# A Hybrid Multilayer Error Control Technique for Multihop ATM Networks

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**Abstract**

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

The error detection and correction techniques above are applied to connectionless oriented traffic. The hierarchy of the error control technique above is presented and the end-to-end user performance in terms of net throughput and reliability is analyzed. 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.

## 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) [1]-[2]. Error detection and/or correction for ATM networks attracted great attention. In [3]-[6], the end-to-end use of an error correction table was investigated, while [7] 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, as in [3].

The system is described in more details in Section 2, whereas performance analysis is furnished in Section 3. Results are presented and discussed in Section 4. Section 5 concludes with observations and remarks.

## 2. The Multilayer Error Control Scheme

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.

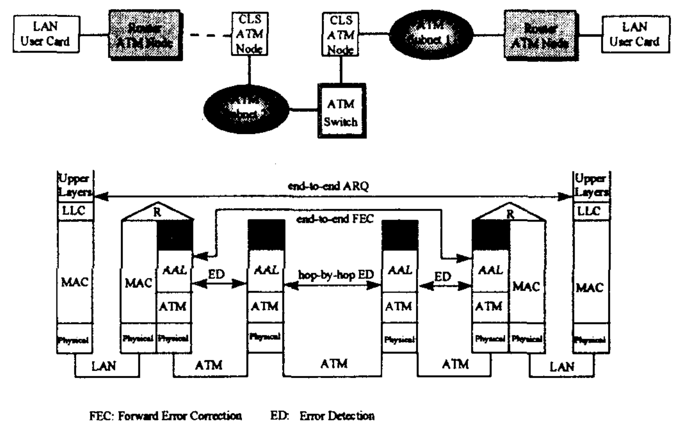


**Fig. 1.** Location of the various error detection and correctiom mechanism in the LAN/ATM interconnection (The shaded areas exist only in CL or CLS ATM nodes, not CO ATM nodes)

In ATM systems [2], the AAL (3/4) layer handles both connection oriented (class C) as well as connectionless oriented (class D) traffic. 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. It is this latter case that will be emphasized in this paper, i.e. we assume that both the LAN and the ATM hops are connectionless.

The multilayer error control scheme that will be analyzed consists of combined end-to-end error concealment and hop-by-hop error detection techniques. On the top of that Automatic Repeat reQuest (ARQ) scheme is utilized at the transport layer, as illustrated in Fig. (1).

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 8, are normally used to protect the cell header only. However, by using more CRC bits one can also checks (protects) the payload. In this paper both cases will be examined. 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).

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. (2.a) shows the structure of the table used for detection and recovery of lost cells. Data cells are arranged in $M$-1 rows and

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$N$-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. The format of each type of cells in the table is sketched in Figure (3.b,c,d,e). Once the table is completed, its constituting cells are transmitted row by row.

The table decoding operates as follows. At the receiving ATM node, the $M \times N$ 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 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 erronous cells.

## 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.

We start by looking at the outcomes due to the ATM cell process at the $h$ intermediate ATM nodes, including the destination node, on the virtual path VP. At these nodes, only error detection and possible cell dropping takes place. This cell dropping adds to the cell dropping due to the buffer overflow.

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

$f_i$ = probability of cell loss due to buffer overflow in node number $i$,

$p_i$ = bit error probability on the physical link terminated at the $i^{th}$ node,

$n$ = number of bits of the payload,

$n'$ = number of bits of the header,

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

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 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 link and the CRC code employed. When no CRC coding is applied to the payload, then

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

The probability that the cell is lost due to buffer overflow and/or appropriate dropping by CRC is given by:

$$P_{l,i} = 1 - P_{c,i} - P_{e,i} \tag{3}$$

For a cell traversing the $h$ ATM nodes enroute to destination the overall probabilities at the destination node can be written as:

$$\overline{P}_c = P_c^h \tag{4}$$

$$\overline{P}_e = \sum_{j=1}^{h} \binom{h}{j} P_e^j P_c^{h-j} \tag{5}$$

$$\overline{P}_l = 1 - \overline{P}_c - \overline{P}_r \tag{6}$$

In deriving (4)-(6) it was assumed that all links of the VP are identical on the average, i.e. have the same bit error probability $p$, an thus the subscript $i$ was dropped. Furthermore, the independence of all events was assumed.

Next we evaluate the above probabilities for cell after performing table decoding. Let's first consider the recovery of the lost data cells or 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 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 only one CLD lost cell, in which case the unrecoverable cell loss probability is given by (7). However, If there is more than one lost CLD cell, the decoder does not attempt any recovery operations, and the whole table of data cells is immediately delivered to the upper ARQ layer. Therefore, the probability of lost data cell for this scenario is given by:

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

In each 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

$M(N-1)/MN$ and $M/MN$. The cell loss probability in (7) takes place when the lost cells are confined to the data section, or when 0 or 1 CLD is lost, whereas the cell loss probability in (8) takes place when two or more CLD cells are lost. This translates to the following overall average cell loss probability

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

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,

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

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

$$B_R = 1 - B_C - B_E \qquad (12.c)$$

Where ($n^*$-$k^*$) is the number of check digits for the ARQ system. 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 overall probability of delivery error, **P**, and the net throughput, $\eta$, of the Go-Back-N ARQ are given by [8 ]:

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

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

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

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

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

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

where $\tau$ 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 traffic intensity be $\rho_0$. This traffic intensity is magnified by (possibly) the CRC of the payload, the parity cells of the table and the ARQ retransmissions. Since all these factors are accounted for in $\eta$, the inflated traffic intensity $\rho$ is given by:

$$\rho = \rho_0 \times \eta \qquad (17)$$

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

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

### 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, $\tau$ = 1 msec. Unless stated otherwise, the above values are assumed.

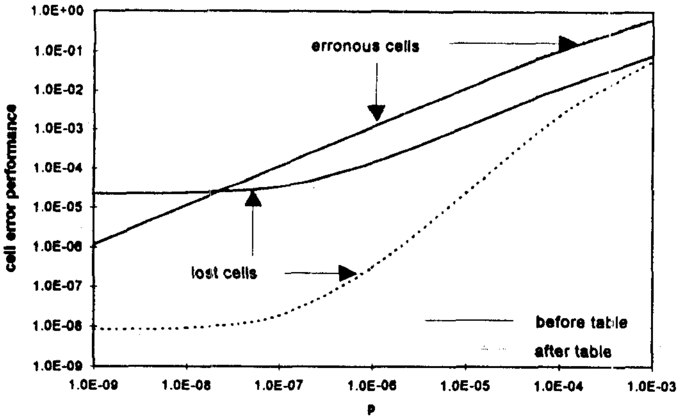


Figure 3: Performance of the cell recovery Table

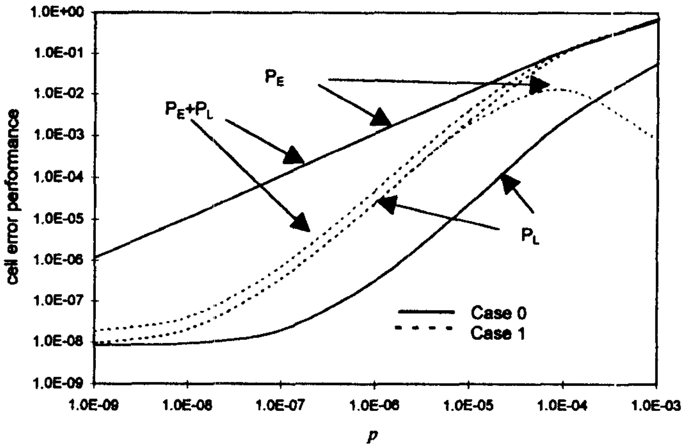


Figure (4) Effect of payload checking on sytem performance for delay-sensitive traffic (no ARQ)

Figure (3) 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 are correct, yielding essentially the same probability of error after decoding.

Figure (4) 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 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. $P_E + P_L$ ) is significantly reduced. The cost of this improvement is a slight reduction in the throughput due to the 10 CRC bits/cell.

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 erronous 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.

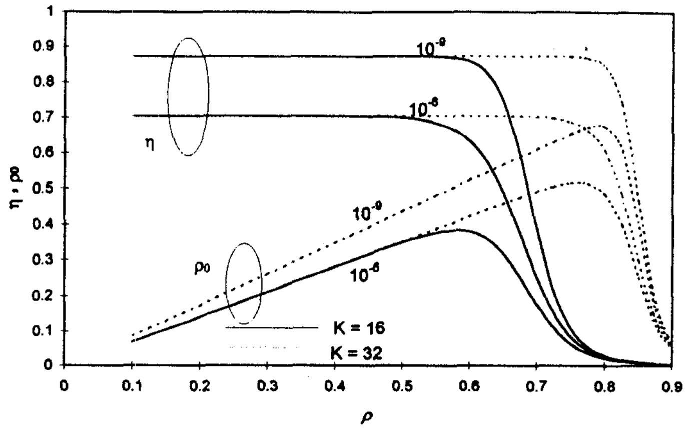


Figure 5 The effect of traffic intensity on the throughput:

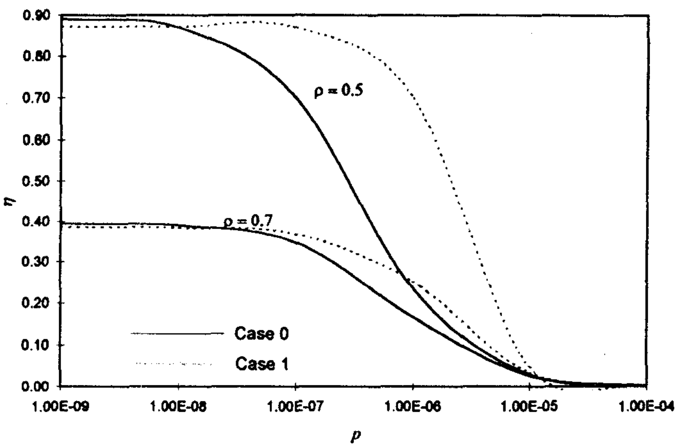


Figure 6: The effect of checking the payload on the throughput for two values of traffic intensity.

Figure (5) investigates the relation between the total traffic intensity $\rho$, the throughput, and the intrinsic intensity $\rho_0$. The linear, monotonically increasing part of the $\rho_0$-vs-$\rho$ curve in Figure 3 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, $\rho$ 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 $\eta$ is directly reflected on $\rho_0$. The value of $\rho$ at which the $\rho_0$-vs-$\rho$ curve assumes its maximum, call it $\rho^*$, is the breakpoint between a light network (to the left of $\rho^*$ ) and a congested network (to the right of $\rho^*$ ). The corresponding value of $\rho_0$, call it $\rho_{0,max}$, 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.

We next examine the cons and pros of checking the payload. Figure (6) 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. The figure shows that the merit of Case 1 over Case 0 diminishes for congested networks ($\rho > \rho^*$).

Now we present some results concerning the design of the cell recovery table. 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, ..). The size of the table affects the throughput in contrary aspects. Referring to Equation (14), when the size of the table is increased: (i) the factor α is increased ($\eta$ improving), (ii) the probability $B_R$ is increased ($\eta$ deteriorating), and (iii) the overall delay $a$ is increased ($\eta$ deteriorating).

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 $\eta$ (through decreasing α ) equals to, and in many situations overcomes, its effect on increasing $\eta$ (through decreasing $a$). For these reasons, $N$ was fixed to 16.

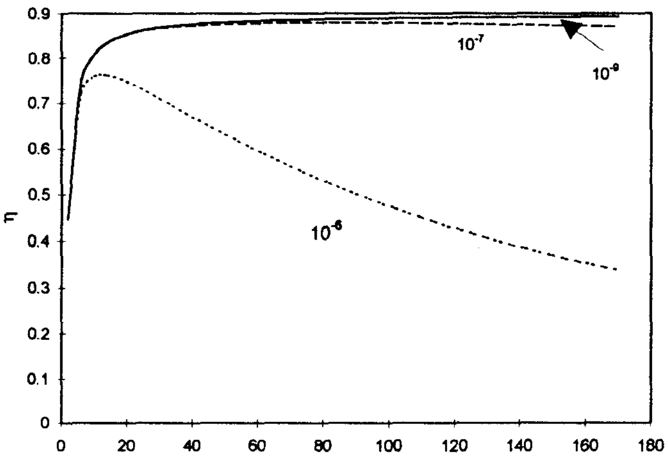


Figure 7: Studying the effect of the channel BER on the design of

On the other hand, the choice of $M$ will depend on the network parameters. To see the effect of $p$ on $M$, Figure (7) shows 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 (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.

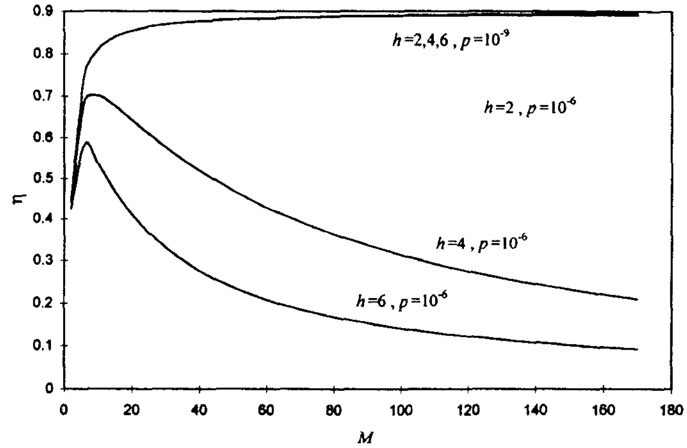


Figure 8: Studying the effect of the number of hops on the design of M.

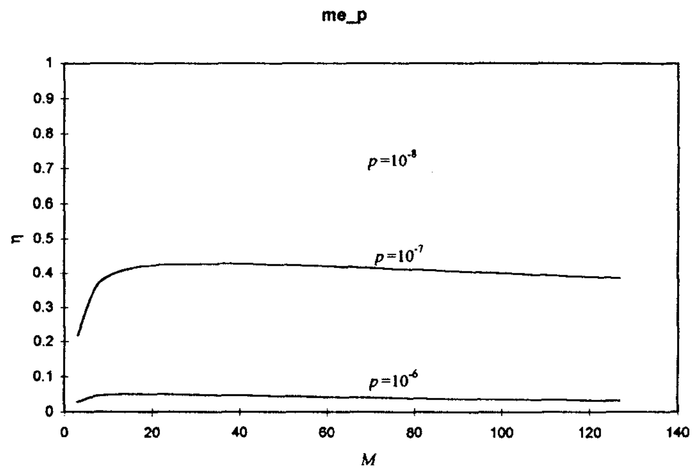


Figure 9: Studying the sensitivity of the throughput to M when the payload is not checked, for different channel BERs.

The effect of the number of hops $h$ on the choice of $M$ is studied in Figure (8). Once again this effect is negligible for good channels provided $M$ is sufficiently large. The throughput starts to become sensitive to an increase in $h$ for worse channels ($p=10^{-6}$). The sensitivity of the throughput to $M$ increases with increasing $h$. The effect of the propagation delay τ and the number of cells per packet $r$ was found to be very similar to that of $h$.

Figures 5-8 belong to Case 1 (i.e. both payload 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 (9).

## 5. Conclusion

In this paper we presented a complete analysis of the error performance of a multihop ATM network. Error detection is performed after each hop, while cell recovery and request for retransmission are performed at the terminating ATM node. 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 main emphasis was on designing the cell recovery table. The design was aimed towards finding the optimum size for a given network. As for $N$ , the value $N$=16 was found to be the most appropriate one to use. The optimum value of $M$ depends on $p$, $h$, $\tau$ and $r$ with different degrees, and therefore has to be designed carefully for a given network parameters.


### Acknowledgment:

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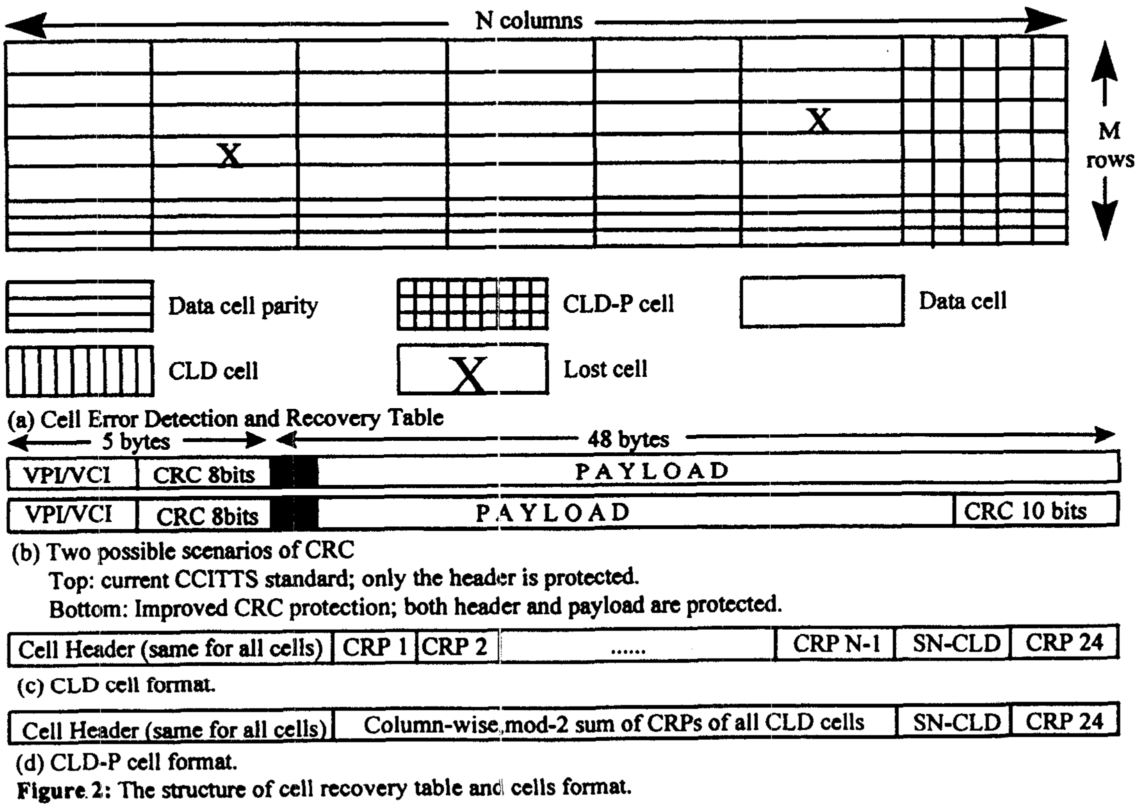


**Figure 2:** The structure of cell recovery table and cells format.