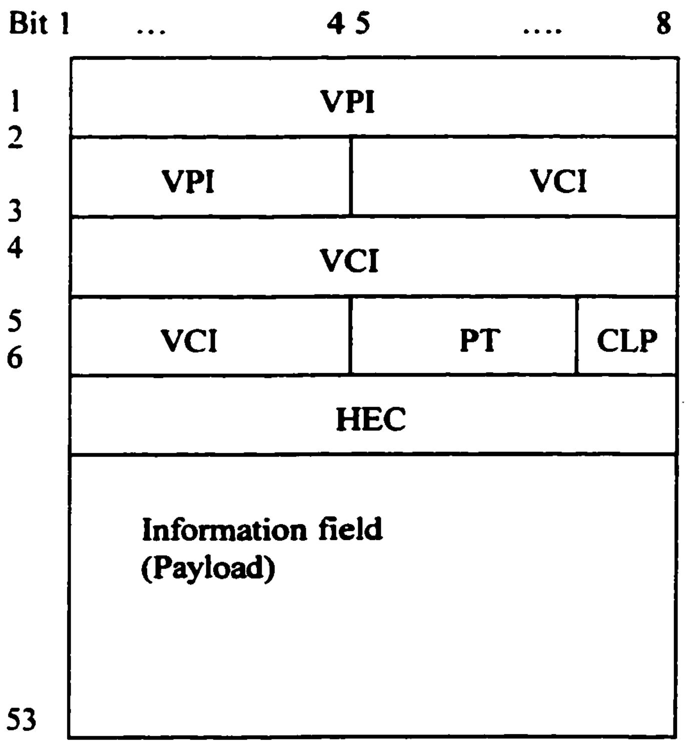


Figure 2.2 ATM cell format: network-to-network interfaces

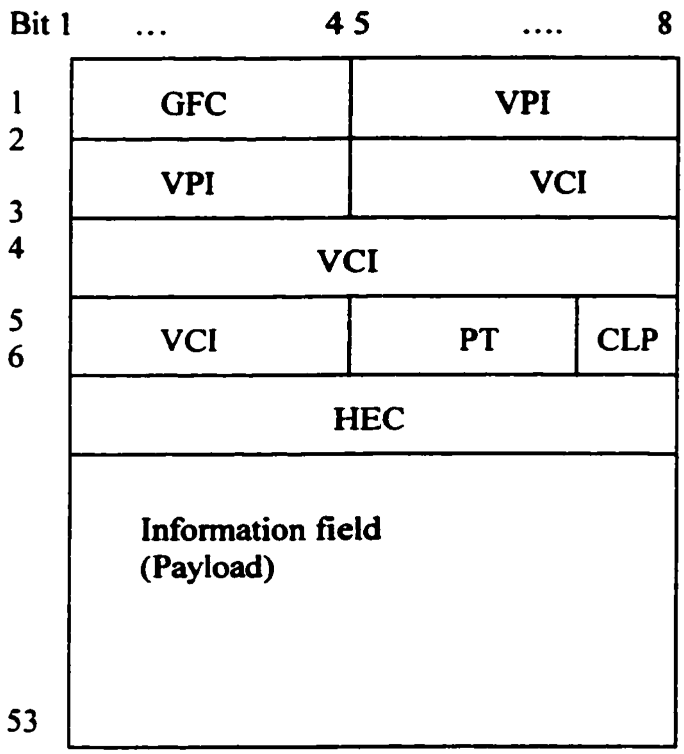


Figure 2.3 ATM cell format: user-to-network interface

The ATM cell header illustrated in Figure 2.2 and Figure 2.3 consists of five fields: virtual path identifier (VPI), virtual channel identifier (VCI), payload type (PT), reserved field (Res), cell loss priority (CLP), and header error check (HEC). At a demarcation point between an ATM end station and the network, the cell header also includes a generic flow control (GFC) field. This 4-bit field is part of the VPI inside the network. The five field is used for the Network-to Network Interface (NNI), while all six are used for the User-to-Network Interface (UNI).

2.2.1 Virtual Path Identifier (VPI)

The VPI is a routing field for the ATM network, which is used for routing cells in a virtual path. Each virtual path is composed of 65 K virtual channels. The VPI field in the UNI ATM cell contains eight bits for routing: therefore, allowing 256 virtual paths. The VPI in the NNI ATM cell consists of the first 12 bits of the cell header, which results in providing enhanced routing capabilities of 4096 virtual paths.

2.2.2 Virtual Channel Identifier (VCI)

The VCI is another routing field in the ATM cells, which is used for routing ATM cells in a virtual channel. Thus, the routing information of an ATM cell is included in the two routing fields of the header: VCI and VPI. A VCI consists of 16 bits that allow for 65 K virtual channels.

2.2.3 Payload Type (PT)

The payload Type identifier is a three-bit field that indicates the type of traffic in the information field. The cell can contain user, management or control traffic. This field can also be used for congestion notification operations.

2.2.4 Cell Loss Priority (CLP)

The CLP field is composed of one bit that is used to indicate the cell loss priority. If the CLP bit is set to 1, the cell is subject to being discarded by the network. Otherwise, the CLP is set to 0 that indicates a higher priority cell in the network. Due to the statistical multiplexing of connections, it is unavoidable that cell losses will occur in ATM networks.

2.2.5 Header Error Control (HEC)

The HEC field is used mainly for two purposes: for discarding cells with corrupted headers and for cell delineation. The 8-bit field, when used for HEC, provides single-bit error correction and a low probability corrupted cell delivery capabilities. The field is also used to identify the cell delineation (I.e., determining cell boundaries from received bit stream). The HEC field is computed based on the five-byte header in an ATM cell only, and not the 48-byte user information field.

2.2.6 Generic Flow Control (GFC)

The GFC is a 4-bit field that provides a framework for flow control and fairness to the user to network traffic and does not control the traffic in the other direction (i.e., network-to-user traffic flow). The GFC field has no use within the network and is meant to be used by access mechanisms that implement different access levels and priorities. In another words, the GFC appears only in the UNI ATM cells. The use of GFC has not been specified yet and is set to zeros in the UNI ATM cells.

2.3 B-ISDN Layered Model and ATM

The B-ISDN protocol Reference Model (PRM) is based on the OSI model that used the concept of separate planes to differentiate between user, control and management functions. The B-ISDN PRM with ATM is shown in figure 2.4. which illustrates that the transfer mode of choice for B-ISDN is ATM. The control plane handles all connection-related functions, addressing, and routing. These functions play a particularly important role for connections that are established dynamically (on demand) in the network. The user plane transmits end-to-end user information between two or more communicating entities. The management plane provides for operations and management functions, and also provides the mechanisms to exchange information between the user and the control planes. This plane is further divided into two layers: layer and plane management. Layer management deals with layer-specific management functions that include the detection of failures and protocol abnormalities. Plane management provides management and coordination functions related to the complete system. Layer management performs Operation, Administration and Maintenance (OAM) functions and services[4].

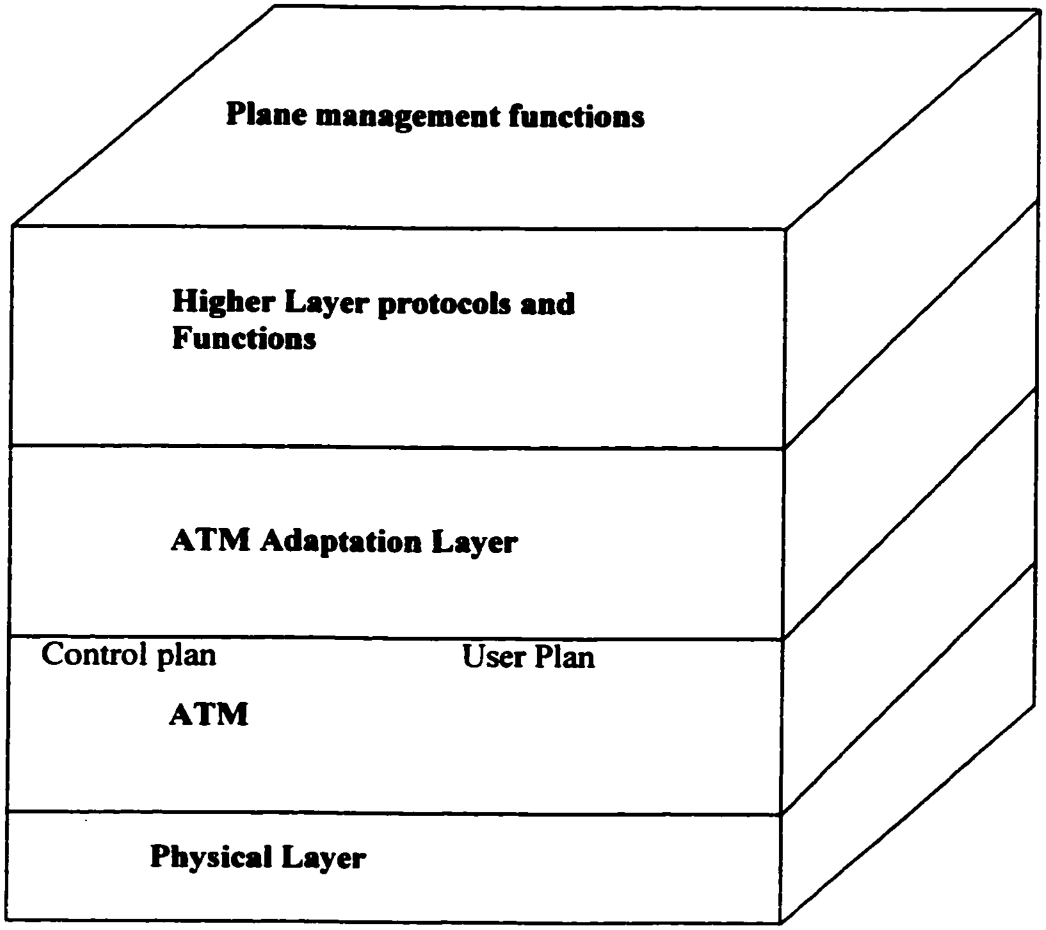


Figure 2.4 ATM protocol reference model

For each plane, a layered approach is used with independence between the layers. There are three main layers: the Physical Layer, the ATM layer, and the ATM Adaptation Layer (AAL). All three planes use the physical and the ATM layers. The ATM adaptation layer is service-specific and may or may not be used depending on the requirements of the (user, control and management) applications [4].

Layer Name		Layer Functions
AAL	Convergence Sublayer (CS)	Service specific (SSCS) common part (CPCS)
	Segmentation and Re-assembly (SAR)	Segmentation and Re-assembly
ATM Layer		Generic flow control Cell header generation /extraction Cell VPI/VCI translation Cell multplexing/ demultiplexing
Physical Layer	Transmission Convergence (TC)	Cell rate de-coupling Cell delineation transmission frame generation/recovery HEC generation/verification
	Physical Medium dependent (PMD) sublayer	Bit timing Physical medium

Figure 2.5 ATM adaptation, ATM and Physical layers

On top of these three layers, we have the higher layer protocols, as shown in figure 2.4. This layer provides connectivity between the ATM network and higher protocols such as: Internet Protocol (IP), LAN Emulation (LANE), multi-Protocol Over ATM (MPOA) and WAN service inter-working.

2.4 Physical Layer (PL)

The physical layer handles transmission operations such as: packaging of cells for transmission, sending data across a transmission medium, recovering data, and determining cell boundaries within a bit-stream. The physical layer transports ATM cells between two adjacent ATM layers. The ATM layer is independent of the physical layer and it is able to operate over a wide variety of physical link types. The physical layer in ATM has more functionality than is typically associated with this layer.

The Figure 2.6 illustrates the structure of the ATM physical layer. The physical layer provides the ATM layer with access to the transmission media. In the transmit direction, the ATM layer passes ATM cells (the 48-byte cell payload and the 5-byte header excluding the HEC value) to the physical layer. In the receiving direction, the ATM layer receives 53-byte cells from the physical layer. Various functions performed at the physical layer are classified into two sublayers: transmission convergence (TC) and physical media dependent (PMD) [4].

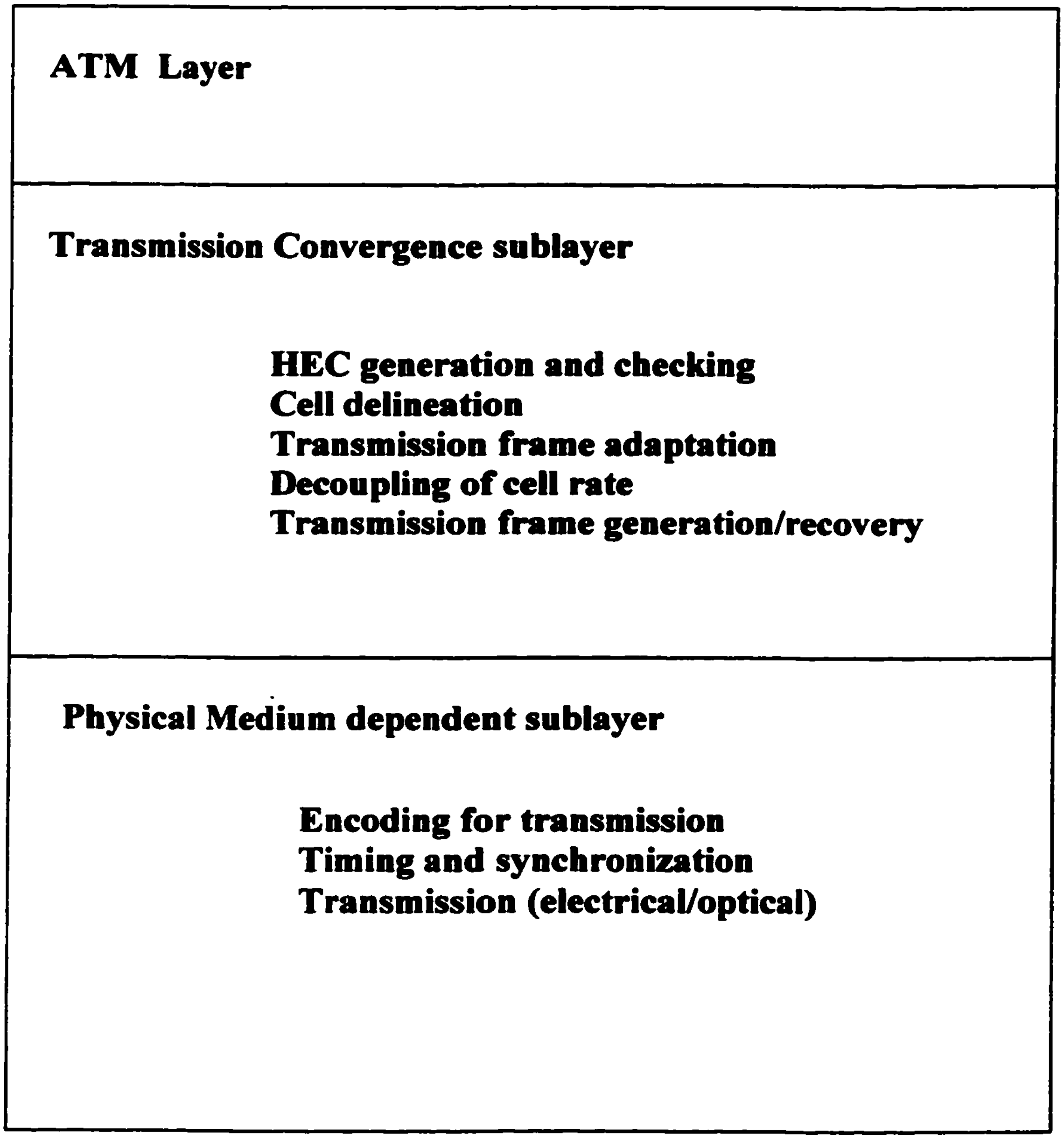


Figure 2.6: Structure of the ATM physical layer

2.4.1 Transmission Convergence Sublayer (TC)

The TC sub-layer has five main functions as illustrated in figure 2.6. the first function is generation and recovery of the transmission frame. The second function is transmission frame adaptation. The cells are fit within the transmission system according to a standardized mapping.

The third function, cell delineation function allows the receiver to recover the cell boundaries. Scrambling and de-scrambling are to be done in the information field of a cell before the transmission and reception, respectively, to protect the cell delineation mechanism.

The fourth function, the HEC sequence generation is done in the transmit direction and its value is recalculated and compared with the received value and thus used in correcting the header errors. If the header errors can not be corrected, the cell will be discarded.

The last function, cell rate de-coupling inserts the idle cells in the transmitting direction in order to adapt the rate of the ATM cells to the payload capacity of the transmission system. It suppresses all idle cells in the receiving direction. Only assigned and unassigned cells are passed to the ATM layer.

2.4.2 Physical Medium (PM)

The PM sub-layer provides the correct transmission and reception of bits on the physical medium. It also performs line coding as well as media conversion, if necessary. It includes bit-timing functions such as the generation and reception of wave forms suitable for the medium and also insertion and extraction of bit timing information. Since this sub-layer is at the lowest level, it is dependent on the physical medium.

2.5 The ATM layer

The ATM layer is above the physical layer, has four main functions: cell header generation/extraction, cell multiplexing and de-multiplexing, VPI/VCI translation and generic flow control, as shown in Figure 2.7 [4]

ATM Layer	**Generic flow control** **Cell header generation and extraction** **Cell VPI/VCI translation** **Cell multiplexing and de-multiplexing**

Figure 2.7: ATM Layer Sub-layers

The ATM layer transfers cells between peer ATM layer entities. It provides in sequence delivery of cells among ATM layer users by utilizing services provided by the physical layer. At the originating end station, it receives any 48-byte cell payload from an ARM layer user, adds the 4 bytes of the corresponding cell header (excluding the HEC byte), and passes the cell to the physical layer for HEC calculation and transmission. At the destination end stations, the ATM layer receives cells from the physical layer, removes the cell header, and passes the cell payloads to their corresponding ATM layer users. Inside an ATM transport network, there is no ATM layer user for the user traffic (i.e. in the user plane), and cells are passed from the receiving ATM layer entities to the transmitting counterparts at each switching node along their paths between the source and destination end stations. Accordingly, the ATM layer mainly provides the switching function of ATM networks. Cells with error headers (i.e. bit errors) are discarded at the intermediate nodes.

Similarly, cells that arrive at a time when the transmission link buffer is full may be dropped at a switch. However, the ATM layer provides its services unreliably. That is, there is no retransmission of error and lost cells inside the network and it is up to the end stations to ensure the integrity of the data carried in ATM cell payloads.

2.5.1 GFC (Generic Flow Control)

The GFC mechanism is used to control traffic flow from end stations to the network by limiting their effective ATM layer transport capacity. The GFC takes place using the first 4 bits of the ATM cell header. This field is used as a part of the VPI field inside the network and the NNIs (network to network interface). GFC is used to implement a flow control mechanism on the ATM traffic for the User-to-Network Interface (UNI).

2.5.2 VPI/VCI Translation

The translation of the cell identifier is performed when switching a cell from one physical link to another in an ATM switch or cross-connect. At a VC switch, the values of VPI and VCI of incoming cells are translated into new values. At the VP switch, the VPI value is translated.

VPIs are used to route packets between two nodes that originate, remove, or terminate the VPs, whereas VCIs are used at the VP end points to distinguish between different connections. Cells can be relayed from one VP to another, or one VC to another, either in the same or a different VP. The VPI/VCI pair used at a switching node has a local meaning only. Even the VCI does not change within a VPC; the VPI/VCI is translated as the VPI is translated at every switch.

2.5.3 Cell multiplexing and de-multiplexing

This function performs the multiplexing and de-multiplexing of cells form different connections that are identified by different VPI/VCI values onto a single cell stream.

2.5.4 Cell Header Generation and Extraction

This function is applied at the end points of the ATM layer. In the transmit direction, it adds the appropriate ATM cell header without the HEC value to the received cell payload from the AAL. In the receive direction, cell payload field is passed to the AAL after removing the cell header.

The figure 2.8 shows the ATM cell structure

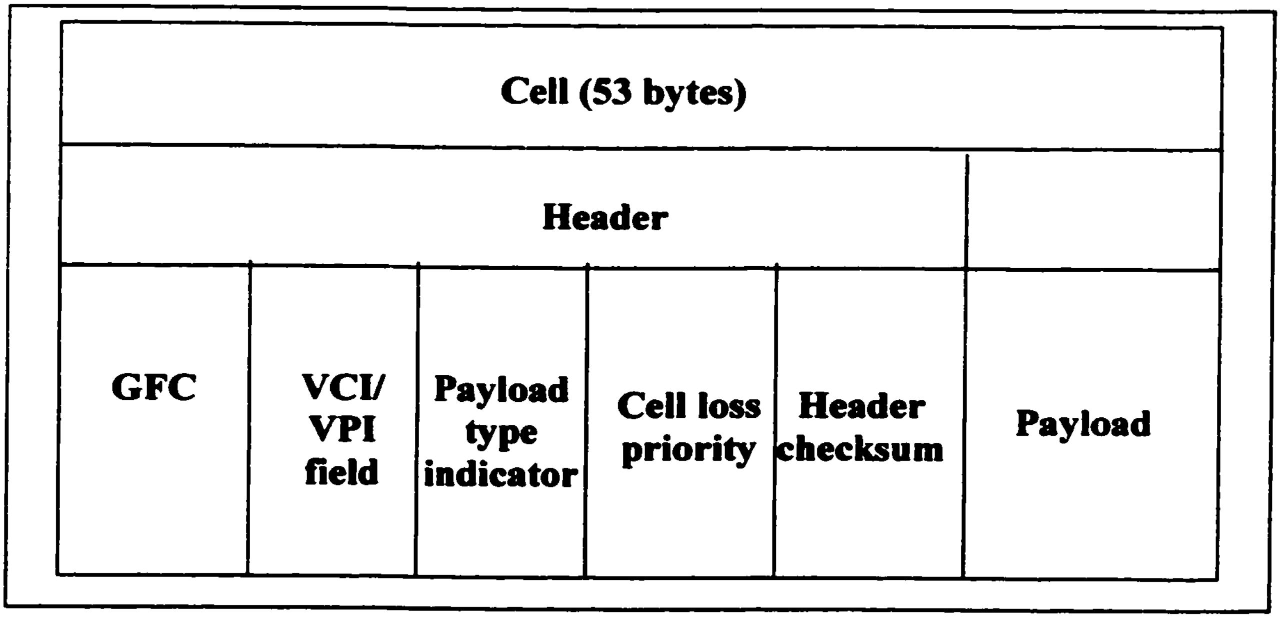


Figure 2.8 ATM cell structure

2.6 ATM Adaptation Layer (AAL)

The AAL is the uppermost layer in the ATM architecture. The AAL is used between the ATM layer and the next higher layer in both the user plane, and the control plane is used to enhance the services provided by the ATM supporting the functions required by the next higher layer. Accordingly, AAL is service-dependent. It isolates the higher layers from the specific characteristics of the ATM layer by mapping the higher layer protocol data units (PDU) into the ATM cell payload and vice versa.

There are four service classes. The classification is performed according to destination, constant or variable bit rate, and connection mode. The service classes are:

Class	A	B	C	D
Timing relationship between source and destination	required		Not required	
Bit rate	constant	variable		
Connection mode	Connection - oriented			Connect-ionless

Figure 2.9 Class services

The AAL function is divided into two sub-layers: segmentation and re-assembly (SAR) sub-layer and convergence sub-layer (CS). The SAR sub-layer performs segmentation of a higher layer information into a size suitable for the payload of the ATM cells. at the receive side, the SAR reassembles the contents of the cells of a virtual connection into data units to be delivered to a higher layer.

AAL	CS	Convergence
	SAR	Segmentation and Re-assembly

Figure 2.10 AAL sub-layers

The CS performs a set of AAL service specific functions. The CS is further divided into a service-specific convergence sub-layer (SSCS) and a common part convergence sub-layer (CPCS). SSCS may be null for applications that do not require any service-specific function. The CS sub-layer functions include message identification and time/clock recovery. AAL service data units are transported from one AAL service access point (SAP) to one or more others through ATM networks. The AAL users can select a given AAL-SAP associated with the quality of service required to transport the AAL service data unit (AAL-SDU).

2.6.1 AAL and Traffic Classes

Based on ATM traffic classes, the ITU has recommended four types of AAL protocols. The figure 2.9 shows the AAL type: AAL1, AAL2, AAL3/4, and AAL5.

2.6.2 AAL1

AAL1 is intended for Class A CBR service that requires information to be transferred between the source and destination at a constant bit rate. Example of such services include CBR audio, CBR video, and CBR voice.

The services provided to AAL1 users include the following:

- Transfer of SDUs with a CBR to the destination AAL1 users with the same bit rate;
- Transfer of timing information between the source and destination;

- Transfer of structure information between the source and destination;
- Indication of lost or error information.

Typical applications of AAL1 are voice and high quality constant bit rate audio and video.

AAL1 CS may include the following functions:

- Handling of cell delay variation;
- Processing of the sequence count;
- Providing a mechanism to transfer a timing information;
- Providing the transfer of structure information between source and destination;
- FEC Forward Error Correction

The AAL1 (SAR-PDU) header is illustrated in figure 2.11[4]

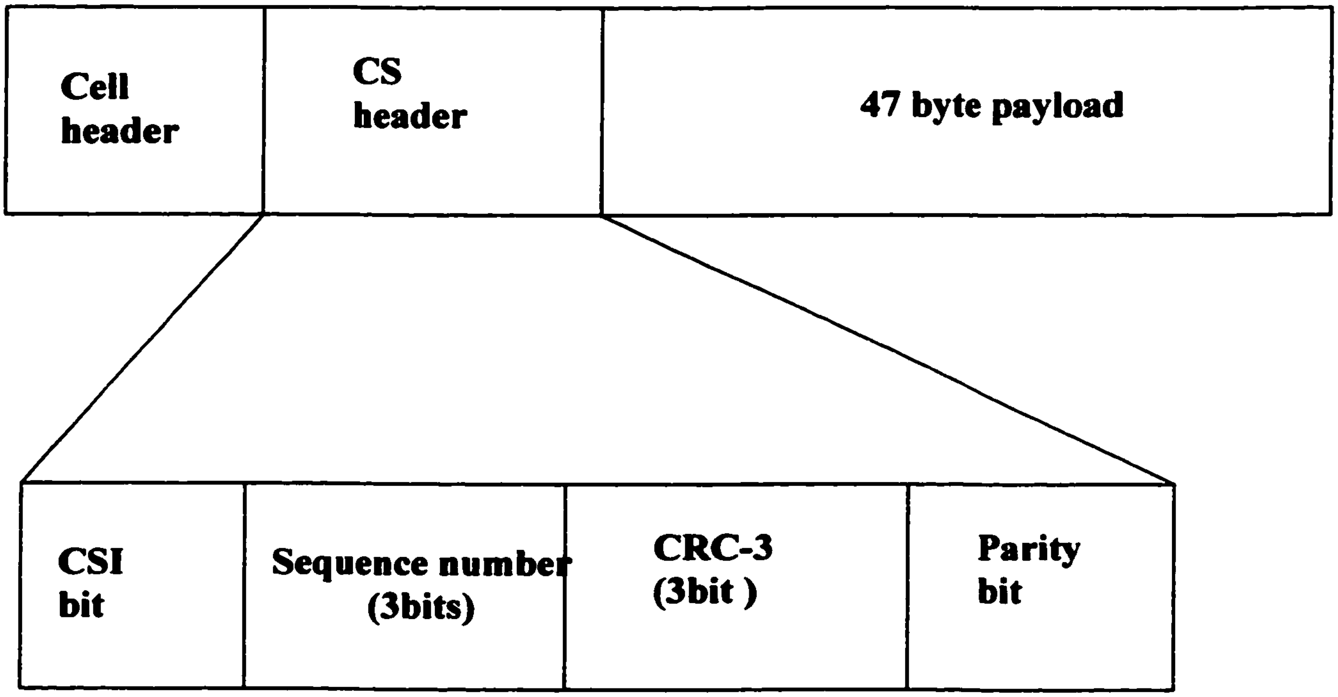


Figure 2.11 AAL1 SAR-PDU header

2.6.3 AAL2

AAL2 is employed for class B for connection-oriented VBR services where timing relationship is required between the source and destination. Typical examples of services that would use AAL2 include VBR video, VBR audio, and VBR voice. AAL2 CPCS services are expected to include:

- Transfer of data units with a variable source rate;
- Transfer of timing information between source and destination
- Indication of lost or error information not recovered by AAL2, if needed.

These services would require different AAL functions, such as

- SAR of user information
- Handling of cell delay variation
- Source clock frequency recovery at the receiver
- Recovery of source data structure at the receiver
- Monitoring and handling of AAL protocol control information for bit errors
- Monitoring of user information field for bit error and possible corrective action.

2.6.4 AAL 3/4

AAL ¾ is defined for connection-oriented and connectionless VBR services that do not require a timing relationship between the source and the destination. It has the basic functionality to support a connectionless network access (Class D), as well as connection-oriented frame relay service (Class C)

Various functions performed at the AAL ¾ CPCS include the following

- Message or streaming service mode
- Preservation of CPCS_SDUs, which provides the delineation and transparency of CPCS_SDUs
- Error detection and handling, which provides the detection and handling of CPCS_PDU corruption.

2.6.5 AAL5

AAL5 is proposed for VBR services that do not require a timing relationship between the source and destination. AAL5 was recommended to offer a service with less overhead and better error detection below the CPCS layer. The service provided by AAL5 is the same service provided by the CPCS of AAL ¾ without multiplexing. Should multiplexing be required at AAL 5, it will be done in SSCS layer. AAL 5 offers no error checking and supports only a single data stream per channel but devotes the entire cell data field to user data. The AAL 5 is used with Class C services that have variable bit rate sources without timing relationship between source and destination.

Various functions performed at the AAL 5 SAR sublayer are defined as follow:

- Preservation of SAR-SDU, which provides an "end of SAR-SDU" indication

- Handling of congestion information, which provides for the passing of congestion information between the layers above the SAR sublayer and the ATM layer in bother directions
- Handling of loss priority information, which provides for the passing of CLP information between the layers above the SAR sublayer and the ATM layer in bother directions.

Various functions defined at the AAL 5 CPCS are summarized as follows

- Preservation of CPCS-SDU, which provides for the delineation and transparency of CPCS_SDUs, using the SDU type indication
- Preservation of CPCS user-to-user information, which provides for the transparent transfer of CPCS user –to- user information using the CPCS_UU field of the CPCS_PDU
- Error detection and handling, which uses the length indicator and the CRC fields to determine whether a CPCS_SDU is corrupted or not
- Abort, which provides the means to abort a partially transmitted CPCS_SDU
- Padding, which provides for the 48-byte alignment of the CPCS_PDU
- Handling of congestion information, which provides for the passing of congestion information between the layers above the CPCS and the SAR layer in both directions
- Handling of loss priority information, which provides for the passing of CLP information between the layers above the CPCS and SAR layer in both directions

2.6.6 AAL 3/4 versus AAL 5

Both AAL 3/4 and AAL 5 protocols are defined for VBR connection-oriented as well as connectionless applications that do not require and end-to-end timing relationship between the communicating entities. The natural question is , why are the two AALs?

AAL 3/4 supports multiplexing AAL connections into a single ATM connection using the MID field. It constitutes a large part of the SAR-PDU overhead. Another SAR layer overhead is the 10-bit CRC field. Arguments against the use of the CRC field are mostly based on the fact that errors in the cell payload would be detected by end station protocols (i.e. applications), and there is no need to have this in the cell payload.

Essentially, the effective payload of an ATM cell with AAL ¾ is at best equal to 44/53. Seeing that the last cell of a PDU may be filled only partially, the real utilization that can be achieved with AAL ¾ is even lower than this value. The total overhead of an AAL 5 CPCS_PDU, on the other hand, is 8 bytes, and there is no SAR overhead. AAL 5 requires the additional overhead bits at the last cell of the PDU if the PDU is not a multiple of 48 bytes. Compared with the AAL 3/4 , type 5 has the same effective payload usage for CS_PDU sizes of 88 bytes or less and smaller overhead for 88 bytes or larger CS_PDUs. As the CPCS_PDU size increases, the effective utilization increase and it is less than or equal to at 90.5%, that is , the maximum effective utilization that can be achieved in an ATM network (48/53).

The main disadvantage of AAL 5 is that the multiplexing of AAL connections into a single ATM layer connection requires a special solution that can be provided only at the SSCS. An SSCS with this feature is not yet defined and feasible solutions appear to be rather complex to implement and limited in capability.

2.7 ATM Network Management

Network management is concerned with monitoring the operation of components in the network, reporting on events that occur during network operation, and controlling the operational characteristics of the network and its components.

ATM management protocols for operations administration and maintenance (OA&M) define functions for performance monitoring, defect and failure detection, system protection, failure and performance reporting, and fault isolation. ATM OA&M functions have layered structure defining levels.

2.8 Connectionless Service in ATM network

2.8.1 LAN and ATM

ATM is quite different from LAN technology. ATM is a connection-oriented. LAN provides connectionless service. Supporting LAN applications in ATM networks requires hiding the connection-oriented nature of ATM from these applications. ATM connections can be either permanent/semi-permanent or they can be established on demand. Permanent connections are pre-established by the management plane. On-demand connections are established by the control plane dynamically.

LANs provide broadcast and multicast natively with special MAC addresses. Various LAN protocols rely on these features, and they are needed in ATM networks if these protocols will be used in ATM networks without any changes. ATM networks are switching -based. An ATM connection can be point-to –point or point –to- multipoint. Multipoint-to-multipoint connections can be supported in different ways through the use of point –to –point and /or point-to multipoint connections.

Connectionless service does not require explicit QOS guarantees from the network. ATM best effort service with an unspecified QOS class can be used to support LAN applications. Although no explicit service guarantees are required by LAN applications, these applications implicitly require the minimization of CLR in ATM networks to reduce the possibility of retransmission and therefore effective network throughput degradation.

ATM uses fixed size 53 byte cells to transmit data in the network. LANs, on the other hand, are frame oriented and transmission is based on variable length frames. The transmission of LAN frames over ATM requires the SAR functions. Two AALs may be used for connectionless traffic: AAL ¾ and AAL 5.

2.8.2 Connectionless Network Interface Protocol

CLNAP functionality provides the connectionless layer service, which includes routing, addressing, and QOS selection.

The CLNIP layer supports the transfer of connectionless data among network nodes. The protocol uses AAL ¾, which provides a sequential transfer of CLNIP_PDUs in the un-assured mode. No retransmission capability for lost or corrupted data is provided at the CLNIP.

2.9 ATM End-to-End Network

This chapter presented the ATM. We described the ATM cell structure and the value of each field of the ATM cell. The B_ISDN/ATM reference model was provided. We give the main functions of each of the three main layers. The physical layer and the ATM layer provide the facilities for the connection – oriented transport of cells. These two protocol layers must be implemented in every ATM device. More over, the AAL layer was presented, at the end we also have brief discussion about ATM network and LAN & ATM.

Chapter 3

Wireless ATM and associated FEC techniques

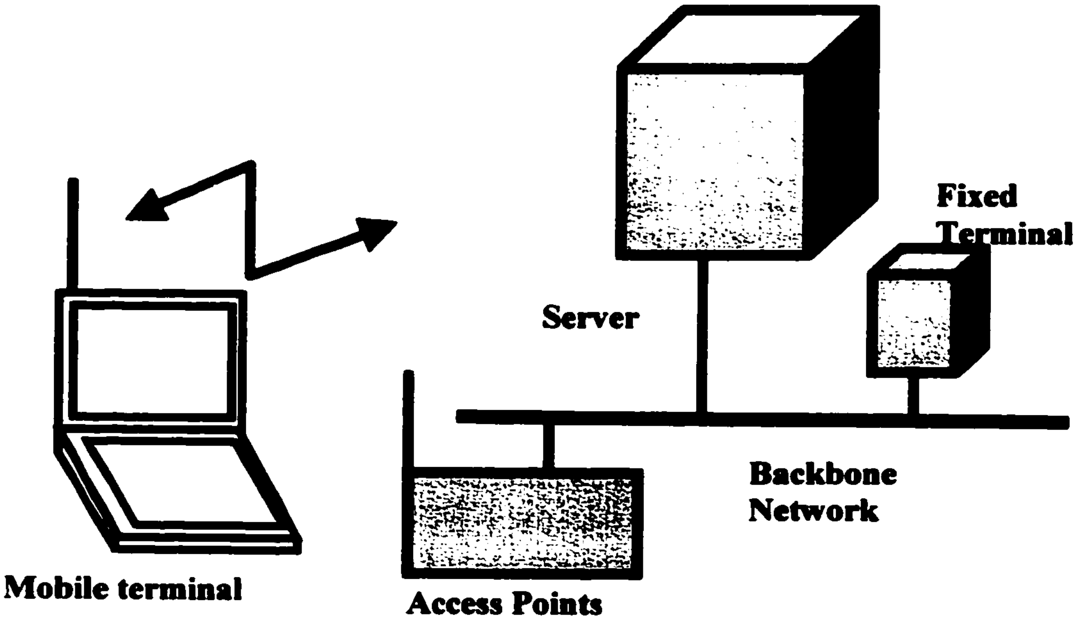
3.1 Wireless ATM networks

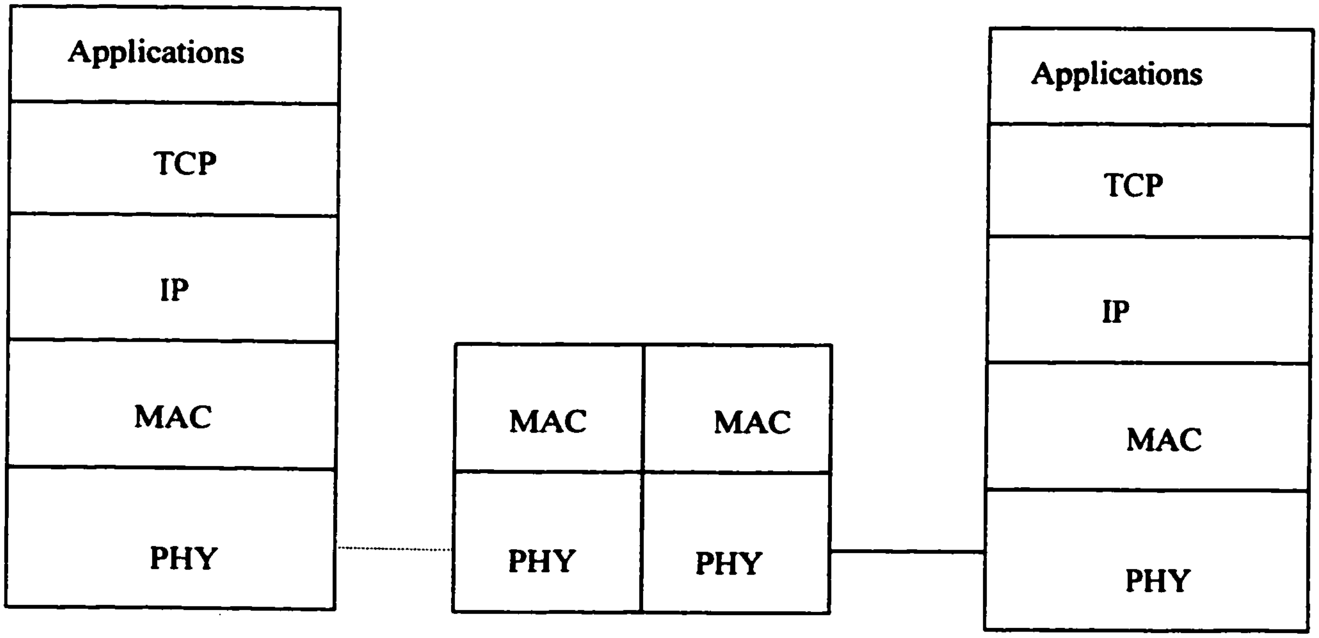
3.1.1 Wireless ATM Introduction

Wireless personal communication networks (PCN) based on new digital technologies have emerged as an important field in telecommunication. This is mainly due to the success of mobile phones, pagers, personal computers, fast e-mail, fast speed connection sand so on. The distinction between telephony and computing will disappear as communication becomes the integrated transmission of information in voice, data, image, and etc. Nowadays more and more telecommunication company put wireless business as their target key business in the future. Therefore people are studying integrating wireless with Broadband High Speed Networks. In this chapter we will introduce wireless ATM and associated FEC techniques.

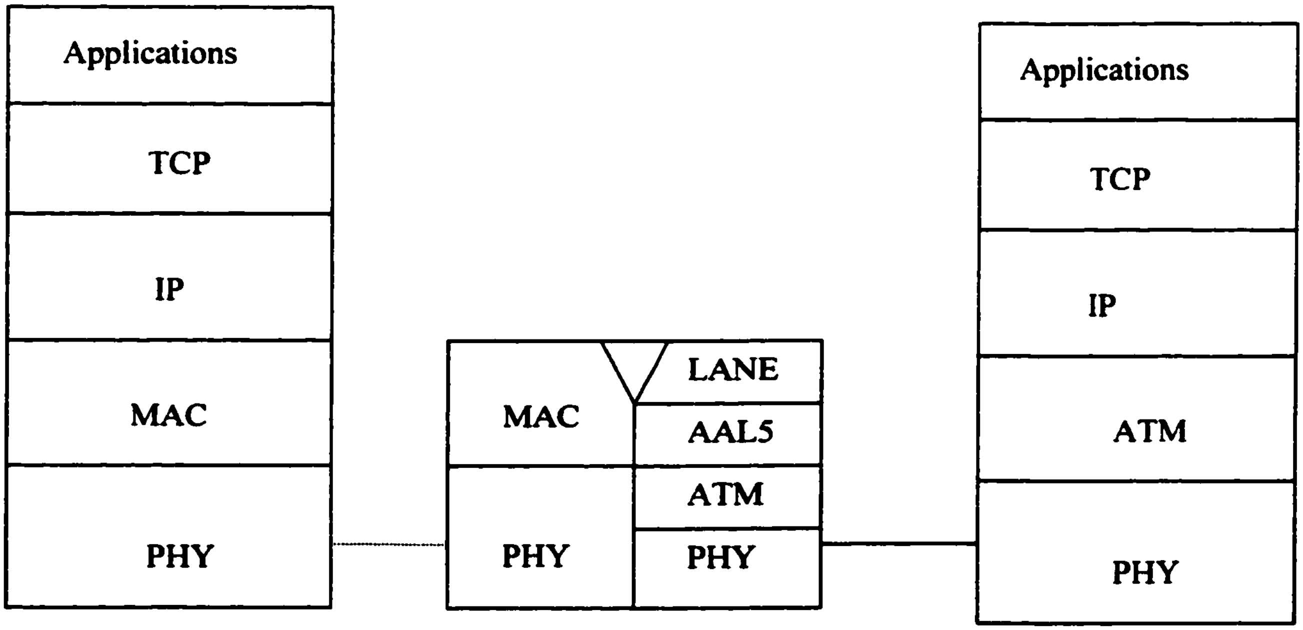
Wireless ATM (WATM) networks will play an important role in the broadband communications network in the future[5] [6][25][26][27].

Fig. 3.1 WLAN connection to the backbone.

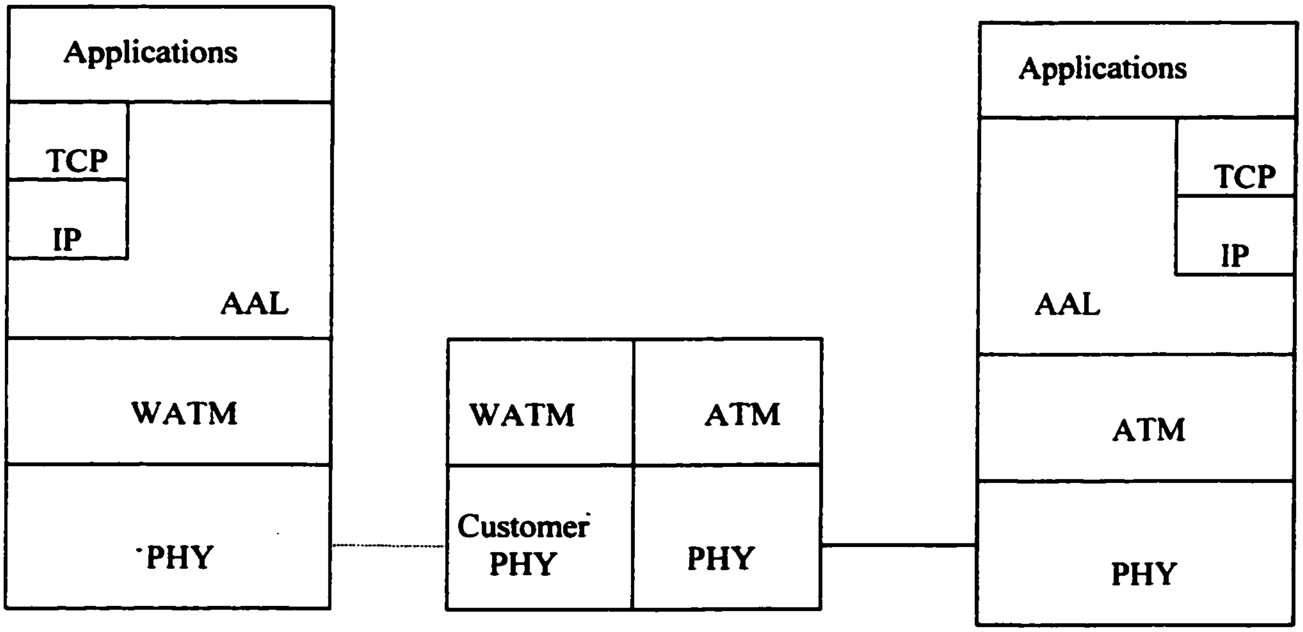




a


Applications
TCP
IP
MAC
PHY
MAC
LANE
AAL5
ATM
PHY
PHY
Applications
TCP
IP
ATM
PHY

b


Applications
TCP
IP
AAL
WATM
PHY
WATM
ATM
Customer PHY
PHY
Applications
TCP
IP
AAL
ATM
PHY

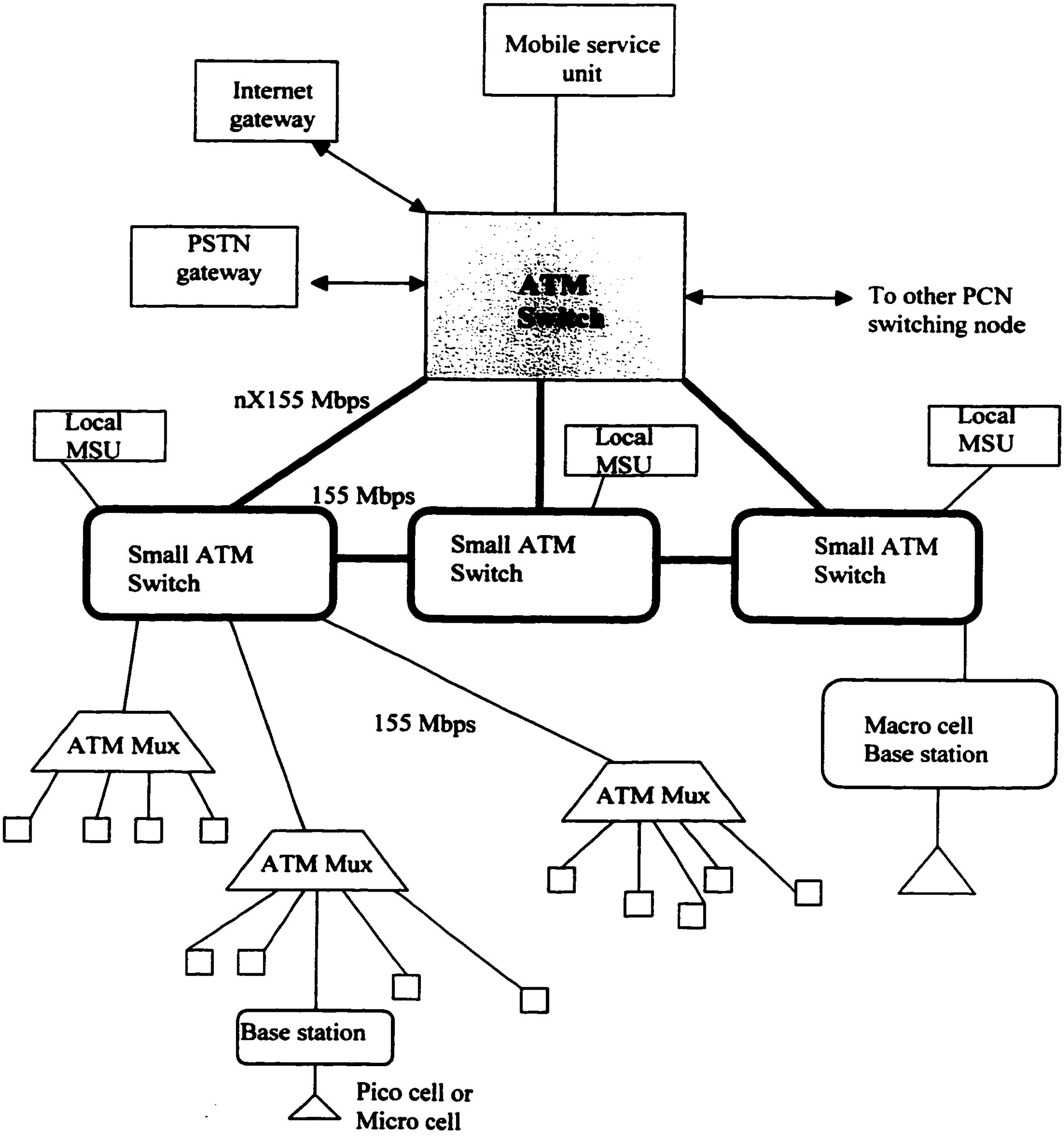
c

3.1.2 Wireless ATM (WATM)

WATM is expected to provide end-to-end ATM connectivity and quality of service (QoS) in the wireless channel. It has:

- flexible bandwidth allocation and service type selection for a range of applications,
- efficient multiplexing of traffic from burst data/multimedia sources,
- end-to-end provisioning of broadband services over wireless and wire networks
- available ATM switching equipment for inter-cell switching,
- packet switching techniques,
- ease of interfacing with wired B-ISDN systems which is the backbone for telecommunication.

Figure 3.2 illustrates a typical backbone network structure composed of several hierarchical layers of ATM switches and multiplexers. It is observed that the ATM multiplexes at the leaves of the interconnection network are used to support several base stations in pico/micro cell environments; Macrocells with large traffic volume may be connected directly to an ATM switch port, as shown. This type of interconnection network is attractive for microcellular wireless networks in general [7].



The fig. 3.2 Typical ATM interconnection network for ATM

3.1.3 Protocol layers

The proposed WATM network follows a protocol layering harmonized with that of standard ATM. It can be Medium Access Control (MAC), Data Link Control (DLC), and wireless network control layers into the ATM protocol stack as shown in fig.3.3 [7].

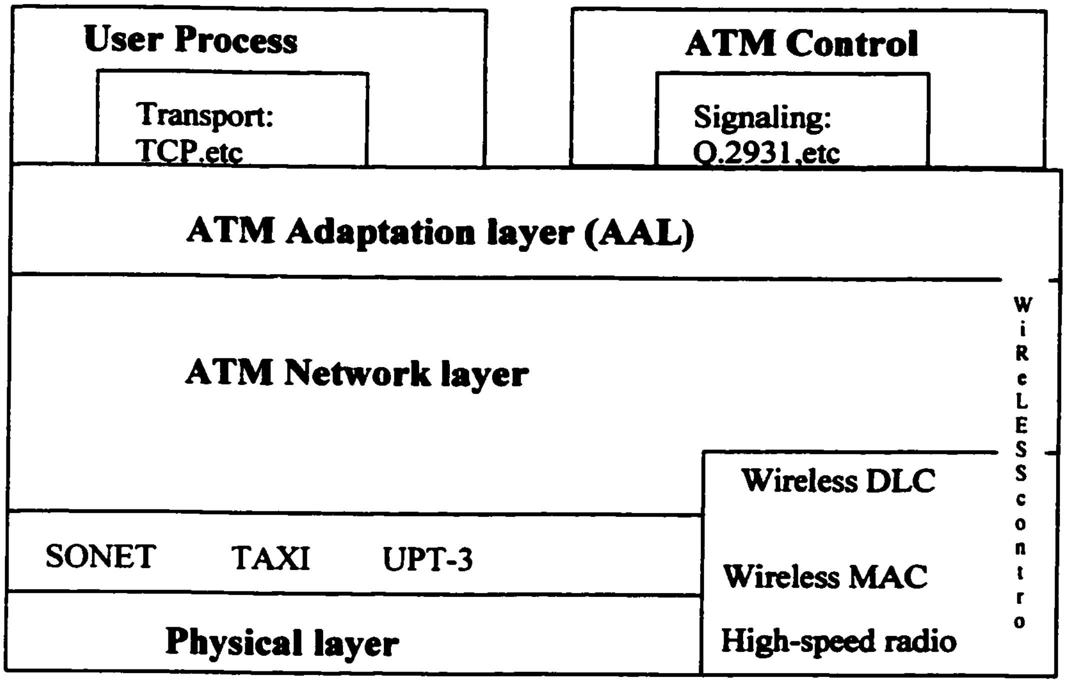


Fig.3.3 relation of wireless network protocol layers and ATM

Fig. 3.3 shows the regular ATM layer and control services will continue to be used for mobile service. Note, a limited number of wireless extensions to ATM network and control layers will be required to support additional functions such as location management, handoff, QoS specification/renegotiation, etc. AAL will be as option for support of wireless applications [7].

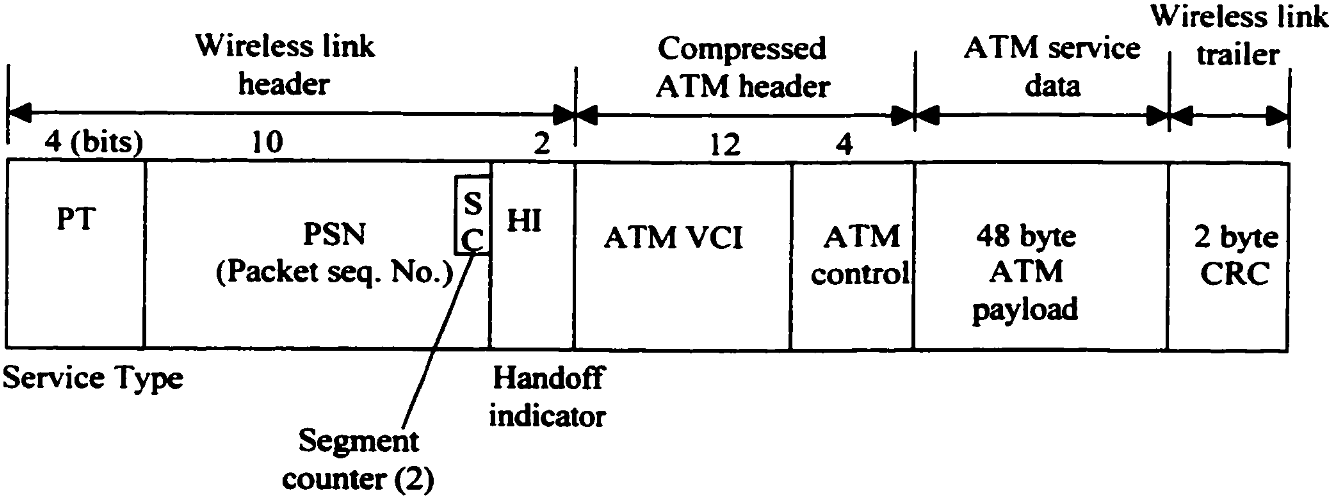


Fig. 3.4 Typical Wireless ATM cell format

Fig. 3.4 shows typical wireless and ATM cell headers corresponding to the WATM protocol stack shown in Fig. 3.3. the wireless header incorporates a 12 bit packet sequence number required to support DLC error recovery over moderately large cell error bursts. This header also contains fields supporting other wireless network functions such as service type definition, handoff recovery and cell segmentation. The Fig. 3.4. shows a compressed 2-byte ATM header with 12 bits VCI (and no VPI) and 4 bits for ATM control, used as a means of improving radio channel efficiency at the expense of a modest amount of base station processing. The HEC function is not used on the radio link (Backbone link) in view of the CRC error detection service provided by the DLC layer.

3.1.4 Media Access Control (MAC)

One of the major problems of Wireless ATM is to find a suitable channel sharing/media access control technique at the data-link layer. Shared media access leads to poor quantitative performance in wireless network.

The challenge in designing the MAC protocol for Wireless ATM is to identify a wireless, multimedia capable MAC, which provides a sufficient degree of transparency for many ATM applications.

3.1.5 Data Link Layer

Wireless ATM needs a customer data link layer protocol, and it should be as transparent as possible. A customer data link protocol is needed due to high error rate and different packet size of Wireless ATM. WATM may use16 to 24 byte payload, as 53 byte may be too long for WATM. The data link protocol may contain service type definition, error control, segmentation and reassembly, and handoff support.

A service type field is needed so as to indicate whether a packet is of type supervisory/control, CBR, VBR, ABR and etc. the service type field simplifies base station protocol processing.

WATM should provide an error control due to high noise interference and poor physical level characteristics of the wireless medium. This is achieved using a PCN packet sequence number field (e.g. 10 bits) in the header along with a standard 2-byte CRC frame check sequence trailer. HDLC style retransmission can be used for connectionless data.

Since WATM may use 16 to 24 byte cells, segmentation and reassembly is required. This can be achieved with a segment counter that uses, for example, the two least significant bits of the error control sequence number.

Handoff is an important characteristic of wireless. Handoff occurs when the mobile unit leaves the area of one cell and enters the area of another. Therefore soft handoff without any data loss is important for any wireless network, and it should be transparent. This can be implemented by using bits in header, which indicates PDUs before and after the handoff.

3.1.6 Wireless network control

A wireless control syntax is needed for control and management functions between the base stations and mobile terminals. Primary functions of this wireless control layer are terminal migration, handoff management and wireless resource management related functions. A framework for wireless control supporting the MAC and DLC layers has been identified and specific functions and syntax are under consideration.

High-speed wireless networks capable of supporting integrated voice, video and data services have been identified as a key enabling technology for multimedia systems. A specific "wireless ATM" network has been proposed to be the solution of this need.

3.2 Error control schemes for networks

3.2.1 Introduction

Wireless network will be needed to provide voice, video and data communication capability between mobile terminal and permit terminal, backbone networks. Wireless channels provide error rates that are typically around 10^{-2}. Such high error rate plus backbone network transmission fading, it really necessitates increasing the transmission quality.

To increase the apparent quality to a communication channel there exist two distinct approaches:

- Forward Error Correction (FEC) which employs error correcting codes to combat bit errors (due to channel imperfections) by adding redundancy (henceforth parity bits) to information packets before they are transmitted. This redundancy is used by the receiver to detect and correct errors.
- Automatic Repeat Request (ARQ) wherein only error detection capability is provided and no attempt to correct any packets received in error is made: instead it is requested that the packets received in error be retransmitted.

FEC and ARQ are two basic methods of error control techniques. ARQ is simple and achieves reasonable throughput levels if the error rates are not very large. But ARQ leads to variable delays which are not acceptable for real-time services. FEC schemes maintain constant throughput and have bounded time delay. However the post decoding error rate rapidly increases with increasing channel error rate. It makes coder-decoder pair hard to implement and also imposes a high transmission overhead. In order to overcome FEC and ARQ individual drawbacks, the combination of these two basic classes of error control called hybrid ARQ has been developed[25].

3.2.1 Forward error correction

FEC involves addition of redundant bits (henceforth referred to as parity bits), that are used to aid in correcting any bits that are received in error [8].

1. Block coding schemes divide a bit stream into non-overlapping blocks and code each block independently. A coding scheme is referred to as being linear if the sum of two code vectors is also a code vector. Similarly a coding scheme is referred to be being cyclic shifts of a code vector results in a valid code vector. Binary Bose-Chaudhuri-Hocquenghem (BCH) codes and non-binary Reed-Solomon (RS) codes are two kinds of widely used linear cyclic block codes.
2. BCH
    - Block length $n=2^m-1$
    - Number of parity check bits $n-k \leq mt$
    - Minimum distance: $d_{min} \geq 2t+1$

Each binary BCH code (n, k, t) can correct up to t-bit errors, and thus it is also referred to as a t-error-correcting code.

3. Reed-Solomon (RS) codes

BCH and RS block coding schemes have a well defined algebraic structure, which has facilitated the development of efficient coding and decoding schemes. In addition, RS code has optimal "distance properties", i.e. provide optimal error correction capability given a fixed number of parity bits, and excellent "burst error suppression" capabilities.

3.1.2 Code shortening

A block code of desirable natural length or suitable number of information digits may not exist. Then code shortening is performed, which involves choosing a code with block length greater than the required length and subsequently shortening it to meet the requirement.

3.2.3. Convolution codes

Convolution code is a popular class of coders with memory. I.e. the coding of an information block is a function of the previous blocks.

3.2.4 code puncturing

The characteristics of a wireless channel typically vary with time, and therefore to obtain optimal performance it is necessary to adapt the error coding scheme to the changing channel characteristics. Code puncturing allows an encoder/decoder pair to change code rates i.e. code error correction capabilities. Without changing their basic structure.

3.2.5 code selection

Above are various coding schemes. We now consider criteria that must be taken into account when selecting a FEC scheme for any given application.

- Probability of uncorrected errors: since it is impossible for any coding scheme to detect all errors and correct them. It is very important to choose scheme for which the probability of both undetectable and uncorrectable errors is minimized (or satisfies the application)
- Overhead: the FEC codes should add as little as possible overhead and maximize the code rate. But increased code capability generally leads to lower code rate,
- Complexity: the implementation complexity of the coding/decoding scheme which typically increases with increase in code length and its capability to detect and correct errors.

3.3 Packet Transmitting Methods

3.3.1 Automatic Repeat Request (ARQ)

ARQ is an error control mechanism that relies on re-transmitting data that is received errors.

ARQ operation: the transmitter Numbers the packets. The receiver acknowledges (ACK) , at the very least, the receipt of each successful packet by transmitting a packet, referred to as an ACK bearing the sequence number of the packet being ACK. Packets that have not been successfully ACK. I.e. an ACK has not been received, in a predetermined time interval, hence referred to as timeout, are assumed to be lost and are retransmitted. There three popular ARQ : stop and wait, selective repeat and go-back-N.

3.3.2 stop and wait

When using the stop and wait (SW) ARQ, the DLC transmits a packet only when all previously transmitted packets have been successfully ACK. Therefore in SW there is never more than a single packet that is unACK at any given instant of time.

3.3.3 Selective Repeat (SR)

When using SR, packets are transmitted continuously by the DLC layer. When SR is used packets can be accepted out of sequence. Hence, packets received out of sequence have to be buffered and sequenced before they can be delivered.

3.3.4 Go-Back-N (GBN)

When GBN applied, packets are transmitted continuously. But at the receiver the DLC layer accepts packets only in the order in which they were transmitted. Packets received out of sequence are discarded and not ACK. Since the receiver accepts packets only in-sequence, after a timeout the transmitter retransmits the packet that time out and all packets with sequence numbers that follow the one that was retransmitted. So each time a timeout occurs all packets that are yet to be ACK are retransmitted. GBN operate, packets are transmitted continuously, without the need to buffer out of sequence packets and there is no re-sequencing overhead.

In a word, neither FEC nor ARQ alone can deliver the desired performance it is necessary that hybrid ARQ error control, that means use both FEC and ARQ.

3.4 Error control for Wireless ATM

ATM is designed for very low error rate and bandwidth rich media, but wireless channels are time-varying and error prone with limited bandwidth. So data link control (error control and flow control) are necessary to support ATM over wireless channels. [9][10][27]

An error control architecture should avoid performance degradation when using ATM over wireless links.

- Channel interleaving to randomize burst errors among different cells.
- FEC to reduce channel error rate. The Reed-Solomon/viterbi concatenated code is used, it is a very powerful FEC code with reasonable complexity using currently available VLSI decoder chips.
- ATM interleaving to randomize the error bursts out of the FEC decoder within one cell. The cell headers (five bytes each) are interleaved with the data stream so that no more than a single error from a burst error appears in any cell header. Recall that in ATM the cell header is capable of correcting a single bit error.

- Data Link ARQ to provide reliable transmission for applications that require reliable delivery. Data link protocol parameters can be determined in a straightforward manner given the channel characteristics. The Go-Back-N protocol may be used on relatively good channels, whereas Selective Repeat protocol is preferred over severely impaired channels.

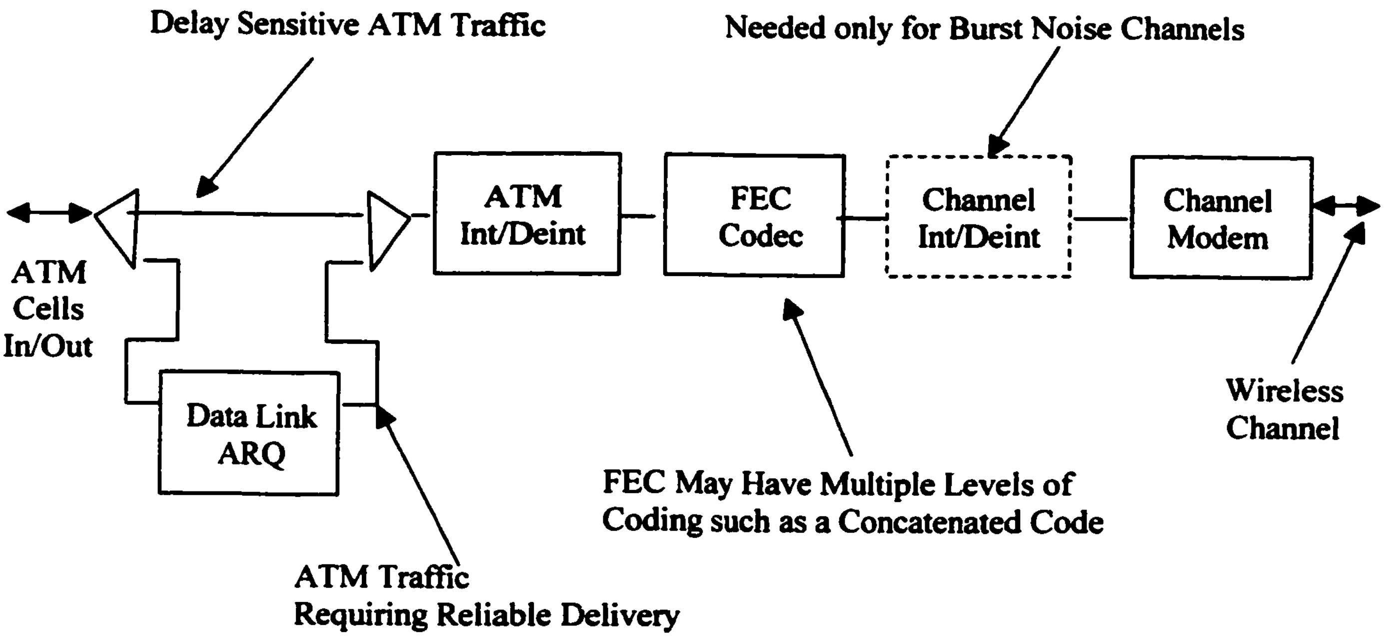


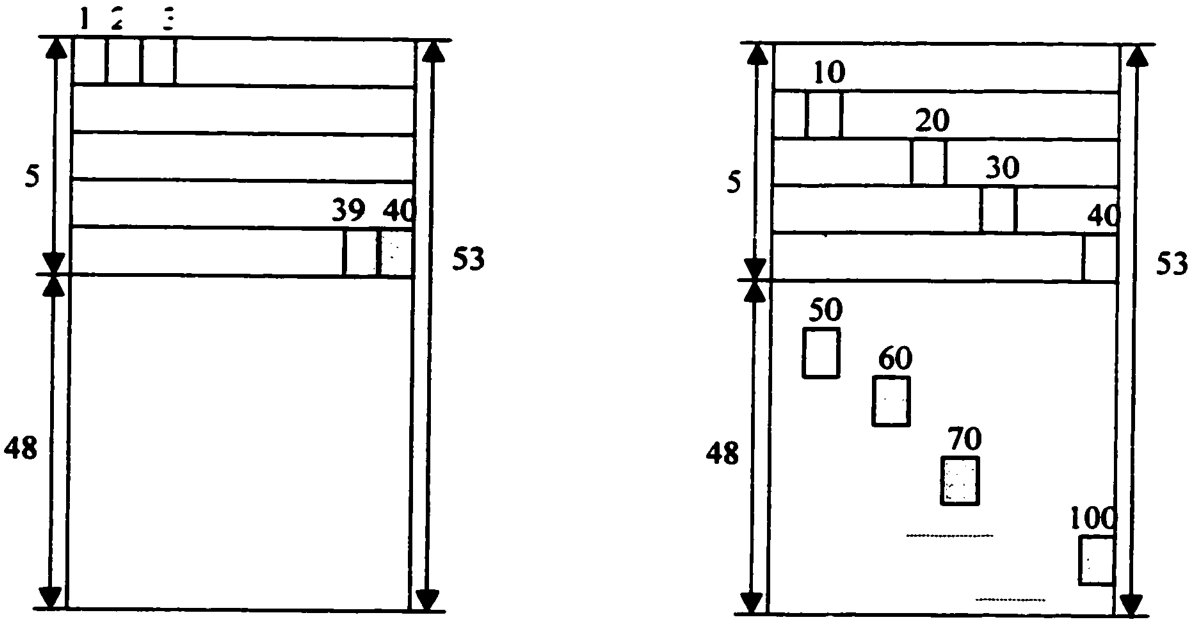
Fig. 3.5 a recommended error control architecture for application of FEC, interleaving, and data link ARQ to provide wireless ATM services.

We can use a method to reduce the cell loss probability by interleaving the header and the payload bits over a wireless ATM link.

For example we use

- Interleaving headers of multiple cells (Block unit interleaving), and

- Spreading each bit of a header over the payload field within the cell (cell unit interleaving).



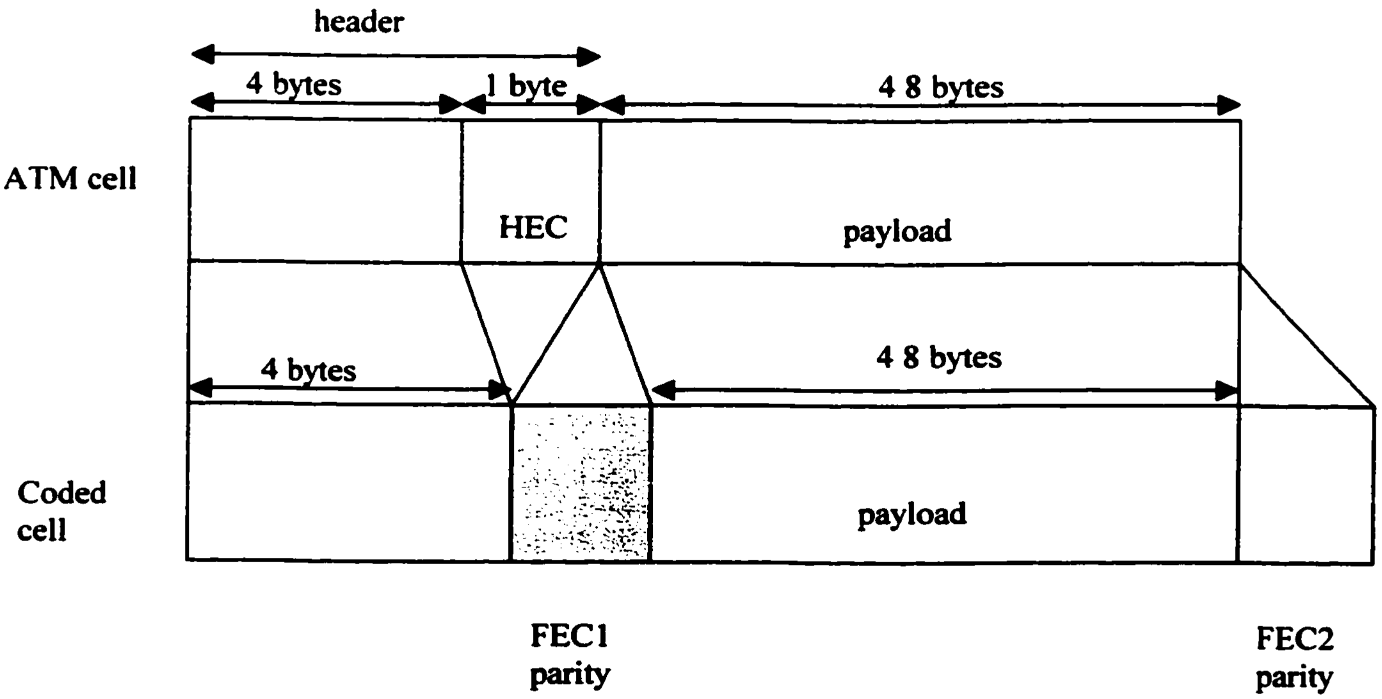
ATM cell

Interleave cell

Fig. 3.6 one method of cell unit interleaving method

To evolve from ATM to wireless ATM is to use a standard ATM cell for network level functions, while a wireless header-tailer is added on the backbone link for wireless channel specific protocol: MAC, DLC, and the network control layer.

ATM uses header Error Correction (HEC) to protect the ATM cell header from single-bit errors. However, WATM requires a more powerful scheme to improve BER performance. Here is a scheme for improving error correction ability.



FEC1 is for header

FEC2 is for payload

HEC : Header Error Control

Fig. 3.7 ATM cell and coded cell format

Note: the coded cell is modified into a wireless ATM cell in which the HEC is discarded and two FECs are added. After replacing the HEC in the ATM cells with FECs, the WATM cells are transmitted. After error correction at the receiver, the FECs are discarded and a new HEC is generated to regenerate the original ATM cell stream.

Because of time varying of wireless link, layered coding and unequal error protection schemes has two concerning. One is how to code the source information into different priority layers, and the other is how to choose appropriate error protection for different priority layers. Most wireless link combine two modes to solve this problem: one is the random loss model, where the wireless channel is characterized by uncorrelated bit errors introduced by random noise and interference components, the other is the multipath loss model, where the transmitted signal undergoes impairment due to multipath fading, shadowing and co-channel interference. Error control on the wireless link is achieved by the way of encoder-decoder. The FEC based scheme could be three level:

- Bit-level FEC. This is done at the physical layer typically in hardware.
- Byte-level FEC: this is done on a per-packet basis
- Cell-level FEC, this is done by allocating some redundant cells for error correction.

3. 5 Conclusions

In this chapter, we investigated WATM, WATM networks, error control scheme, error control for wireless link especially for WATM.

An overall optimal solution for WATM error control does not exist. A solution should be based on the application, the environment and the QoS requirements to design the error control scheme and achieve the best solution.

Chapter 4

A Hybrid Multilayer Error Control Technique for Multihop ATM Networks [24]

4.1 Introduction

There has been a great interest lately in the utilization of the ATM technology for both wire and wireless networks and before its own implementation it has been adapted as the platform for Broadband Integrated Service Digital Networks (B-ISDN). Because ATM was devised to be a connected oriented service, the interconnection of such platforms to LANs and MANs posed certain problems because of the latter main amenability to connectionless services. Some of these problems were addressed in [11] and [12]. On the other hand, error detection and/or correction for ATM networks gained more attention. In [3]-[6], the end-to-end use of an error correction table was investigated, while [17] dealt mainly with error detection.

In the work herein we analyze the end-to-end error performance of a LAN user who is connected to a multihop ATM network. We investigate the case where no retransmission is allowed (as in delay-sensitive applications) as well as the case when the use of Go-Back-N ARQ scheme at the transport level is assumed. Error checking and cell dropping are implemented at the ATM hop level, whereas error concealment is implemented end to end via a 2-dimensional parity check, table based technique [3]. We also propose to add a field for data checking at the ATM hop level and to use the cell loss, end to end efficiency and residual cell delivery error as the main performance criteria.

The system is described in more details in 4.2, whereas performance analysis is furnished in 4.3. Results are presented and discussed in 4.4. 4.5 concludes with observations and remarks.

4.2 Description of the LAN/ATM Interconnection

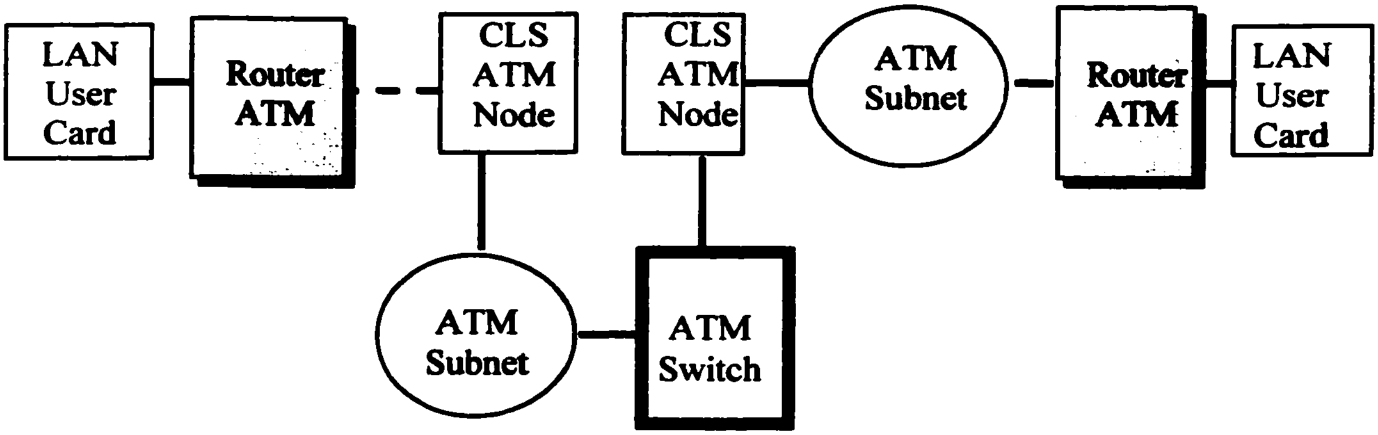
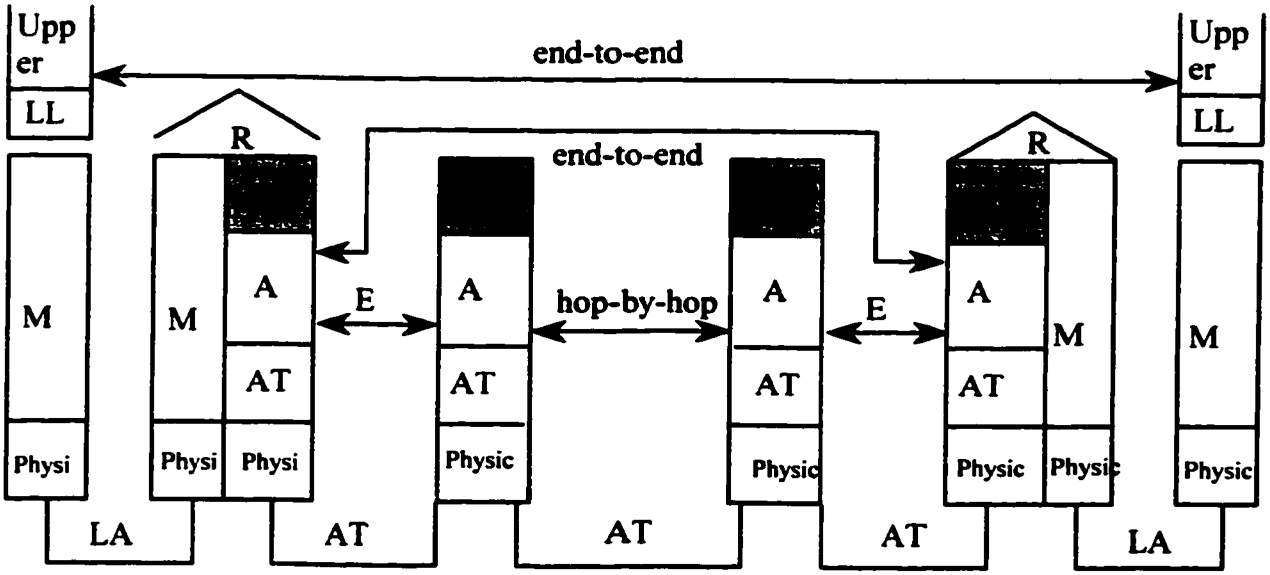


Figure 1: A typical end-to-end communication link over TAM networks

Figure 1 shows a typical scenario involving end to end, LAN user, data communication via *h* hops, ATM nodes and ATM switches. User Transport Protocol Data Units (TPDU) go through IP and LLC processing where appropriate headers are added. Subsequently MAC and physical layer processing and addition of headers take place according to IEEE LAN standards. This functionality is assumed to reside at the LAN user card. At the routers, the data is translated from LAN packet format to cell format by means of the CLNAP, AAL, ATM, and physical layers. These processes are illustrated in Figure 2.



FEC: Forward Error Correction ED: Error Detection

Figure 2: Location of the various error detection and correction mechanism in the LAN/ATM interconnection (The shaded areas exist only in CL or CLS ATM nodes, not CO ATM nodes)

Connectionless data intercommunication within the global ATM network is handled by special ATM nodes called connectionless service (CLS) units as in Figures 1 and 2. The units are connected by point to point high-speed links or by the appropriate mobile or satellite channel in the wireless case. This scenario is amenable to the interconnection of medium or large number of LANs, as opposed to the other possibility of having all routers fully connected by special lines which is convenient for a small number of routers.

The ATM node comprising the CLSF terminates the LAN CL protocols, and relaying of information is based on the address field included in the CLNAP connectionless Network Access protocol PDU [12] to accommodate all types of LANs addressing schemes.

The source inter-networking units (routers) replace the MAC address of the LAN TPDUs with E164 addresses [11], [12]. This address is included in the first

ATM cell which is called Beginning of the Message (BOM). The BOM is indicated in the Segment Type field (ST) of the Segmentation and Re-Assembly (SAR) type (3/4) protocol. The rest of the ATM segments (cells) comprising the TPDU carry a multiplexing identifier (MID) label which corresponds to the address of the BOM cell. This way, the ATM cells comprising TPDU will never be assembled or disassembled within the intermediate CLSF, ATM nodes.

The addition of the CLNAP layer on the top of the ATM layer makes for the difference between connection-oriented (CO) ATM nodes and connectionless (CL) or (CLS) nodes. The allocation of VPI/VCI values among CLS nodes and the bandwidth assignment and bandwidth advertisement [1] are handled by the ATM network management. Compared to the other alternative of interconnecting all subject LANs by dedicated point to point ATM channels (in a topological mesh), the aforementioned use of CLS reduces the number of such channels but at the cost of more processing at each CLS (address translation, etc).

In ATM systems [12] and [18] the AAL (3/4) layer handles both connection-oriented (class C) as well as connectionless-oriented (class D) traffic. It is this latter case that will be emphasized in this work of thesis, i.e. we assume that both the LAN and the ATM hops are connectionless.

Now, we move to the main emphases of this work of thesis, which is the system and performance aspects of a multilayer error control scheme which consists of combined end-to-end error correcting and hop-by-hop error detecting techniques. On the top of that, Automatic Repeat re-Quest (ARQ) scheme is utilized at the transport layer, as illustrated in Fig. (2).

In Wireless Multimedia Networks, this is more than needed due to the changing channel conditions (loss, multipath fading,...etc.) and the higher bit error rates. In terrestrial networks, the cell loss is mainly attributed to traffic congestion and processing conditions in intermediate ATM switches, routers and cross connects which worsens as the traffic builds and/or number of hops increases.

As for the first level of checking, the AAL (3/4) layer adds CRC bits at the segment level (a segment is one cell minus overhead). The CRC bits, set to x_0 =10, are normally used to protect the cell header only. The CRC size is typically based on the number of bits being protected and a size of 10 was found to be satisfactory for header protection [17].

However, by using more CRC bits one can also checks (protects) the payload. In this work of thesis both cases will be examined. The corresponding format of the cell for each case is depicted in Fig. (3) a and b. The CRC bits are checked at the AAL layer of each transit (intermediate) ATM node as the cell traverses each link of the virtual path (VP) enroute to destination, and the cell is dropped whenever the CRC succeeds in detecting errors in the header or the payload of the ATM cell (if it is protected). Some switch vendors are working on such implementation for the AAL5 layer. Of course this requires some processing delay at intermediate ATM nodes and effectively increases the network traffic.

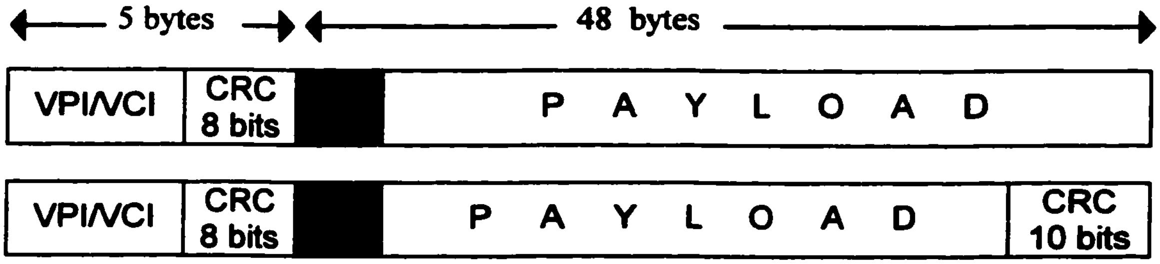
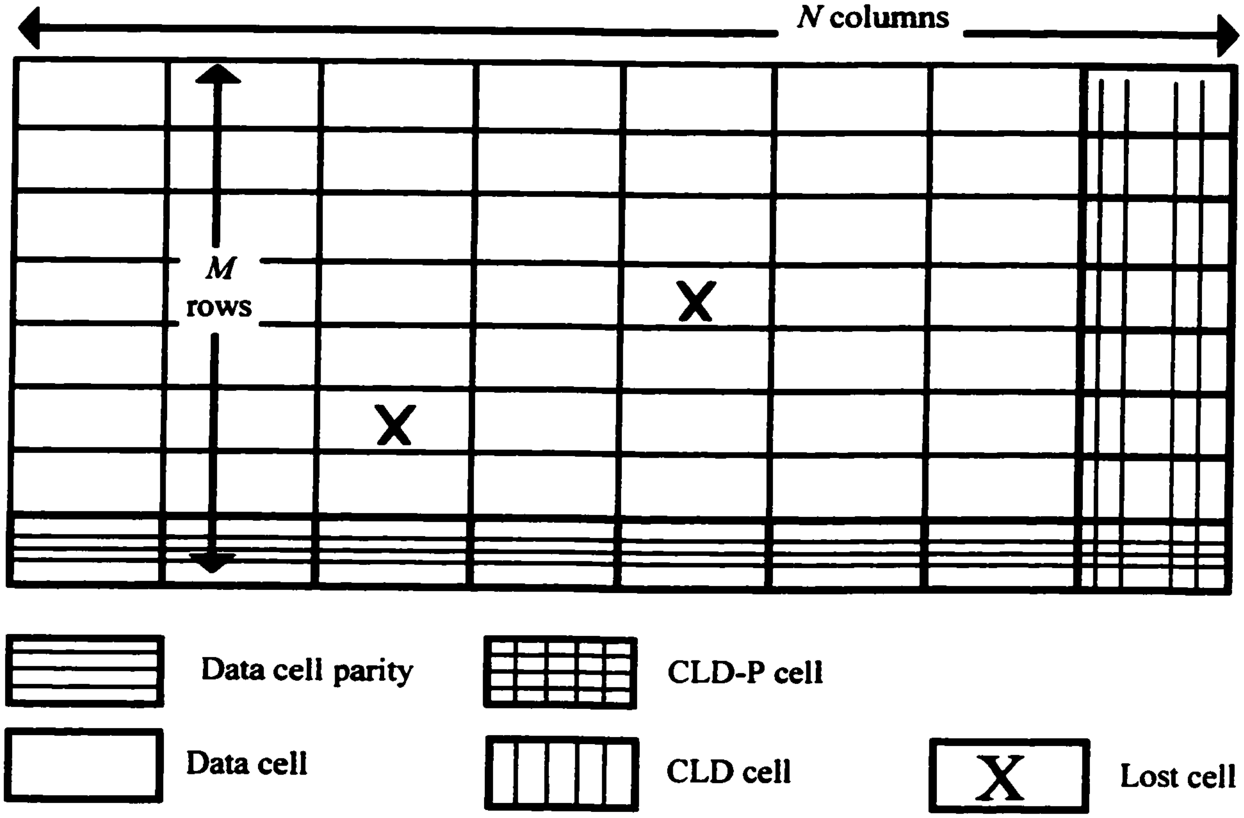


Figure 3: Two possible scenarios of CRC
(a) Top: current CCITTS standard; only the header is protected.
(b) Bottom: Improved CRC protection; both header and payload are protected.

The second level of error control is the lost-cell recovery technique [3] that applies end to end at the AAL level of the source/destination ATM node. This level recovers cells that were lost either because they were dropped earlier due to channel errors or because of buffer overflow at any intermediate node. Fig. (4.a) shows the structure of the table used for detection and recovery of lost cells. Data cells, as those in Figure 3, are arranged in M-1 rows and N-1columns. An N^{th} column is formed from special cells, called cell-loss-detection (CLD) cells that aid in *detecting* the lost cells, while an M^{th} row is formed from parity cells that aid in *recovering* the lost cells. The most bottom right cell is a CLD parity (CLD-P) cell and an extra cell called PARSEQ, newly suggested in this work of thesis, is added to the whole table. This cell resembles the CLD cell that terminates each row. It carries the sequence number of all regular parity cells of the table, and serves to detect the loss of one or more of these regular parity cells. The reader is cautioned however that the introduction of this new PARSEQ cell renders the table irregular and becoming of size (MN+1) and the effects on the analysis of this single cell are neglected. The effects of regular parity and other cells are however all accounted for. Once the table is completed, its constituting cells are transmitted row by row.



(a) Cell Error Detection and Recovery Table

Cell Header (same for all cells)	CR P 1	CR P 2	....	CR P N-1	SN-CLD	CRC 24

(b) CLD cell format

Cell Header (same for all cells)	Column-wise, mod-2 sum of CRPs of all CLD cells.	SN-CLD	CRC 24

(c) CLD-P cell format.

Figure 4: The structure of cell recovery table and cells format.

Five cell types are encountered, namely:

1. Data cell (as in Fig. 3)
2. Cell Loss Detecting cell (CLD). Fig. 4.b shows that this cell consists of the header (VPI which is shared by all cells of the table of Fig. 2) followed by the *N*-1 cell recognition patterns (CRPs), one byte of SN-CLD and a 24 bit CRC calculated over the *N*-1 CRPs and SN-CLD fields of this cell. The CRP is a 22 bit field, consisting of the VCI field (2 bytes) and the first six bits of the data field of each cell in a certain row of the encoding table (each row consists of *N*-1 data cells). The sequence number of the CLD cell (SN-CLD) is an identification given to each CLD cell to help discover lost CLD cells. An 8-bit SN-CLD is enough to span 256 values i.e. enough for the maximum number of columns in the encoding/decoding table.

   It is worth noting that ATM cells will be carrying their own sequence number. However in many applications only priority cells pass through the cell recovery table and so cells in a row may not be in sequence, thus necessitating the advent of another sequence number related to the table so as to detect lost or dropped cells.
3. CLD parity (CLD-P) cell (Fig. 4.c) is the last cell in the column, and is calculated by simple module 2 addition of all CLDs in the last column.
4. Regular parity cell is the bottom cell of each data cell column. It is formed as the module-2 addition of all cells of a certain column at the transmitting end ATM node.

5. PARSEQ, the extra cell mentioned above.

The table decoding operates as follows. At the receiving ATM node, the *M*×*N* table is formed. First, the last column, consisting of CLD cells, is examined. Once a CLD cell is found to be missing, as per the absence of its sequence number, it is replaced by an all-zero cell. Performing module-2 addition of all bits in the last column, including the CLD-P cell, recovers the lost CLD cell. Next each row is examined to check if any of its data cells are lost. The identity of lost data cells is found by comparing the CRP field of each data cell to the corresponding CRP field in the CLD cell of the corresponding row. A dummy all-zero cell is substituted instead of the lost cell. Once again, performing module-2 addition of cells in that column recovers the lost cell.

The identities of lost regular parity cells are similarly found and concealed by means of the sequence fields in the newly introduced PARSEQ cell, similar to the way regular cells lost are identified by the sequence fields in the CLD cells.

The above recovery process works well if there is one lost cell per column. If it is found that more than one cell is lost per column the recovery process terminates completely or partially, as will be elaborated on in the coming analysis. Any remaining lost cells will be delivered to the upper layer where ARQ recovery takes place.

An ARQ scheme, incorporating a powerful error detection code, provides the third level of error control. A retransmission is requested whenever a packet (formed of few cells) contains lost or erroneous cells.

4.3. Performance Analysis

In the following, we evaluate the overall efficiency and probability of error considering the three levels of error control described earlier, for data transmission from a source to a destination ATM user. (Traffic is assumed symmetrical in the other direction).

We start by looking at the outcomes due to the ATM cell process at h intermediate ATM nodes, including the destination node. At these nodes, only error detection and possible cell dropping takes place. This cell dropping adds to the usual cell dropping due to the intermediate ATM buffer overflow as will follow shortly. Also in all cases we investigate both CRC types as in Fig. 2.b., i.e. checking only the cell header and checking both header and payload.

Denoting, for $i = 1, 2, \ldots, h$:

f_i = probability of cell loss due to buffer overflow in node number i on the h-hop VP,

p_i = bit error probability on the physical wireless or terrestrial network of the i^{th} hop,

n = number of bits of the payload,

n' = number of bits of the header,

c = cell size in bits = $n + n'$

We now obtain the probability $P_{c,i}$ that the cell survives both physical layer errors and buffer loss at the i^{th} node, i.e.

$$P_{c,i} = (1-p_i)^c(1-f_i) \tag{1}$$

The probability, $P_{e,i}$, that a cell is received in error, which will take place when the cell encounters no buffer loss but the CRC failed to detect the errors and therefore did not drop the cell, is given by:

$$P_{e,i} = (1-f_i)\left\{P_{u,i} + P'_{u,i} - P_{u,i}P'_{u,i}\right\} \tag{2.a}$$

where $P_{u,i}$ and $P'_{u,i}$ are the undetected error probabilities of the payload and the header, respectively. The undetected error probability is a function of the bit error probability of the hop and the CRC code employed. When no CRC coding is applied to the payload, we have

$$P_{u,i} = 1-(1-p_i)^n \qquad (2.b)$$

The undetected error probability when a CRC code of length x_0 is incorporated is upper bounded by:

$$P_{u,i} < 2^{-x_0} \qquad (2.c)$$

The goodness of this bound and the justification for adopting it here are furnished in Appendix B. It is shown in [17] that the above bound gives the probability that the CRC code of size x_0 will fail to detect a burst error. It is concluded also in the same reference that per segment (cell) CRC yields very good protection against random bit errors and reasonable protection under burst error. Later on we will use the per frame (packet) CRC but at the ARQ level which was proven effective [17] against long burst of errors.

The probability that the cell is lost due to buffer overflow and/or appropriate dropping by CRC, $P_{l,i}$ is given by:

$$P_{l,i} = 1- P_{c,i} - P_{e,i} \qquad (3)$$

A typical cell traversing the h ATM nodes enroute to destination would repeat the outcomes in (1)-(3) h times. Assuming that all channels (hops) are identical on the average, i.e. have the same bit error probability p, the subscript i may be dropped and the overall probabilities at the destination node can be written as:

$$\overline{P}_c = P_c^{\,h} \qquad (4)$$

$$\overline{P}_e = \sum_{j=1}^{h} \binom{h}{j} P_e^{\,j} P_c^{\,h-j} \qquad (5)$$

$$\overline{P}_l = 1 - \overline{P}_c - \overline{P}_r \qquad (6)$$

In deriving (4)-(6), the independence of all events was assumed.

Next we evaluate the modifications in the above probabilities (4)-(6) due to using the cell recovery table of Fig. (4.a). Let's first consider the recovery of the lost data cells and data parity cells, assuming all CLD cells are present. It is easily seen that exactly one lost cell per column could be recovered, but two or more lost cells lead to unrecoverable cell loss. Therefore, the cell loss probability after decoding (i.e. the residual cell loss probability) is:

$$E_1 = \frac{1}{M}\sum_{j=2}^{M} j\binom{M}{j}(\overline{P}_l)^j(1-\overline{P}_l)^{M-j} \tag{7}$$

Now consider the case of lost cells in the CLD column. The CLD-P cell can compensate for no or only one CLD lost cell. In both cases the unrecoverable cell loss probability is given by (7). However, If there is more than one lost cell the decoder does not attempt any recovery operations, and the whole table of data cells is immediately delivered to the upper end-to-end ARQ layers as it was received. Therefore, the probability of lost data cell for this scenario is given by:

$$E_2 = \frac{1}{M}\sum_{j=1}^{M} j\cdot\binom{M}{j}(\overline{P}_l)^j(1-\overline{P}_l)^{M-j} \tag{8}$$

The probabilities in (7) and (8) are obtained under the assumption of random cell loss.

The analysis under burst (correlated) cell loss assumption is provided in Appendix A. The derivations and results of the Appendix (Table A.1) clearly show the closeness of E_1, E_2 for random and burst error after table decoding. This result should not be surprising. The cells constituting a table are transmitted raw-wise and decoded column-wise. It follows that the burst error will have to be very long to have two or more lost cells in the same column. In other words the table serves as an interleave that, for all practical values of N, M and q, randomizes the burst errors. The results of Appendix A are also supported by [13], [14].

Both E_1 and E_2 contribute to the total post-decoding cell loss probability with different weights. The averaging process is explained as follows. In each decoding table we have M CLD cells and $M(N$-1) data cells, including parity cells in both. Since cell errors are equally likely to occur anywhere within the table, the probability that a lost cell hits the data cells (the first N-1 column) and the probability that a lost cell hits the CLD cells (the last column) are respectively $M(N\text{-}1)/MN$ and M/MN. The cell loss probability E_1 takes place when the lost cells are confined to the data section, or when 0 or 1 CLD is lost (corresponding to j =0,1 in the first term of Equation (9)), whereas the cell loss probability E_2 takes place when two or more CLD cells are lost. This translates to the following overall average cell loss probability

$$
\begin{aligned}
P_L = & \left\{ \frac{M(N-1)}{MN} + \frac{M}{MN} \sum_{j=0}^{1} \binom{M}{j} (\overline{P}_l^{\,*})^{j} (1-\overline{P}_l^{\,*})^{M-j} \right\} \cdot E_1 \\
& + \left\{ \frac{M}{MN} \sum_{j=2}^{M} \binom{M}{j} (\overline{P}_l^{\,*})^{j} (1-\overline{P}_l^{\,*})^{M-j} \right\} \cdot E_2
\end{aligned}
\qquad (9)
$$

The probabilities marked (*) are evaluated for a CLD cell (where its non-header segment is protected with 24 bits).

Next, let's calculate the probability that the cell is correct, P_c, and the probability that the cell is in error, P_E, both after table decoding. When a lost cell is recovered it will be correct if all the other (M-1) cells in the column are correct, otherwise it is assumed wrong. The probabilities in (4) and (5) should then be modified to:

$$P_C = \overline{P}_c + (\overline{P}_c)^{M-1}(\overline{P}_l - P_L) \qquad (10)$$

$$P_E = \overline{P}_e + [1-(\overline{P}_c)^{M-1}](\overline{P}_l - P_L) \qquad (11)$$

Note that $P_C + P_E + P_L = 1$.

Now consider a packet B of r cells at the ARQ level. Define:

B_C = the probability that the packet is correct.

B_E = the probability that the packet contains undetectable errors.

B_L = the probability that the packet contains lost cells.

B_D = the probability that the packet contains detectable errors.

The packet will be accepted and delivered to the user when it is correct, or when it contains undetectable errors. Otherwise, it will be retransmitted. The probability of retransmission $B_R = B_D + B_L$. It can easily be seen that,

$$B_C = (P_C)^r \qquad (12.a)$$

$$B_E < 2^{-(n^* - k^*)} \tag{12.b}$$

$$B_R = 1 - B_C - B_E \tag{12.c}$$

Where (n^*-k^*) is the number of check (CRC) digits for the ARQ system. This operates on a frame (packet) error detection basis (the packet is a group of cells as per the definition of [17]). Equation (12.b) implies that the only residual errors left in the packet are those which are not detectable by the error detecting code employed by the ARQ protocol, independent of the undetectable errors passed from the previous error detection at the cell level.

The ultimate probability of delivery error, P, and the net throughput, η, of the Go-Back-N ARQ are given by [18]:

$$P = B_E / (B_E + B_C) \tag{13}$$

$$\eta = \alpha \cdot \frac{(1 - B_R)}{(1 + 2aB_R)} \tag{14}$$

where α is the ratio of the number of information bits to the number of total bits, transmitted per second. That is

$$\alpha = \begin{cases} \dfrac{k^*}{n^*}\left\{\dfrac{(M-1)(N-1)}{M \cdot N}\right\} & \text{if only header is protected} \\ \dfrac{k^*}{n^*}\left\{\dfrac{(M-1)(N-1)}{M \cdot N} \times \dfrac{(c-10)}{c}\right\} & \text{if both header and payload are protected} \end{cases} \tag{15}$$

The factor a is the user end-to-end propagation delay in packets, that is

$$a = \frac{h\tau}{T_P} + 2\left(\frac{MN}{2}\right)\left(\frac{cT_b}{r \cdot T_P}\right) = \frac{h\tau}{T_P} + \frac{MN}{r^2} \tag{16}$$

where τ is the one-way propagation delay and T_b and T_P are the bit length and the packet length, respectively, in seconds ($T_P = r \cdot c \cdot T_b$). The first term in (16) is due to the one-way propagation delay over h ATM hops while the second term is due to the table encoding/decoding storage at source and destination nodes. Encoding/decoding processing at the end nodes, and CRC processing times at intermediate nodes were neglected in the above calculations.

We proceed next to the evaluation of the probability of buffer overflow at a certain node. For convenience purposes, we assume a simple *M/M/1/K* node buffer, where each node multiplexes its own traffic (from its own LAN or LANs) and the passing-by transit traffic.

Let the intrinsic (pure data) traffic intensity be ρ_0. This traffic intensity is magnified by the CRC of the payload, the parity cells of the table and the ARQ retransmissions. Since all these factors are accounted for in η, the inflated traffic intensity ρ is given by:

$$\rho = \rho_0 / \eta \tag{17}$$

The reduction in traffic at a node due to dropped cells at earlier nodes on the VP is neglected. For an M/M/1/K buffer of size *K* and traffic intensity ρ, the probability of overflow is then given by:

$$f = \frac{(1-\rho)\rho^K}{1-\rho^{K+1}} \qquad 0 \le \rho \le K \tag{18}$$

Substituting *f* from Equation (18) for f_i in Equations (1) and (2.a) implies a worst case condition where the retransmission of a certain packet means the retransmission of all constituting cells. This is not generally true since packet retransmission depends also on channel errors beside buffer loss. Under channel errors, packet errors are higher than cells errors, (Equation 12.a) and the worst case is evident.

4.4 Results and Discussion

The multilayer error control scheme analyzed above was applied to a LAN/ATM Network. Initially, the system parameters were set to the following values: h =3, M =17, N =17, r =4, K=16, transmission rate =150 Mbps, τ = 1 msec and x_0 =10. Unless stated otherwise, the above values are assumed.

Figure (5) provides a good indication of the power of cell recovery table. It shows that a large percentage of the lost cells were recovered, which results in reducing the cell loss rate by up to three order of magnitudes for $p < 10^{-6}$. The Figure also shows that most of the recovered cell is correct, yielding essentially the same probability of error after decoding (the curve for the probability of erroneous cells following recovery is close to that before recovery).

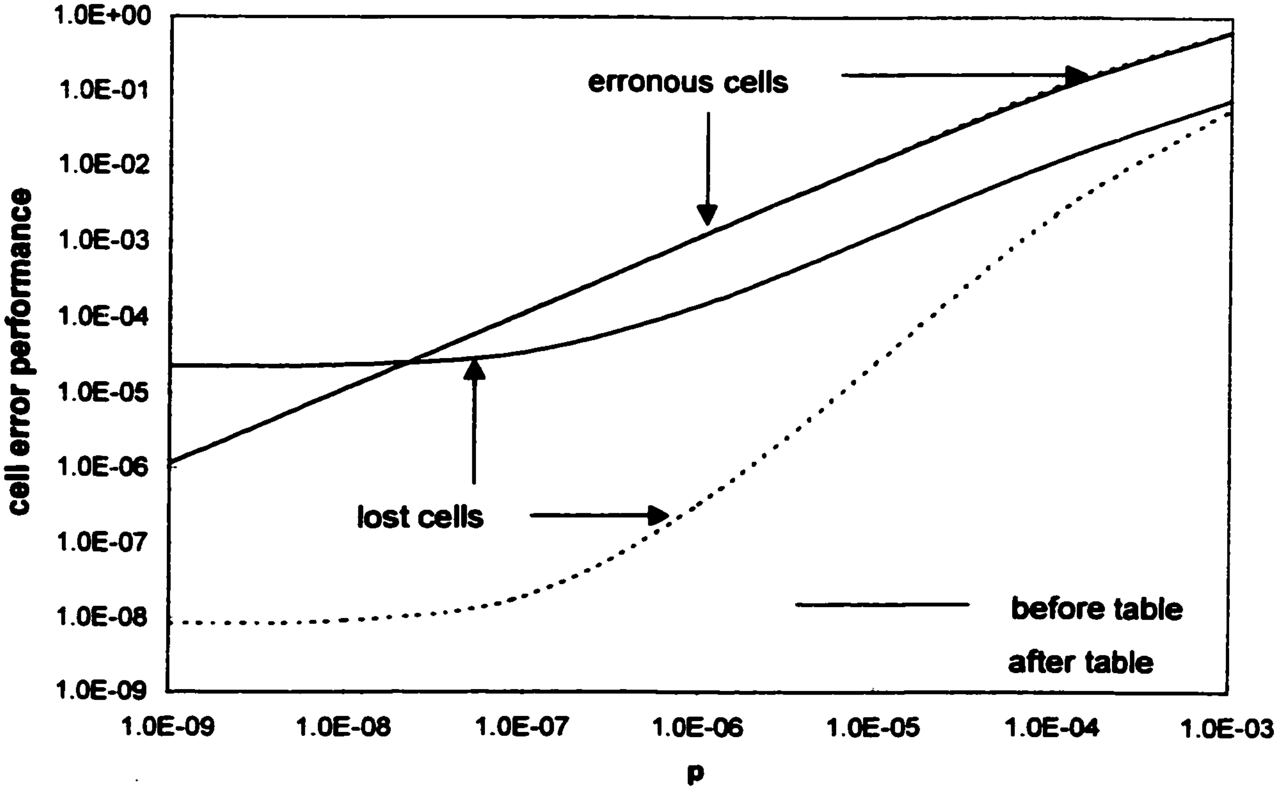


Figure 5: Performance of the cell recovery Table

Figure (6) illustrates the cell error performance when no ARQ retransmission is used. Such systems are appropriate for delay-sensitive traffic. Two sets of curves are shown, one for the case when the payload is not checked (referred to as Case 0) and the other for the case when x_0 =10 bits are used to check the errors in the payload (Case 1). The results show that although the cell loss rate increases when the payload is checked, the overall probability that a received cell is not correct (i.e. $P_E + P_L$), which is of concern to the end user, is significantly reduced. The cost of this improvement is a slight reduction in the throughput due to the 10 bits/cell CRC bits, by only 10/424 ≈ .024.

The rest of the analysis applies to the case when a GBN-ARQ scheme is invoked. A CRC-32 code is used for detecting the remaining erroneous cells after the table. Using this code as the final detection stage guarantees a post-decoding undetected block error probability $B_E < 2^{-32} \approx 2\times10^{-10}$, regardless of the error before packet decoding. The throughput is then the main performance criterion.

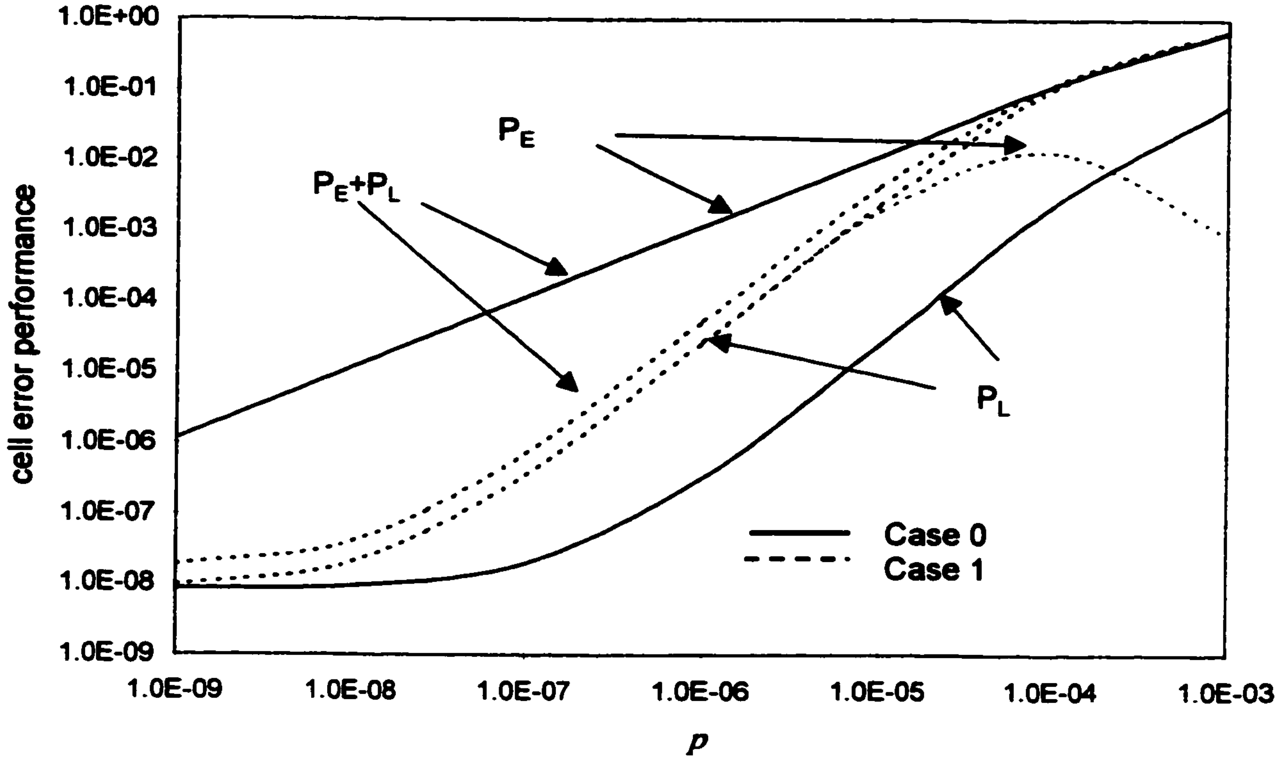


Figure 6 Effect of payload checking on sytem performance for delay-sensitive traffic (no ARQ)

Figure (7) investigates the relation between the total traffic intensity ρ and the throughput. The curves in this figure are produced for two different channels (p=10^{-9} and p=10^{-6}) and two values of the buffer capacity K =16 & 32. Also shown on the same figure the corresponding intrinsic traffic intensity ρ_0.

The linear, monotonically increasing part of the ρ_0-vs-ρ curve in Figure 7 represents the situation where most cells circulating in the network are original cells. That is, the cell loss probability is very low, and there is hardly any need for retransmission. Over this range, ρ does not affect the throughput of the system (note the flat part of the efficiency curves). However, as more intrinsic traffic is injected to the network the probability of buffer overflow, and thus the probability of lost cells, increases resulting in a drastic drop of the throughput. The drop in η is directly reflected on ρ_0 which, after reaching a maximum value of $\rho_{0,max}$ starts to decrease. The value of ρat which the ρ_0-vs-ρ curve assumes its maximum, call it ρ^*, is the breakpoint between a light network (to the left of ρ^*) and a congested network (to the right of ρ^*). In the figure $\rho^* = 0.6$ at 10^{-6} and .62 at 10^{-9}. The value of $\rho_{0,max}$ represents the maximum intrinsic traffic that the network can handle. It can be seen that the better channel can withstand a higher $\rho_{0,max}$ ($\rho_{0,max} = 0.5$ and 0.35 at 10^{-9} and 10^{-6}, respectively). However both values are significantly increased to 0.7 and 0.5 by doubling the buffer size to 32. In fact, it was found that increasing the buffer size further to 64 cells phases out any influence of ρ on η.

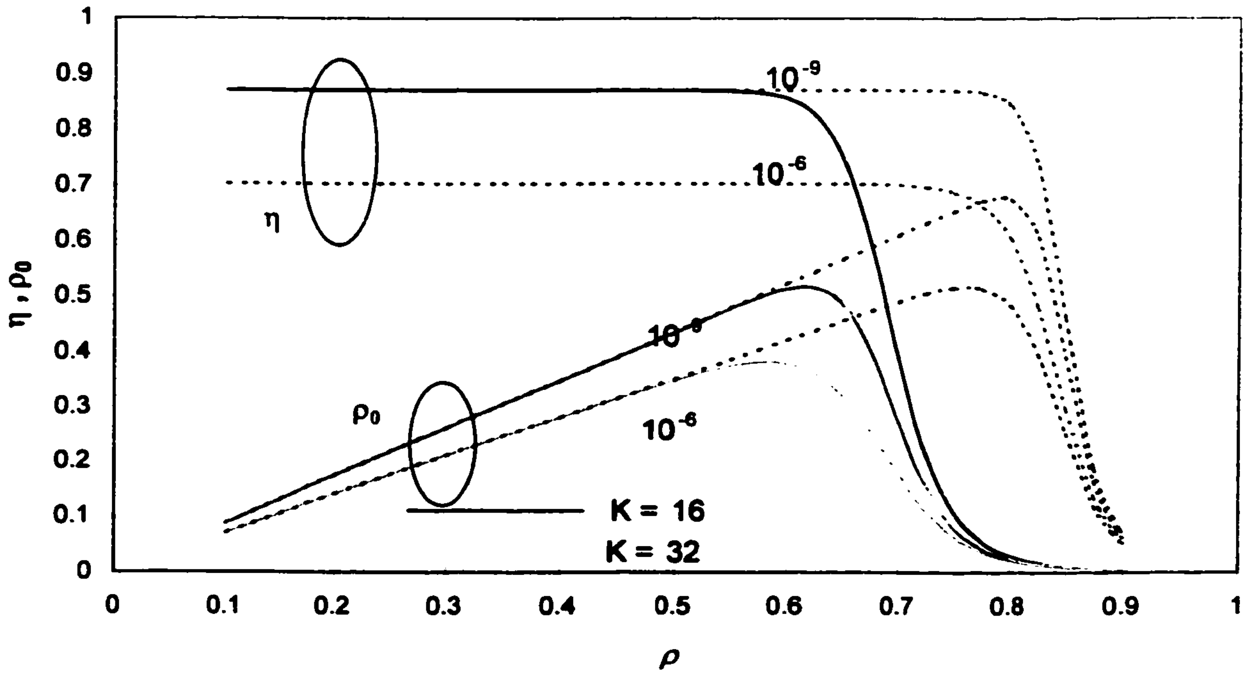


Figure 7 The effect of traffic intensity on the throughput:

We next examine the cons and pros of checking the payload. Figure (8) shows the throughput versus the channel BER when the payload and header are checked (Case 1) and when only the header is checked (Case 0). The throughput for each case is examined at two values of ρ, namely 0.5 (light network) and 0.7 (congested network). Due to the increased redundancy of Case 1, the throughput efficiency is slightly lower than that of Case 0 for very good channels ($p<10^{-8}$). On the other hand, the effect of redundancy is more than compensated for at higher BER. This can be explained by recalling that the system in Case 1 yields lower values of $P_\varepsilon + P_L$ than those in Case 0, or, in other words, higher values of P_C. Consequently less retransmissions are requested. The figure shows that although the merit of Case 1 over Case 0 diminishes for congested networks (ρ > ρ *).

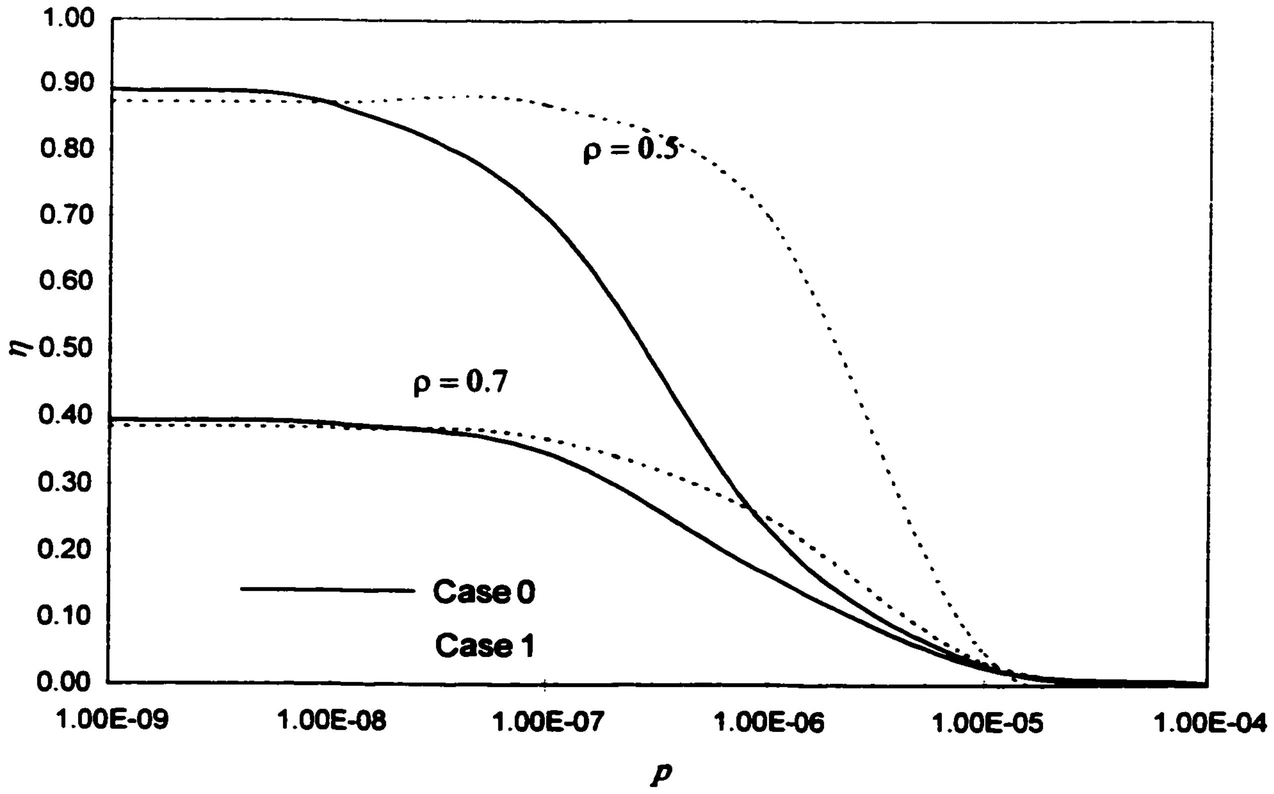


Figure 8: The effect of checking the payload on the throughput for two values of traffic intensity.

Now we present some results concerning the design of the cell recovery table. From this point onward we take ρ =0.5. The size of the cell recovery table ($M \times N$) has to be designed to yield the maximum throughput for a given network. (A network is defined by the parameters p, η, ρ, τ, ..).

Let's consider N first. The CLD cell is formatted for a maximum value of N =16. The CLD cell has the capability of detecting a lost cell independent of the status of the other cells in the row. Therefore B_R is not sensitive to N. It was then found that the effect of decreasing N on decreasing η (through decreasing α) equals, and in many situations overcomes, its effect on increasing η (through decreasing a). Even when it is advantageous to decrease N, the same amount of improvement in η can be obtained by varying M. For these reasons, N was fixed to 16, and the design of the table reduces to finding the optimum M.

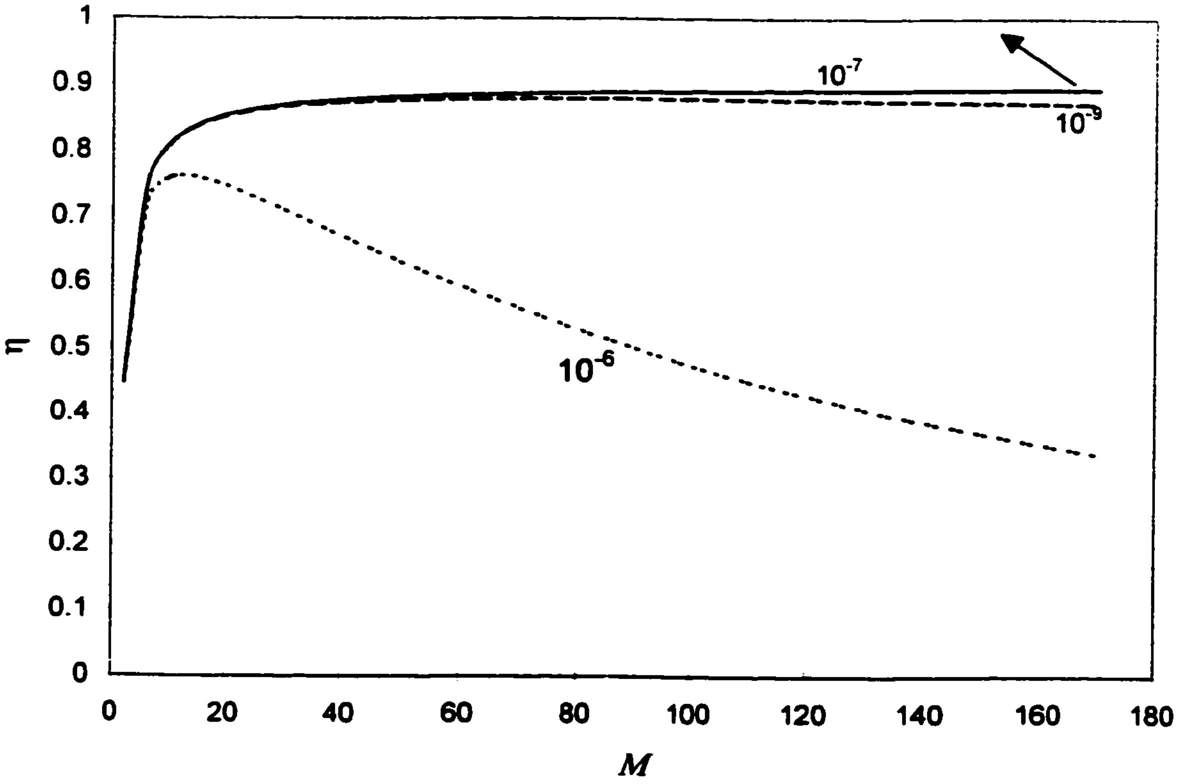


Figure 9: Studying the effect of channel BER on the design of *M*.
($\rho = 0.5$)

To see the effect of *p* on *M*, Figure (9) depicts the throughput versus *M* for different channels. For good channels ($p<10^{-7}$) *M* should be selected to be sufficiently large (>40) to justify the amount of redundancy added by adding one data parity cell per column.. However, since the cell loss probability over such good channels is very low, and hence the retransmissions are very infrequent, the throughput is not sensitive (i.e. flat) for larger values of *M*. For worse channels (for example $p=10^{-6}$), where the cell loss probability increases and retransmissions are more frequent, large values of *M* affects the throughput badly. For the network considered, the value of *M* that achieves the highest throughput is around 16. The sensitivity of the throughput to *M* increases with increasing *p*.

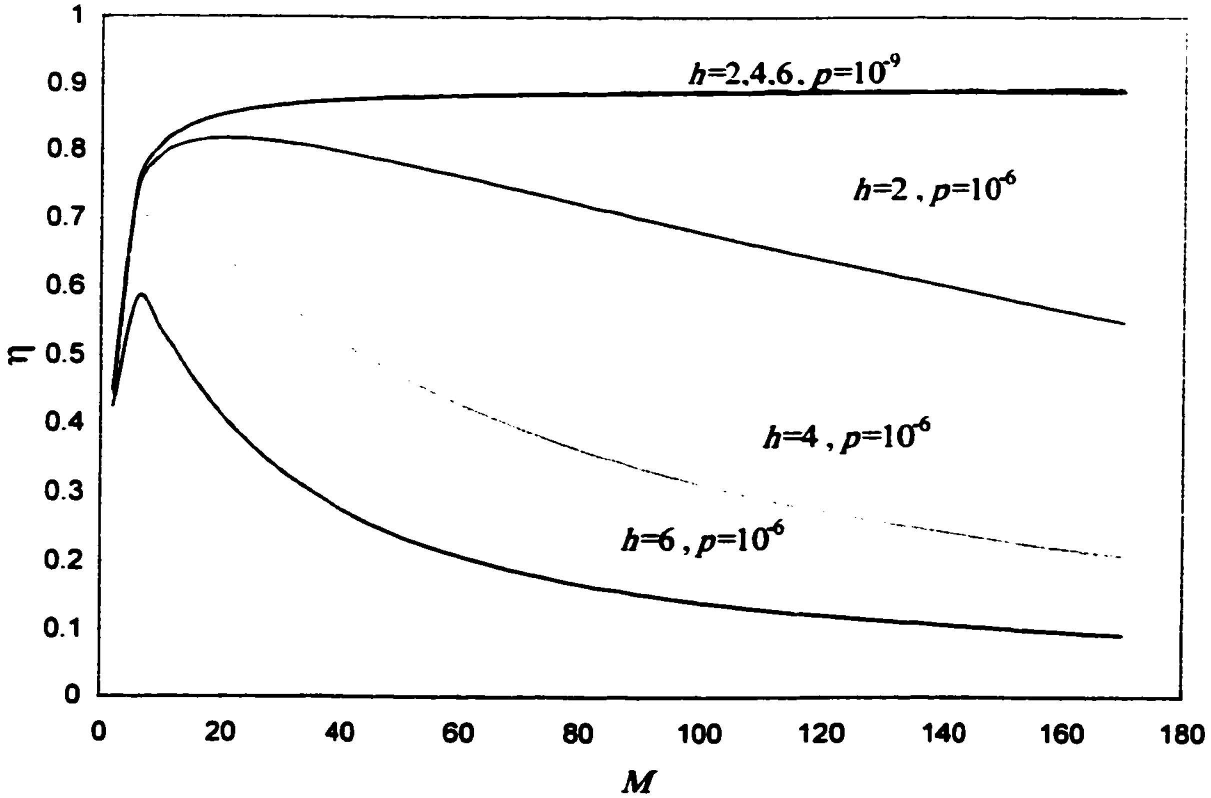


Figure 10: Studying the effect of the number of hops on the design of M(α= 0.5).

The number of hops h affects the throughput through the probability B_R, (as well as the delay a, but to a much lesser degree) and therefore influences the design of M. But, again, for good channels this effect is negligible, and the throughput curves are flat over the range of large M. The throughput starts to become sensitive to an increase in h for worse channels ($p=10^{-6}$). Again, the sensitivity of the throughput to M increases with increasing h, see Figure (10).

The effect of r on the design of M is illustrated in Figure (11). Two networks with the same parameters except r have the same post-decoding probabilities.

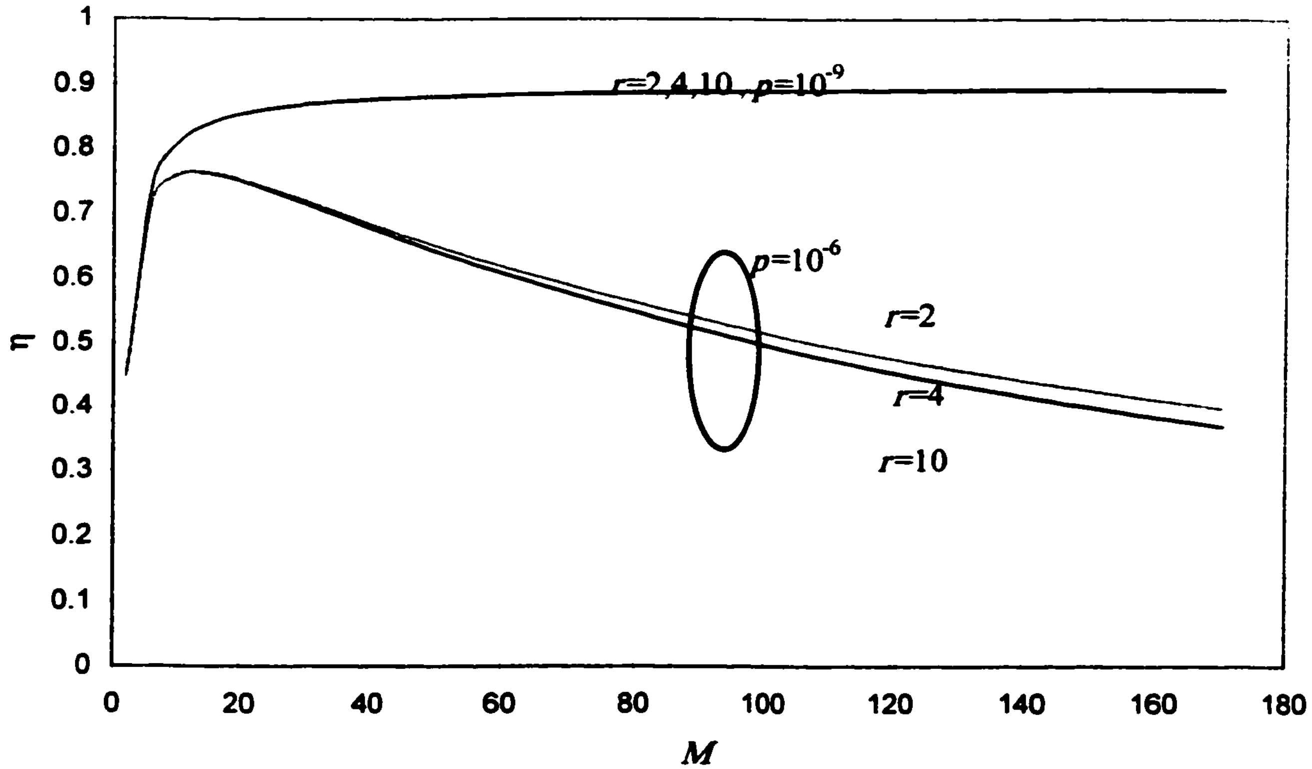


Figure 11: Studying the effect of the number of cells per packet on the design of *M*. ($\rho = 0.5$)

However, the system with longer TPDU packets is subject to more transmission errors, and thus more retransmissions. As a result, increasing r results in decreasing η. (It should be noted that this is valid in our case because the amount of redundancy we are assuming at the PTDU level (32 bits per packet) is negligible. If more overhead is considered then there will be an optimum value of r). Since increasing M increases the post-decoding cell loss probability, the throughput is more sensitive to increasing M at large values of r. However, it is interesting to note that the curves for different r but the same p are identical before reaching the peak. This is so because at such small values of M the probability of having more than one lost cell in a column is very small. As a result, the cell recovery table performs equally well. Consequently the value of M which achieves the highest throughput, call it M^* is not sensitive to r, and all curves reach their peaks at $M^* = 14$.

Figure (7-12) shows the throughput versus M for three values of the τ, namely 10^{-5}, 10^{-3}, and 10^{-1} seconds. The figure helps in finding the best value of M.

Figures 7-12 are obtained for Case 1 (i.e. both data and header are protected). Similar plots were obtained for Case 0. It was found that the dependency of the throughput on M for different p, r, h, is less sensitive for Case 0, see for example Figure (7-13). However, the sensitivity to M at different delays is the same, see Figure (7-14).

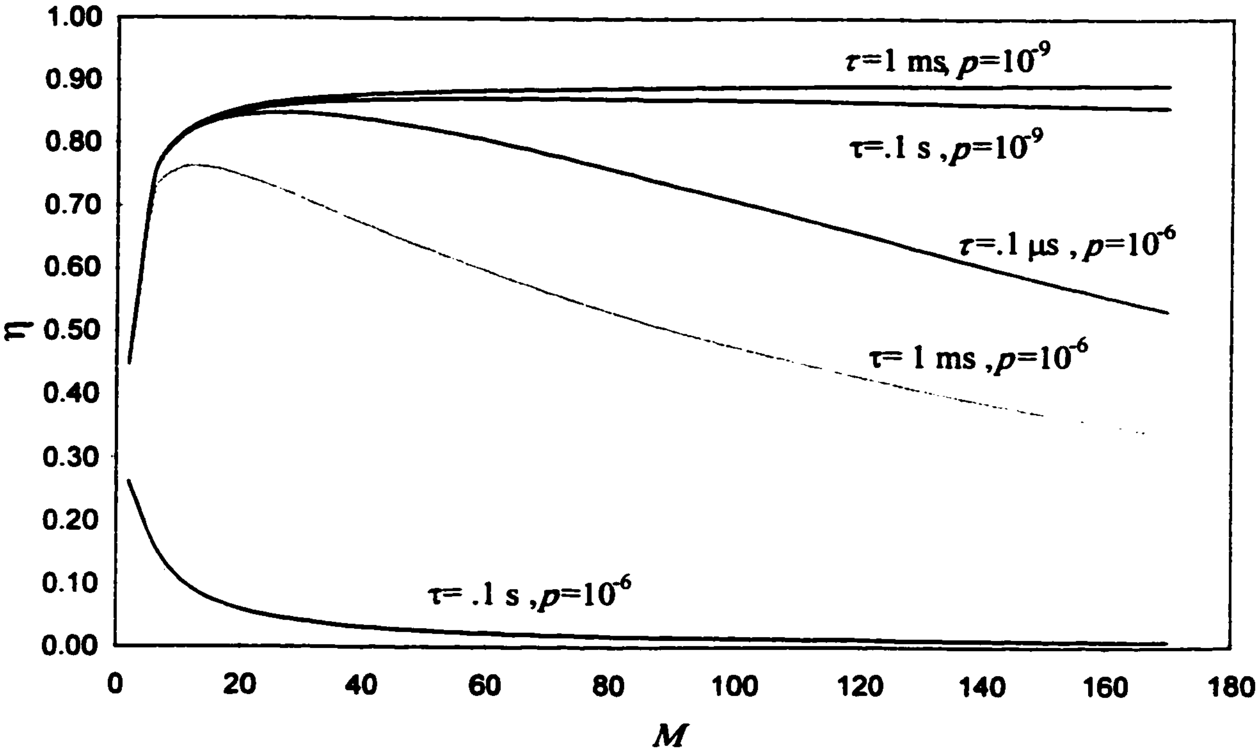


Figure 12: Studying the effect of the propagation delay on the design of M. ($\rho = 0.5$)

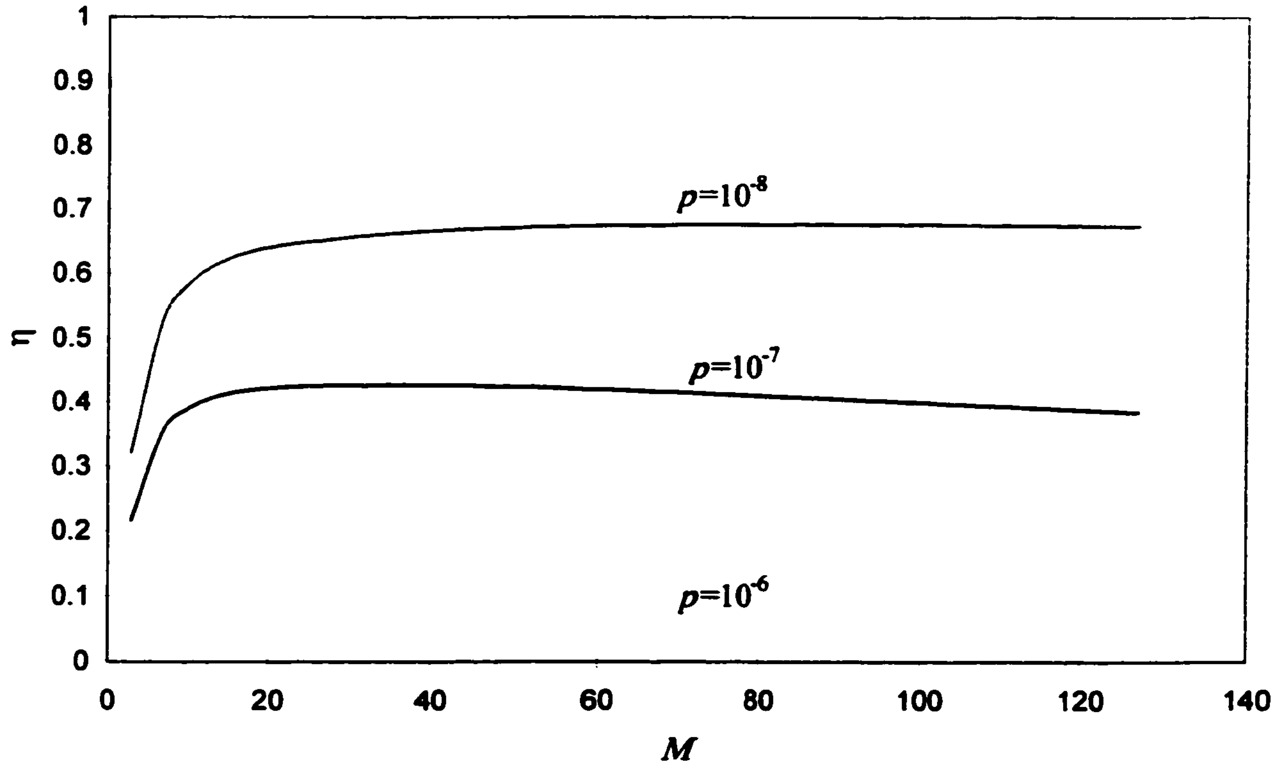


Figure 13: Studying the sensitivity of the throughput to M when the payload is not checked, for different channel BERs.

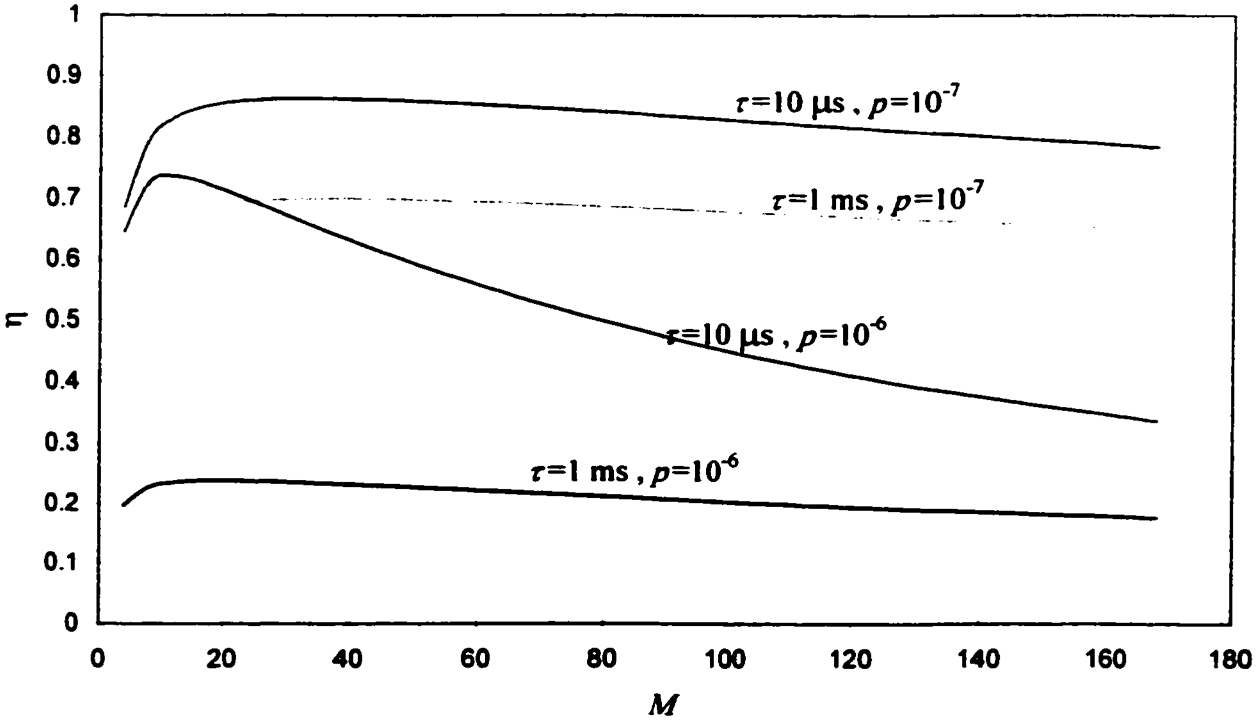


Figure 14: Studying the sensitivity of the throughput to M when the payload is not checked, for different propagation delays.

To illustrate how the cell recovery table should be designed, taking all network parameters into account, we will consider different networks. The design will be based on worst case assumptions, in particular: the worst link BER ($p_{\max}$), the maximum number of hops between any two communicating parties, ($h_{\max}$) and the longest propagation delay per link ($\tau_{\max}$). The other parameters are assumed identical. The following networks are considered:

Network 1: $p_{\max} = 10^{-7}$, $h_{\max} = 6$, $\tau_{\max} = 1$ms.

Network 2: $p_{\max} = 10^{-6}$, $h_{\max} = 2$, $\tau_{\max} = 1$ms.

Network 3: $p_{\max} = 10^{-6}$, $h_{\max} = 6$, $\tau_{\max} = .1$ μs.

Network 4: $p_{\max} = 10^{-6}$, $h_{\max} = 6$, $\tau_{\max} = 1$ms.

Figure (7-15) shows the throughput for these selected networks. The optimum values of *M* are 35, 22, 18 and 7, and the maximum throughput achieved is: .85, .82, .81 and .58 respectively.

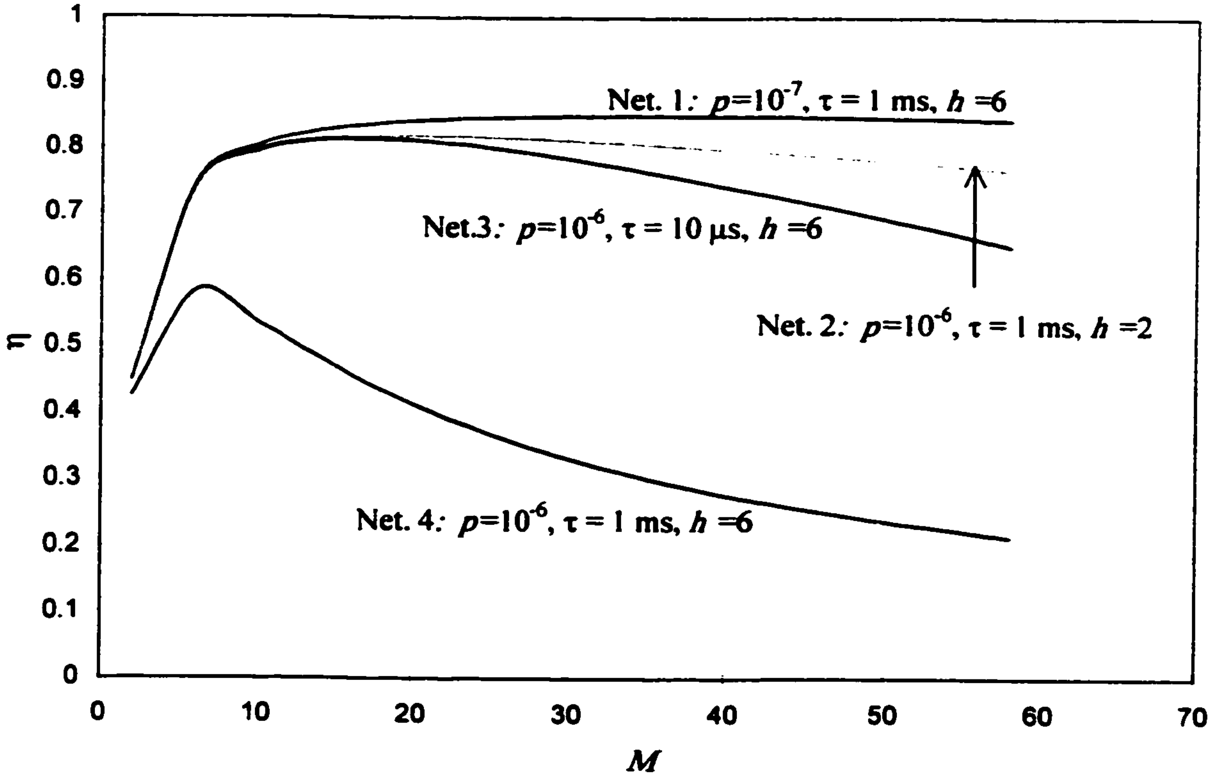


Figure 15: Study cases.

In a word, from the analysis, we can see:

Since the BER (p_{max} =10^{-6} normally is the worse case for telecommunication), our hop can not be too many. It depends on the networks or say customer requirement such as τ_{max} and p_{max}. The figure 15 shows the one channel limitation situation.

We analysis our table the Number of M and N we could get the best economic BER. From the analysis, we found the value N=16 is the most appropriate one to use. The number of M depends on p, h, τ, and r, depends on customers requirement of networks.

From equation 18, in order to get less loss probability, we chose one channel.

5 Conclusion

5.1 Thesis Summary

In Chapter 1, we give a brief overview of ATM and its role in Broadband Integrated Service Digital Networks (B_ISDN). Then, we provide ATM traffic classes which are class A, class B, class C, and class D. Then we introduce ATM traffic class D connectionless service and the connectionless server (CLS) approach, Local Area Network Technology (LAN) brief introduction, MAC concept. The AAL-3/4 protocol Error-Detection Mechanisms are presented.

In Chapter 2, we discussed the ATM standard. We provide ATM cell structure and ATM cell head. The ATM cell head consists five fields virtual path identifier (VPI), virtual channel identifier (VCI), payload type (PT), reserved field (Res), cell loss priority (CLP), and header error check (HEC), and the each value of the field is given. The B_ISDN and ATM reference model, ATM adaptation, ATM and Physical layers are given. Then, the AAL 1, AAL2, AAL3/4, AAL5 and AAL3/4 versus AAL5 are described. Lastly, we brief introduce the ATM networks management, connectionless service in ATM network and ATM end-to-end network.

We presented Wireless ATM and associated FEC techniques in Chapter3. We start presenting Wireless ATM (WATM) network, then we introduce error control schemes for networks, packet transmitting methods, finally we present the error control for wireless ATM.

Chapter 4 contains the performance analysis and simulation of a hybrid multilayer Error Control Technique for multihop ATM networks. The first, we present the description of the LAN/ATM interconnection, then we do the performance analysis, finally we do the simulation on: Effect of payload checking on system performance for delay-sensitive;Traffic (no ARQ; The effect of traffic intensity on the throughput; The effect of checking the payload on the throughput for two values of traffic intensity; the effect of channel BER on the design of M ($\rho=0.5$) ; The effect of the number of hops on the design of M ($\rho=0.5$); the effect of the number of cells per packet on the design of M. ($\rho\overset{-}{=}5$); the effect of the propagation delay on the design of M. ($\rho\overset{-}{=}5$); the sensitivity of the throughput to M, when the payload is not checked for different channel BERs; the sensitivity of the throughput to M when the payload is not checked for different propagation delays.

5.2 Conclusions

In this thesis, we presented Wireless ATM and FEC association. A complete analysis of the error performance of a multihop ATM network is provided. Error detection is performed after each hop, while cell recovery and request for retransmission are performed at the terminating ATM node. Both options of checking the cell header and the payload and checking the cell header only were considered. It was seen that the cell recovery table, although very simple, is very efficient in recovering lost cells. For good channels ($p<10^{-7}$), and when an ARQ scheme is invoked, there is no need to check the payload. However checking the payload pays off the cost of redundancy very effectively at higher BER. On the other hand, for delay sensitive traffic where retransmissions are not allowed, it is always recommended to check the payload.

The intrinsic traffic intensity may have a severe effect on η even for very good channels. Increasing the queue buffer size helps the network to withstand higher intrinsic intensities, at the cost of increased queuing delay.

Our main emphasis was on designing the cell recovery table. The size of the table affects the throughput in contrary aspects. For example, when the size of the table is increased:

(a) the factor α is increased (η improving),

(b) the probability B_R is increased (η deteriorating), and

(c) and the overall delay a is increased (η deteriorating).

The design is aimed towards finding the optimum size for a given network. As for N (the number of columns), the value N=16 was found to be the most appropriate one to use. The optimum value of M (number of rows) depends on p, h, t and r with different degrees, and therefore has to be designed carefully for a given network parameters. The work of thesis presented detailed analysis on the effect of these parameters on the table size.

As for the effect of checking the payload on the design of the table, it was found that since in Case 1 a cell is dropped if either the header or data are wrong, the cell loss probability is increased at a faster rate with increasing M compared to Case 0, where only the header is detected. As a result, the dependency of the throughput on M for different p, r, h, is less sensitive for Case 0.

Design curves and study cases were demonstrated for different networks.

APPENDIX A

Burst (correlated) cell loss and/or errors are not so uncommon in terrestrial or Wireless ATM networks, due to buffer overflow, congestion, processing bottlenecks, channel fading, multipath and deep wells (Wireless Networks). Gilberet models [13], [14] has been used to analyze their effects. Figure A.1., shows the two states of this model, G, denoting Good and B denoting Bad. In the G state, no cell loss takes place, in the B state, cell loss takes place. The cell loss probabilities Vi+1, Vi, in 2 neighboring cells in same column of the FEC table, spaced by N cells on the transmission channels (due to burst cell loss), are related by:

$$\begin{bmatrix} 1-V_{i+1} \\ V_{i+1} \end{bmatrix} = \begin{bmatrix} Q & p \\ P & q \end{bmatrix}^N \cdot \begin{bmatrix} 1-V_i \\ V_i \end{bmatrix} \qquad \text{(A-1)}$$

Where Q, p, P, q are the transition probabilities in Fig (A-1). The average cell loss rate is given by

$$\overline{P_l} = \frac{P}{P+p} \qquad \text{(A-2)}$$

denoting

$$\begin{bmatrix} Q & p \\ P & q \end{bmatrix}^N = \begin{bmatrix} Q_N & p_N \\ P_N & q_N \end{bmatrix} \qquad \text{(A-3)}$$

The probability of one cell loss in a typical column of the table under the burst (corrected) errors above given by:

$$x_1' = \overline{P_l} \cdot p_N \cdot P_N{}^{M-2} + (1 - P_l) \cdot P_N \cdot p_N \cdot Q_N{}^{M-3} \cdot (M-2) + (1 - \overline{P}) \cdot p_N \cdot Q_N{}^{M-2} \qquad \text{(A-4)}$$

The improved cell loss probability now follows,

$$E_1' = \overline{P_l} - x_1/M \qquad \text{(A-5)}$$

Which resembles E_l of equation (7) that was based on random independent (not correlated burst losses/errors). On the other hand, for the event of having at least one cell loss per column (E_2 of equation (8) for the independent error case and E_2' for the correlated errors case) one may write: $E_2' = E_2$ (since the table can recover from only one cell loss per column!)

The reader may check that equations (9)-(18) mainly depend on E_1, E_2 (for random errors) and E_1', E_2' (for correlated errors).

Since, $E_2' = E_2$ the performance under correlated (burst) losses/errors will be approximated by the independent errors case iff $E_1' \geq E_1$.

However from (7) it follows, $E_1 = \overline{P_l} - x_1/M$ (A-7)

Where $x_1 = M\overline{P_l}(1 - \overline{P_l})^{M-1}$ (A-8)

For all practical values of P_l and M and for burst errors, references [3], [4] compute for many cases of N, M, q the improvements $E_1' / \overline{P_l}$ and E_1' respectively.

Table A.1 shows a sample of their results from which we obtain x_1' while x_1 is computed from (A-8). The table clearly shows that $x_1 \approx x_1'$ hence $E_1 \approx E_1'$ and the performances under random and burst errors/losses are very close. Several tables for different values of q, N, M, P_l have confirmed this observation (Not shown for space considerations).

This is not very strange, it is well known from FEC theory that the use of interleaving tables of sufficient depth would break long bursts of channel bit errors and bring them down to the same error level as that of random channel errors.

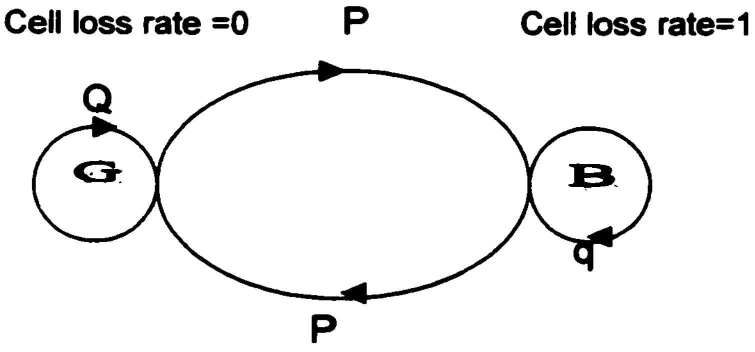


Fig. A.1. The two state Gilbert Model

Table A.1.A sample of the comparison of x_i, x_i' of the random and burst errors models.

$$N = 16, M - 20, q - 0.1, 0.2$$

$\overline{P}_i$	10^{12}	10^{11}	10^{10}	10^{9}	10^{8}	10^{7}	10^{-6}	10^{-5}	10^{-1}
x_i	2×10^{11}	2×10^{10}	2×10^{9}	2×10^{8}	2×10^{7}	2×10^{6}	2×10^{5}	2×10^{4}	2×10^{3}
x_i'	2×10^{11}	2×10^{10}	2×10^{9}	2×10^{8}	2×10^{7}	2×10^{6}	2×10^{-5}	$1.99E - 4$	$1.95E - 3$

APPENDIX B

Calculating the Undetected Error Probability of CRC codes

Many communication systems employ error detection to insure a high reliability of the transmitted data. A code of minimum distance *d* can detect all error patterns of *d*-1 or fewer errors. Assume we are using a CRC extended Hamming code. Such a code has a minimum distance of four, therefore at least four bit errors must occur before the CRC fails to detect an error, that is the probability, P_u, of undetected error

$$P_u \leq \sum_{i=d}^{n} \binom{n}{i} p^i (1-p)^{n-i} \tag{B-1}$$

This, however, is much below the actual capability of the code (which explains the inequality sign). In fact, the decoder would be able to detect the errors as long as they don't transform the transmitted codeword to another valid codeword. For example, the (2047, 2035) CRC-12 code (generated by $g(X) = X^{12} + X^{11} + X^3 + X^2 + X + 1$) will detect all errors of weight less than 4 (the minimum distance of the code is 4), all errors of odd weight, all bursts of length less than 12, 99.9% of all bursts of length 12, and 99.5% of all bursts greater than 12 [20]. This information is deduced from the weight distribution of the code.

For that reason the undetected error probability, P_u, is a function of the weight distribution of the code and is given by

$$P_u = \sum_{i=d}^{n} A_i p^i (1-p)^{n-i} \tag{B-2}$$

where A_i is the number of codewords of weight *i*, and *p* is the bit error probability of a BSC with random errors.

Unfortunately, the weight distribution is not known for most codes. Even when they can be obtained by exhaustive search it may be easier to analyze the system using some good bounds for the undetected error probability.

For the case $p=1/2$, Equation (1) yields $P_u(1/2) = (2^k - 1)/2^n \cong 2^{-(n-k)}$.

It may appear that the above assumption (p = 1/2) is the worst case, therefore the undetected error probability may be upper bounded by:

$$P_u \leq 2^{-(n-k)} \tag{B-3}$$

This is only true if the undetected error probability is a monotonically increasing function in p for $0<p<1/2$. A code for which this is not the case is termed an improper code. [21] gave the necessary conditions for the undetected error probability to be upper bounded by (3) , while [22] provided a family of tests for improper codes.

Cyclic Redundancy Codes (CRC) form a powerful class of error detection codes. It was shown that the most commonly used CRC codes are improper codes. Fortunately, the results in [23] show that the impropriety of these codes appears only at $p>10^{-2}$. CRC codes are generally operated on low-noise channels where the channel bit error rate is much smaller than 10^{-2} and, therefore, the above bound is safely a worst-case assumption.

The bound in (3) attracts many researchers. In addition to its simplicity, it is not a function of the code length neither the channel condition. However the bound becomes very loose (by many orders of magnitude) for short codes and/or good channels. For example consider the (512, 496) and the (32,16) CRC-16 codes. Using inequality (3), the undetected error probability is upper bounded by $2^{-16} \cong 10^{-6}$. Simulation shows that at $p=10^{-3}$ the undetected error probabilities for the two codes are approximately 10^{-8} and 10^{-11}, and at $p=10^{-4}$ the undetected error probabilities are in the range of 10^{-11} and 10^{-15}. This bound will be particularly useful when the number of check digits is large, say 30, in which case the undetected error probability would be negligible.

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