Performance Analysis of the UPC/NPC Algorithm for Guaranteed QoS in ATM Networks

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CONTENTS

ABSTRACT

It is well known that if usage parameter control/network parameter control (UPC/NPC) functions are used together with a cell loss priority control scheme in ATM networks, the measurement phasing problem can occur. This makes it difficult for a network provider to define and commit the cell loss ratio as a QoS parameter. To solve the problem, we propose a new UPC/NPC algorithm. By using the proposed UPC/NPC algorithm, we can define the cell loss ratios for CLP = 0 and CLP = 0+1 cell streams without the measurement phasing problem under any conditions. We analyzed the performance of the proposed UPC/NPC algorithm. Using a discrete time model for the UPC/NPC architecture with a discrete-time semi-Markov process (DSMP) input model, we obtained the cell discarding probabilities of CLP = 0 and CLP = 0+1 cell streams and showed that more CLP = 0 cells are accepted compared to what was proposed in ITU–T.

I. INTRODUCTION

In ATM networks, the UPC/NPC function is a set of algorithms taken by the network to monitor and control a traffic contract in terms of input traffic at the user network interface or the network node interface. The cell loss ratio, which is one of the QoS parameters specified by the user in a traffic contract, may depend on the mechanism implemented in the UPC/NPC. If two UPC/NPC algorithms are not equivalent with respect to cell discarding/tagging for a given traffic configuration, a common understanding about legality between the user and the network operator does not exist. For example, cell discarding/tagging in the UPC/NPC may be caused by excess traffic transmitted by the user to the network or by a malfunction of the UPC/NPC.

To solve this legality problem, the concept of cell conformance was developed, and the peak cell rate reference algorithm was defined for the peak cell rate conformance test by ITU–T [1]. The peak cell rate reference algorithm is a virtual scheduling algorithm or a continuous state leaky bucket algorithm as shown in the flowchart of Fig. 1 in the annex to ITU Recommendation I.371. The two algorithms are equivalent in the sense that, for a given cell arrival pattern, they determine the same cells in conformance. The peak cell rate reference algorithm was generalized to a generic cell rate reference algorithm to include other

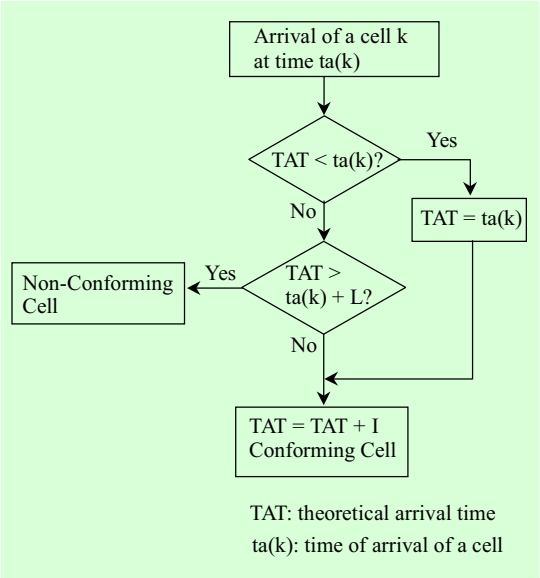

Fig. 1. Virtual scheduling algorithm for cell conformance test.

traffic parameters such as the sustainable cell rate and the burst tolerance within the ATM Forum [2]. The primary goal of the conformance test is to compute the number of cells which are non-conforming with respect to the traffic characteristics specified in the traffic contract for a connection. The number of non-conforming cells is used to calculate the cell loss ratio.

The ITU–T introduced the cell loss priority (CLP) bit in the ATM cell header to discriminate between high priority (CLP = 0) and low priority (CLP = 1) cells. This bit can be used for cell loss priority control schemes for efficient resource management [3]-[4]. The CLP bit allows for two cell loss ratio objectives in a given ATM connection. This is done by means

of a set of traffic parameters associated with the CLP = 0 cell substream and a set of traffic parameters associated with the CLP = 0+1 cell stream [1].[1] Therefore, in a traffic contract, the user can declare the peak cell rates (PCRs) and the cell loss ratios for each CLP = 0 cell substream and the aggregate CLP = 0+1 cell stream. A CLP = 0 cell is considered to be conformed by the UPC/NPC if it conforms both to the CLP = 0 conformance test performed on a CLP = 0 cell substream and to the CLP = 0+1 conformance test performed on a CLP = 0+1 aggregate cell stream. A CLP = 1 cell does not undergo the CLP = 0 conformance test. A CLP = 1 cell is considered to be conformed by the UPC/NPC only if it conforms to the CLP = 0+1 conformance test performed on the CLP = 0+1 cell stream. When two conformance tests are done for CLP = 0 cells, the two tests are coordinated in such a way that the states of the conformance tests are updated if and only if a cell conforms to both tests. The long-term ratio of ATM cells conforming to both tests to all transmitted cells can be used to characterize the commitment of the network regarding the delivered cell loss ratio of the cell stream.[2]

When a fraction of user cells is nonconforming to the CLP = 0+1 cell conformance test, the measurement phasing problem can occur [5]-[7]. The problem arises when two identical conformance test algorithms which started at two different instants give different long-term ratios of nonconforming cells. This makes it difficult for a network to commit the cell loss ratio of an ATM cell stream.

Following the introduction, in Section II, we present the definition of cell conformance and the relationship between cell conformance and the UPC/NPC function. In Section III, We discuss problems in the definition of a cell loss ratio when the measurement phasing problem occurs. In Section IV, we propose a QoS guaranteed UPC/NPC algorithm. By using the algorithm, we show that we can define the cell loss ratio without the measurement phasing problem when the cell loss priority control scheme is used and some cells violate the traffic contract. In Section V, we analyze the proposed UPC/NPC algorithm. Using a discrete time model for the UPC/NPC architecture with a discrete semi-Markov process input model, we obtain the cell discarding probabilities of CLP = 0 and

[1]If a cell loss priority scheme is used as a resource management scheme, the value of CLP bit in the ATM cell header may be 1 or 0 by the significance of the cell. A CLP = 0+1 cell is either a CLP = 0 cell or a CLP = 0 cell. Therefore, a CLP = 0+1 cell stream is the aggregation of CLP = 0 cell substream and CLP = 1 cell substream in a connection.

[2]The long-term ratio means that the number of observed cells is large enough (supposedly infinite), so that the ratio of conforming cells to transmitted cells is independent of the initial conditions and the starting time of conformance testing algorithm.

CLP = 0 + 1 cell streams and show that more CLP = 0 cells are accepted compared to what was proposed in ITU–T. Finally, we make conclusion in Section VI.

II. CELL CONFORMANCE AND UPC/NPC FUNCTION

Traffic parameters which may be subject to control are those included in the source traffic descriptor. Whether all these parameters or a subset are subject to controldepends on CAC and UPC/NPC functions. But the peak cell rate (PCR) has to be controlled for all types of connections. The definition of PCR is given in ITU–T Recommendation I.371 [1] and ATM Forum specification [2].

In ATM networks, the UPC/NPC functions are based on cell conformance, and its basic building block is the generic cell rate reference algorithm (GCRA) [2]. The description of the GCRA as a virtual scheduling algorithm (VSA) is depicted in Fig. 1. The GCRA(I, L) with two parameters, namely the threshold limit L and the size of increment I, maintains a state variable TAT (theoretical arrival time) of an ATM cell. The TAT is updated upon the cell arrival as follows. It is incremented by I upon a cell arrival if it does not exceed a given threshold, L. Otherwise it is left unchanged.

Conformance of the PCR is based on the virtual scheduling algorithm, $VSA(T, \tau)$, where T is the peak emission interval (i.e., the inverse of PCR) and τ is the cell delay variation tolerance. The cell delay variation tolerance of a particular connection at the public user network interface represents a bound of cell clumping phenomenon at the interface due to the slotted nature of the ATM, the physical layer overhead, and the ATM layer functions performed within the customer premises network before the public user network interface. The virtual scheduling algorithm is used to provide a formal definition of conformance to a traffic contract in an operational manner.

In the case of CLP = 0 and CLP = 0+1 traffic contract, the basic conformance testing blocks are $VSA(T_0, \tau_0)$ and $VSA(T_{0+1}, \tau_{0+1})$ performed on CLP = 0 and CLP = 0+1 cell streams, respectively. The $VSA(T_0, \tau_0)$ test is performed first on the CLP = 0 cell substream. If the tagging option is not used by a network operator, CLP = 0 cells non-conforming to the $VSA(T_0, \tau_0)$ test are discarded. If the tagging option is used, those cells are converted to CLP = 1 cells and merged with the CLP = 1 cell substream before the CLP = 0+1 traffic flow enters the $VSA(T_{0+1}, \tau_{0+1})$ test. In this case, tagged cells are considered to be CLP = 1 cells. Since cell sequence integrity is maintained on any ATM connection, the UPC/NPC including its optional tagging action must operate as a single server using the first-in first-out service discipline for each ATM

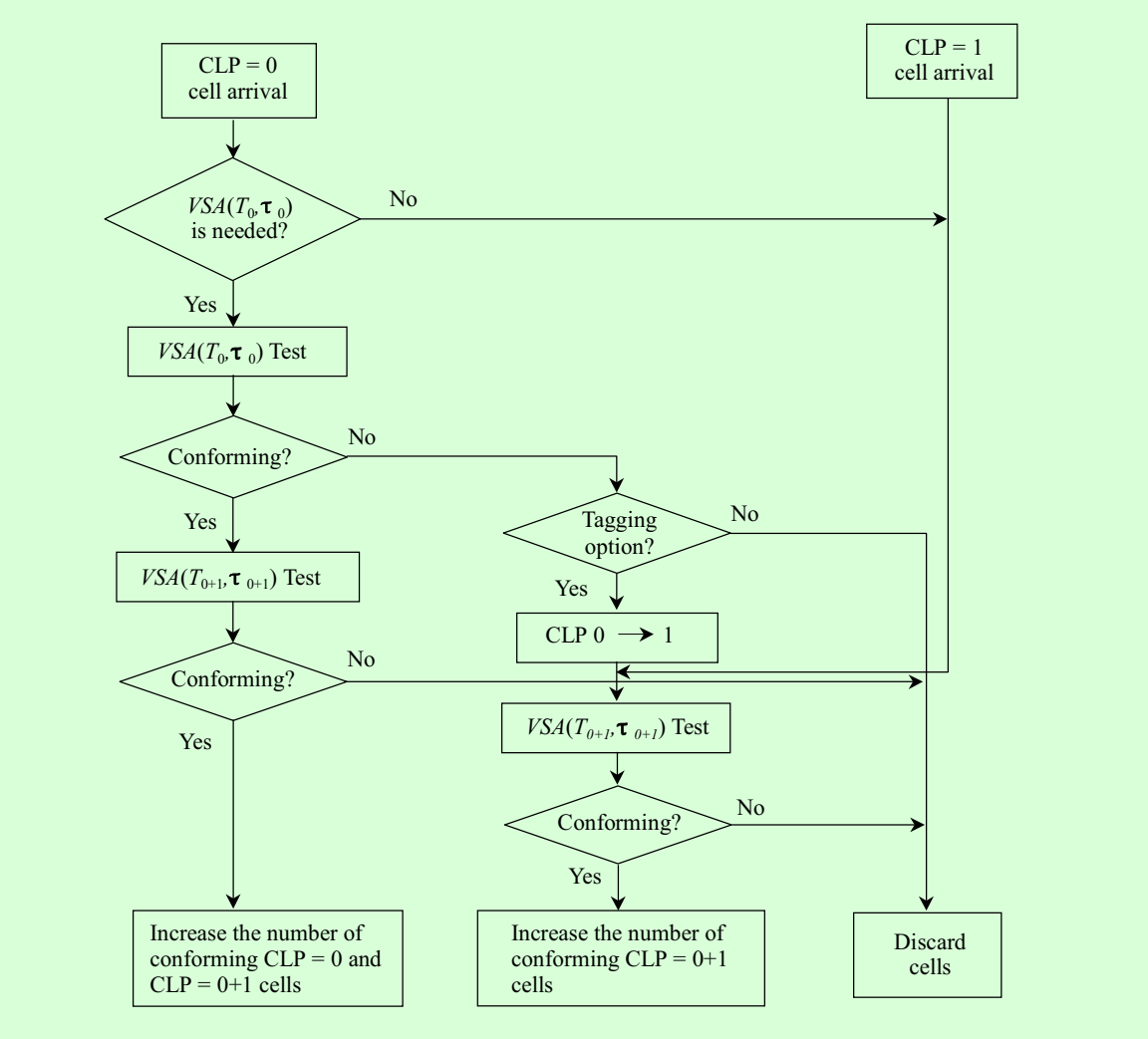

Fig. 2. Possible actions of the UPC/NPC function.

connection.

A CLP = 0 cell is considered to be conformed to the traffic contract by the UPC/NPC function if it passes the $VSA(T_0, \tau_0)$ and $VSA(T_{0+1}, \tau_{0+1})$ tests. A CLP = 1 cell is considered to be conformed only if it passes the $VSA(T_{0+1}, \tau_{0+1})$ test. Possible actions of the UPC/NPC depending on the cell conformance test is shown in Fig. 2.

Although the traffic conformance at the user network interface is defined by the conformance definition based on the virtual scheduling algorithm, the network provider may use any UPC/NPC as long as the operation of UPC/NPC does not violate the

QoS objectives of connections. The conformance definition should not be interpreted as the UPC/NPC algorithm.

III. MEASUREMENT PHASING PROBLEM AND QOS COMMITMENT

1. Measurement Phasing Problem

When a cell loss priority control scheme is used by an ATM connection, and some cells do not conform to the $VSA(T_{0+1}, \tau_{0+1})$ test, the UPC/NPC function performed on the aggregated cell flow may discard CLP = 0 cells which conform to the $VSA(T_0, \tau_0)$ test. In this case, the measurement phasing problem can occur due to the cell-by-cell definition of conformance. Some examples of the measurement phasing problem are shown in [5], [6], [8].

It is shown that there is no measurement phasing problem when the cell loss priority control scheme is not used [8]. The reason for the occurrence of measurement phasing problem is due to the interaction between the $VSA(T_0, \tau_0)$ control and the $VSA(T_{0+1}, \tau_{0+1})$ control. Guillemin *et al.* showed that if these two controls are independent of each other, and if the time structure of the cell stream seen by the second control is not altered by the first control, then no measurement phasing problem can occur [7]. In this case, it is equivalent to the case of a cell conformance test without the cell loss priority control scheme.

2. Definition of QoS Commitment for the Cell Loss Ratio

For a traffic contract in the ATM network, the user specifies traffic parameters and an ATM layer QoS that is requested for connection. If the user transmits only conforming cells, the network commitment applies to all user cells and the cell loss ratio (CLR) is defined as

$$CLR = \frac{N_l}{N}, \tag{1}$$

where N and N_l denote the numbers of transmitted cells and lost cells, respectively. However, some cells may not conform to the traffic parameters that are negotiated. In this case, it is necessary to re-define network commitments.

We define CLR_c as the ratio of the number of cells which are lost by the network in excess of non-conforming cells to the number of cells which conforms to conformance tests. When only a PCR is specified, the network commitment concerning the cell loss ratio is defined in Appendix 1 of I.356 [9]. It is given by

$$CLR_c = \frac{\max(0, N_l - N_{nc})}{N - N_{nc}}, \tag{2}$$

where N_{nc} denotes the number of non-conforming cells. The value of CLR_c is related directly to the way the network meets the negotiated cell loss performance. The quantity $(N - N_{nc})$ is at most equal to the amount of negotiated traffic, and max(0,

$N_l - N_{nc}$) represents the amount of cells which are lost by the network in excess of non-conforming cells.

The definition of CLR_c in (2) reduces to that of CLR in (1) if all cells conform to the traffic contract. The equation (2) may be represented by

$$CLR_c = \frac{max(0, CLR - NCCR)}{1 - NCCR}, \qquad (3)$$

where $NCCR = N_{nc}/N$ denotes the ratio of non-conforming cells to transmitted cells. With this definition, one does not have the measurement phasing problem when only a PCR is specified, since the long-term ratio of non-conforming cells is not dependent on the starting conditions of the conformance testing procedures when the cell loss priority control scheme is not used. It was formally shown that there is no measurement phasing problem when the cell loss priority control scheme is not used [8].

The definition given in (3) is not applicable to connections whose contract specifies the PCR of CLP = 0 cells and the PCR of aggregate CLP = 0+1 cells. For CLP = 0 cells, the $NCCR$ in (3) should be interpreted as the ratio of CLP = 0 cells that are non-conforming to either one of the $VSA(T_0, \tau_0)$ and $VSA(T_{0+1}, \tau_{0+1})$ tests. However, the $NCCR$ does not have a long-term characteristic for the CLP = 0 cell substream due to the measurement phasing problem, and it is not possible to use (3) to define a modified cell loss ratio for CLP = 0 cells. Therefore, it is necessary to define the cell loss ratio when PCRs for CLP = 0 and CLP = 0+1 cell streams are specified.

IV. THE QOS GUARANTEED UPC/NPC ALGORITHM FOR CELL LOSS RATIO

1. QoS Guaranteed UPC/NPC Algorithm

The relationship between the cell conformance tests and the number of admitted cells by the UPC/NPC is shown in Fig. 3. In this figure, the user transmits CLP = 0 and CLP = 1 cells. Let N, A and B be a set of all transmitted CLP = 0+1 cells, that of CLP = 0 cells and CLP = 1 cells, respectively. Also, let A_1 and A_2 be a set of CLP = 0 cells conforming to the $VSA(T_0, \tau_0)$ test and that of non-conforming to the test, respectively. All CLP = 0 cells undergo the $VSA(T_0, \tau_0)$ test first.

If the tagging option is not used by the network, the CLP = 0 cells non-conforming to the $VSA(T_0, \tau_0)$ test, which are in A_2, are discarded. If the tagging option is used, those cells are converted to CLP = 1 cells and merged with the CLP = 1 cells before the CLP = 0+1 traffic flow enters the $VSA(T_{0+1}, \tau_{0+1})$ test. We show the problem in the definition of cell loss ratio of CLP = 0 cells when the tagging option is not used. After the $VSA(T_{0+1}, \tau_{0+1})$ test, the set of

CLP = 0 cells conforming to the traffic contract is named A_3, and the set of CLP = 1 cells B_1. Therefore, the set of conforming CLP = 0+1 cells is $A_3 \cup B_1$. The following relations are satisfied in Fig. 3:

$N = A \cup B$, $A \cap B = \phi$, $A = A_1 \cup A_2$, $A_1 \cap A_2 = \phi$, $B = B_1 \cup B_2$, $B_1 \cap B_2 = \phi$, $A_1 \supseteq A_3$

An important factor for the UPC/NPC function is the number of non-conforming cells needed to compute cell loss ratios. To protect the network and to guarantee the requested QoS of the user, it is desirable that the total number of CLP = 0+1 cells admitted by the UPC/NPC function is the same as the number of CLP = 0+1 cells conforming to the traffic contract (i.e., $A_3 \cup B_1$ in Fig. 3). The amount of CLP = 0 cells admitted by the ideal UPC/NPC function (i.e., A_3) can be changed from 0 to the number of CLP = 0 cells conforming to the $VSA(T_0, \tau_0)$ test (i.e., A_1) depending on the measurement starting point. Therefore, it is impossible to define the cell loss ratio of CLP = 0 cells in the long-term ratio if we use the ideal UPC/NPC function.

The conformance definition does not imply any particular implementation of the UPC/NPC function. The ideal UPC/NPC function which is strictly based on cell conformance may suffer from the measurement phasing problem, when the cell loss priority control scheme is used. In order for a UPC/NPC function not to suffer from the problem, two control functions for CLP = 0 and CLP = 0+1 cell streams must be independent of each other, and the cell stream

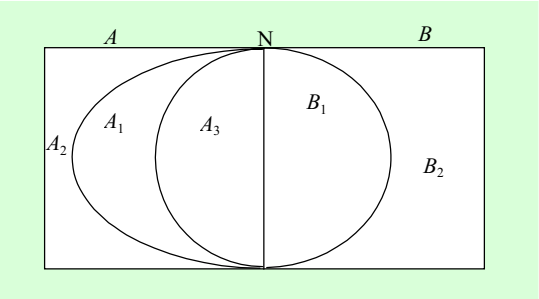

Fig. 3. Relationship between conforming cells and the number of admitted cells.

seen by the CLP = 0 control should not be altered by the CLP = 0+1 control.

In general, the CLP = 0 traffic is important compared to the CLP = 1 traffic, because the user must rely on the transport of this substream even when the network is congested, and the network provider must allocate resources to provide the negotiated QoS for this substream. In order to solve the measurement phasing problem, and to admit the maximum number of CLP = 0 cells, we devised a QoS guaranteed UPC/NPC algorithm that admits the number of CLP = 0 cells conforming to the $VSA(T_0, \tau_0)$ test independent of the $VSA(T_{0+1}, \tau_{0+1})$ test.

The UPC/NPC algorithm is shown in Fig. 4. For the UPC/NPC mechanism, a counter is introduced to indicate the number of CLP = 0 cells conforming to the $VSA(T_0, \tau_0)$ test but not to the $VSA(T_{0+1}, \tau_{0+1})$ test. The counter value is initialized to zero. The UPC/NPC procedure is as follows. The $VSA(T_0, \tau_0)$ test is performed first on the CLP = 0 cell substream. If the tagging option is not used by

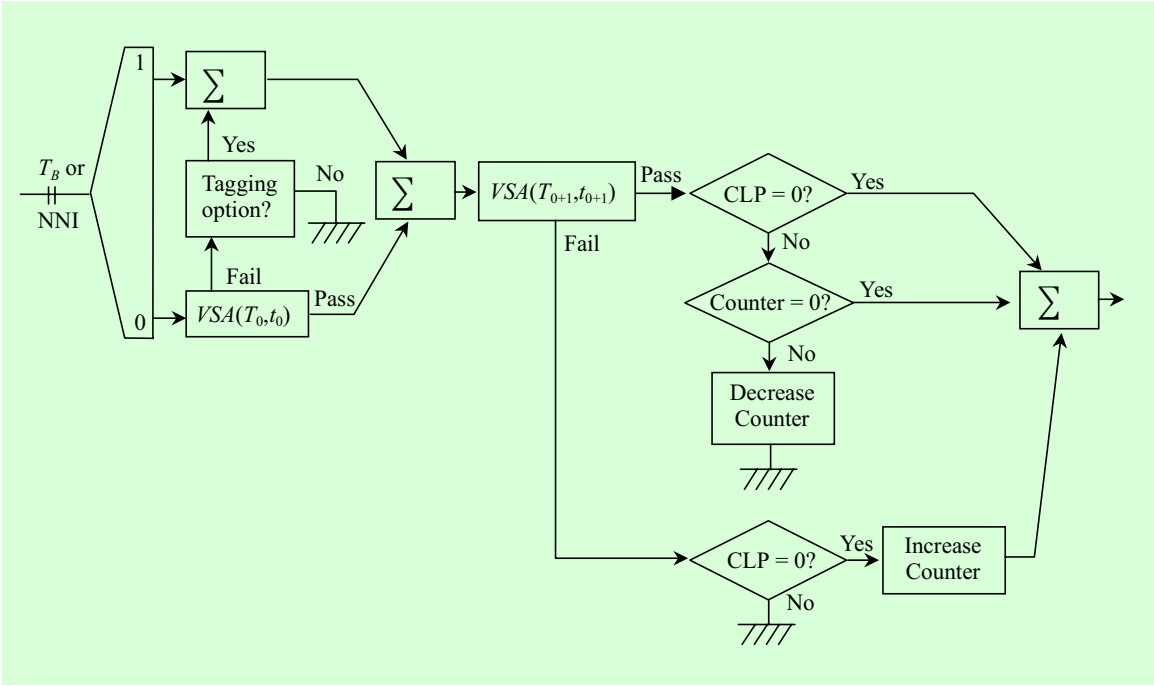

Fig. 4. The QoS guaranteed UPC/NPC algorithm.

a network, CLP = 0 cells non-conforming to the $VSA(T_0, \tau_0)$ test are discarded. If the tagging option is used, those cells are converted to CLP = 1 cells and merged with a CLP = 1 cell stream before the CLP = 0+1 traffic flow enters the $VSA(T_{0+1}, \tau_{0+1})$ test.

The CLP = 0 cells conforming to the $VSA(T_0, \tau_0)$ test are merged with a CLP = 1 cell stream, and undergo the $VSA(T_{0+1}, \tau_{0+1})$ test. When a cell fails in the $VSA(T_{0+1}, \tau_{0+1})$ conformance test, the CLP bit is checked. If the CLP bit is 1, the cell is discarded; but if it is 0, the cell is admitted. Because it has already passed the $VSA(T_0, \tau_0)$ test, we guarantee its admittance into the network. For the admittance of this CLP = 0 cell, the counter value must be increased by one to indicate one more admittance of CLP = 0+1 cell based on the $VSA(T_{0+1}, \tau_{0+1})$ test. This counter value is used to discard CLP = 1 cells conforming to the $VSA(T_{0+1}, \tau_{0+1})$ test in order to adjust the total number of CLP = 0+1 cells admitted by the UPC/NPC function to that of CLP = 0+1 cells conforming to the traffic contract. Therefore, the admittance of CLP = 1 cells which have passed the $VSA(T_{0+1}, \tau_{0+1})$ test depends on the counter value. If the counter value is zero, it is admitted by the UPC/NPC. But, if the counter value is not zero, the cell with CLP = 1 is discarded. By discarding the CLP = 1 cell, the counter value is decreased by one.

As a consequence, the CLP = 0 cells conforming to the $VSA(T_0, \tau_0)$ test are admitted by the UPC/NPC independent of the $VSA(T_{0+1}, \tau_{0+1})$ test. Therefore the amount of CLP = 0 cells admitted by the UPC/NPC algorithm is A_1 in Fig. 3. But, in order to adjust the total amount of CLP = 0+1 cells admitted by the UPC/NPC function to that of CLP = 0+1 cells conforming to the traffic contract, the QoS guaranteed UPC/NPC algorithm discards the same amount of CLP = 1 cells conforming to the $VSA(T_{0+1}, \tau_{0+1})$ test. The amount of discarded CLP = 1 cells is given by $(A_1 - A_3)$ in Fig. 3. As a result, the amount of CLP = 1 cells admitted by the UPC/NPC algorithm is $[B_1 - (A_1 - A_3)]$. The total amount of CLP = 0+1 cells admitted by the UPC/NPC is $A_1 + [B_1 - (A_1 - A_3)] = A_3 \cup B_1$, which is the same amount of CLP = 0+1 cells admitted by the ideal UPC/NPC. Note that as T_0 is not less than T_{0+1} in a traffic contract, the amount of $(A_3 \cup B_1)$ is not less than that of A_1. Therefore, the amount of $[B_1 - (A_1 - A_3)]$ is always not less than zero.

In this QoS guaranteed UPC/NPC algorithm, the difference in the numbers of admitted CLP = 0 cells depending on the starting point is bound by $[\tau_0/T_0]$, where [x] represents the integer part of x. Therefore, the maximum value of the counter is $[\tau_0/T_0]$, and the network can guarantee the cell loss ratios of CLP = 0 and CLP = 0+1 cell streams in the long-term ratio without the measurement phasing problem while admitting the maximum number of CLP = 0 cells.

In the conformance test algorithm, the peak emission interval T and the cell delay variation tolerance τ values are always processed together. Therefore, they should have the same representations in terms of the coding scheme used. To avoid the measurement phasing problem, it is necessary that the ratio of the number of cells detected as non-conforming to the number of cells observed by the UPC/NPC should be an invariant quantity irrespective of the CLP bit in the long-term ratio [8]. The number depends only on τ which quantifies cell clumping on the cell stream. The cell delay variation tolerance τ has to be equal to or larger than T to cope with the measurement phasing problem [10].

2. Definitions of the Cell Loss Ratio

If we use the QoS guaranteed UPC/NPC algorithm, we can define the cell loss ratio of CLP = 0 cell substream and the CLP = 0+1 cell stream when some cells are non-conforming to the CLP = 0+1 conformance test. For the definitions of cell loss ratios, we use the following definitions:

N = Number of transmitted CLP = 0+1 cells

N_0 = Number of transmitted CLP = 0 cells

$N_{l(0)}$ = Number of lost CLP = 0 cells

$N_{l(0+1)}$ = Number of lost CLP = 0+1 cells

$N_{nc(0)}$ = Number of CLP = 0 cells not conforming to $VSA(T_0, \tau_0)$

$N_{nc(0+1)}$ = Number of CLP = 0+1 cells not conforming to $VSA(T_{0+1}, \tau_{0+1})$

Using these definitions, we can define cell loss ratios as follows.

i) When a tagging option is not used, we have

$$CLR_c(0) = \frac{max(0, N_{l(0)} - N_{nc(0)})}{N_0 - N_{nc(0)}} \quad (4)$$

$$CLR_c(0+1) = \frac{max(0, N_{l(0+1)} - N_{nc(0)} - N_{nc(0+1)})}{N - N_{nc(0)} - N_{nc(0+1)}}. \quad (5)$$

ii) When a tagging option is used, we have

$$CLR_c(0) = \frac{max(0, N_{l(0)} - N_{nc(0)})}{N_0 - N_{nc(0)}} \quad (6)$$

$$CLR_c(0+1) = \frac{max(0, N_{l(0+1)} - N_{nc(0+1)})}{N - N_{nc(0+1)}}. \quad (7)$$

The quantity $N_0 - N_{nc(0)}$ is at most equal to the amount of the negotiated CLP = 0 traffic which conforms to the $VSA(T_0, \tau_0)$ test, and $\max(0, N_{l(0)} - N_{nc(0)})$ represents the amount of CLP = 0 cells which are lost by the network in excess of cells non-conforming to the $VSA(T_0, \tau_0)$ test. The cell loss ratio for the CLP = 0 cell substream, $CLR_c(0)$ is not dependent on the $VSA(T_{0+1}, \tau_{0+1})$ test. It is dependent only on the result of the $VSA(T_0, \tau_0)$ test.

Also, the quantity $(N - N_{nc(0)} - N_{nc(0+1)})$ is at most equal to the amount of the negotiated CLP = 0+1 traffic, and $\max(0, N_{l(0+1)} - N_{nc(0)} - N_{nc(0+1)})$ represents the amount of CLP = 0+1 cells which are lost by the network in excess of cells non-conforming to the $VSA(T_0, \tau_0)$ test or to the $VSA(T_{0+1}, \tau_{0+1})$ test. The cell loss ratio for the CLP = 0+1 cell stream, $CLR_c(0+1)$ is dependent on the result of the $VSA(T_0, \tau_0)$ and $VSA(T_{0+1}, \tau_{0+1})$ tests. The definitions of CLR_C of (4), (5), (6), and (7) become the same as that for the cell loss ratio of (1) if all cells conform to the traffic contract.

V. PERFORMANCE ANALYSIS OF THE PROPOSED UPC/NPC FUNCTION

1. System Model and State Analysis

In the previous Section, we showed the effectiveness of the proposed UPC/NPC algorithm for periodic input traffic flows. In this Section, we analyze the proposed QoS guaranteed UPC/NPC function for aperiodic input traffic flows. The first analysis of the UPC/NPC function with GCRA was carried out by *Hübner* [11] using the unfinished work approach [12]. *Hübner* determined the exact cell discarding probability of the GCRA performed on a traffic flow of single CLP class, modeling the CBR cell stream by a discrete-time renewal process with a general distribution. *Do* has developed a discrete-time model for the UPC/NPC function with dual GCRA for two priority traffic flows, which was proposed by ITU–T Recommendation I.371

[13]. We analyze the proposed algorithm in the discrete-time domain by extending the analysis method proposed by *Do* [13]. The input cell stream is modeled by a discrete-time semi-Markov process (DSMP) [14] with two states representing two priorities by the CLP bit in an ATM cell. Based on the analysis, the cell discarding probabilities are obtained and numerical results are presented.

Table 1. Determination of x, y, α in the case of CLP = 0 cell arrival without cell tagging option.

	$X_n^- \in R_0$	$X_n^- \in L_0$
$Y_n^- \in R_{0+1}$	Conforming, passed $x = T_0$ $y = T_{0+1}$ $\alpha = 0$	Non-conforming at P_0, discarded $x = 0$ $y = 0$ $\alpha = 0$
$Y_n^- \in L_{0+1}$	Non-conforming at P_{0+1} but passed $x = T_0$ $y = 0$ $\alpha = 1$	Non-conforming at P_0 & P_{0+1}, discarded $x = 0$ $y = 0$ $\alpha = 0$

The input process considered is a DSMP (defined as $\{(S_n, T_n); n \in IN_0\}$), where IN_0 is the set of non-negative integer, and

- S_n denotes a cell loss priority represented by the CLP value in the ATM cell header, and takes a value in the state space
  $$\mathbf{E} = \{0,\ 1\}.$$
- T_n denotes the arrival instant of cell n.

Let A_{n+1} denote the interarrival time between cell n and $n+1$, then the DSMP has two following properties:

- Markov property:
  $\Pr\{S_{n+1} = j, A_{n+1} = t | S_n, \cdots, S_0, T_n, \cdots, T_0\}$
  $= \Pr\{S_{n+1} = j, A_{n+1} = t | S_n = i\}$
- Time homogeneity:
  $\Pr\{S_{n+1} = j,\ A_{n+1} = t | S_n = i\}$
  $= \Pr\{S_1 = j,\ A_1 = t | S_0 = i\}$

We derive an iterative algorithm to determine the distributions of the state variables of the UPC/NPC function, and the exact cell discarding probability. Considering ATM environments, we discretize time into slots of cell duration length. The following notations are used for analysis.

- $X(t)$: discrete random variable representing the number of slots until a new cell is expected to arrive at the P_0 test,
- X_n^-: $X(t)$ just before the arrival instant of cell n,
- X_n^+: $X(t)$ just after the arrival instant of cell n,
- $Y(t)$: discrete random variable representing the number of slots until a new cell is expected to arrive at the P_{0+1} test,
- Y_n^-: $Y(t)$ just before the arrival instant of cell n,
- Y_n^+: $Y(t)$ just after the arrival instant of cell n,
- $C(t)$: the value of the counter in the proposed UPC/NPC function,
- C_n^-: $C(t)$ just before the arrival instance of cell n at the P_{0+1} test,
- C_n^+: $C(t)$ just after the arrival instance of cell n at the P_{0+1} test,

- $Z(t) = (X(t), Y(t))$: two dimensional discrete random variables satisfying $X(t) \in [0, T_0 + \tau_0]$, and $Y(t) \in [0, T_{0+1} + \tau_{0+1}]$.

Table 2. Determination of x, y, α in the case of CLP = 0 cell arrival with cell tagging option.

	$X_n^- \in R_0$	$X_n^- \in L_0$
$Y_n^- \in R_{0+1}$	Conforming, passed $x = T_0$ $y = T_{0+1}$ $\alpha = 0$	Cell tagged at P_0 i) when $C_n = 0$, passed $x = 0$ $y = T_{0+1}$ $\alpha = 0$ ii) when $C_n \neq 0$, discarded $x = 0$ $y = T_{0+1}$ $\alpha = -1$
$Y_n^- \in L_{0+1}$	Non-conforming at P_{0+1} but passed $x = T_0$ $y = 0$ $\alpha = 1$	Cell tagged at P_0 and discarded at P_{0+1} $x = 0$ $y = 0$ $\alpha = 0$

By definitions, X_{n+1}^-, Y_{n+1}^- are given by

$$Y_{n+1}^- = max(X_n^+ - A_{n+1},\ 0), \tag{8}$$

$$Y_{n+1}^- = max(Y_n^+ - A_{n+1},\ 0). \tag{9}$$

Moreover, X_n^+, Y_n^+, and C_n^+ are determined by X_n^-, Y_n^-, and Z_n^- in the following way:

$$X_n^+ = X_n^- + x, \tag{10}$$

$$Y_n^+ = Y_n^- + y, \tag{11}$$

$$C_n^+ = C_n^- + \alpha, \tag{12}$$

where x, y, and α depend on the value of X_n^-, Y_n^-, C_n^-, and the value of the CLP bit of an arriving cell. The relationship is shown in Table 1, 2 and 3. For simplicity, we define the following set of ranges.

Table 3. Determination of x, y, α in the case of CLP = cell arrival.

	$X_n^- \in R_0$	$X_n^- \in L_0$
$Y_n^- \in R_{0+1}$	Conforming i) when C_n=0, passed $x = 0$ $y = T_{0+1}$ $\alpha = 0$ ii) when $C_n \neq 0$, discarded $x = 0$ $y = T_{0+1}$ $\alpha = -1$	Conforming i) when C_n=0, passed $x = 0$ $y = T_{0+1}$ $\alpha = 0$ ii) when $C_n \neq 0$, discarded $x = 0$ $y = T_{0+1}$ $\alpha = -1$
$Y_n^- \in L_{0+1}$	Non-conforming at P_{0+1}, discarded $x = 0$ $y = 0$ $\alpha = 0$	Non-conforming at P_{0+1}, discarded $x = 0$ $y = 0$ $\alpha = 0$

$$R_0 = [0,\ \tau_0],\quad L_0 = [\tau_0 + 1,\ T_0 + \tau_0],$$

$$E_0 = [0,\ T_0 + \tau_0] \tag{13}$$

$$R_{0+1} = [0,\ \tau_{0+1}],\ L_{0+1} = [\tau_{0+1} + 1,\ T_{0+1} + \tau_{0+1}],$$

$$E_{0+1} = [0,\ T_{0+1} + \tau_{0+1}] \tag{14}$$

$$W = [0,\ [\tau_0 / T_0] + 1] \tag{15}$$

The aim of the state analysis is to derive the iterative equation for

$$Pr\{S_{n+1} = j,\ Z_{n+1}^- = (e, f),\ C_{n+1}^- = n\}, \tag{16}$$

which adequately describes the state of the UPC/NPC function at arrival instants. The equation (16) can be written as follows:

$$Pr\{S_{n+1} = j,\ Z_{n+1}^- = (e, f),\ C_{n+1}^- = n\}$$

$$= \sum_{m \in W} \sum_{k \in E_0} \sum_{l \in E_{0+1}} \sum_{i=0}^{1} Pr\{S_{n+1} = j,\ Z_{n+1}^- = (e, f),$$

$$C_{n+1}^- = n,\ S_n = i,\ Z_n^- = (k, l),\ C_n^- = m\}$$

$$= \sum_{m\in W}\sum_{k\in E_0}\sum_{l\in E_{0+1}}\sum_{i=0}^{1} Pr\{S_{n+1}=j,\ Z_{n+1}^{-}=(e,f), C_{n+1}^{-}=n | S_n=i,\ Z_n^{-}=(k,l),\ C_n^{-}=m\}$$
$$\times Pr\{S_n=i,\ Z_n^{-}=(k,l), C_n^{-}=m\}. \tag{17}$$

In order to derive the equation for

$$Pr\{S_{n+1}=j,\ Z_{n+1}^{-}=(e,f),\ C_{n+1}^{-}=n | S_n=i, Z_n^{-}=(k,l),\ C_n^{-}=m\},$$

we write

$$\begin{aligned} &Pr\{S_{n+1}=j, Z_{n+1}^{-}=(e,f), C_{n+1}^{-}=n | S_n=i, Z_n^{-}=(k,l), C_n^{-}=m\} \\ &= Pr\{Z_{n+1}^{-}=(e,f), C_{n+1}^{-}=n | S_{n+1}=j, S_n=i, Z_n^{-}=(k,l), C_n^{-}=m\} \\ &\quad \times Pr\{S_{n+1}=j | S_n=i, Z_n^{-}=(k,l), C_n^{-}=m\}. \end{aligned} \tag{18}$$

Since the input process does not depend on the internal state $Z(t)$ and $C(t)$ of the function, we can write

$$Pr\{S_{n+1}=j | S_n=i, Z_n^{-}=(k,l), C_n^{-}=m\} = Pr\{S_{n+1}=j | S_n=i\}. \tag{19}$$

Let's define $p_{ij} = Pr\{S_{n+1}=j | S_n=i\}$, and $B_{ij}(k,l,m) = \{S_{n+1}=j, S_n=i, Z_n^{-}=(k,l), C_n^{-}=m\}$. Then

$$\begin{aligned} &Pr\{S_{n+1}=j, Z_{n+1}^{-}=(e,f), C_{n+1}^{-}=n | S_n=i, Z_n^{-}=(k,l), C_n^{-}=m\} \\ &= Pr\{Z_{n+1}^{-}=(e,f), C_{n+1}^{-}=n | B_{ij}(k,l,m)\} \cdot p_{ij}. \end{aligned} \tag{20}$$

Now the equations for $Pr\{Z_{n+1}^{-}=(e,f), C_{n+1}^{-}=n | B_{ij}(k,l,m)\}$ can be derived:

$$Pr\{Z_{n+1}^{-}=(e,f), C_{n+1}^{-}=n | B_{ij}(k,l,m)\}$$
$$= \begin{cases} Pr\{X_n^{+} - A_{n+1} = e, Y_n^{+} = f, C_n^{+} = n | B_{ij}(k,l,m)\}, & e>0 \ \&\ f>0 \\ Pr\{X_n^{+} - A_{n+1} = e, Y_n^{+} \le A_{n+1}, C_n^{+} = n | B_{ij}(k,l,m)\}, & e>0 \ \&\ f=0 \\ Pr\{X_n^{+} \le A_{n+1}, Y_n^{+} - A_{n+1} = f, C_n^{+} = n | B_{ij}(k,l,m)\}, & e=0 \ \&\ f>0 \\ Pr\{X_n^{+} \le A_{n+1}, Y_n^{+} \le A_{n+1}, C_n^{+} = n | B_{ij}(k,l,m)\}, & e=0 \ \&\ f=0. \end{cases} \tag{21}$$

By using (10)–(12), one can derive

$$Pr\{Z_{n+1}^{-}=(e,f), C_{n+1}^{-}=n | B_{ij}(k,l,m)\}$$
$$= \begin{cases} Pr\{A_{n+1} = X_n^{-} + x - e = Y_n^{-} + y - f, C_n^{+} = C_n^{-} + \alpha = n | B_{ij}(k,l,m)\}, & e>0 \ \&\ f>0 \\ Pr\{A_{n+1} = X_n^{-} + x - e \ge Y_n^{-} + y, C_n^{+} = C_n^{-} + \alpha = n | B_{ij}(k,l,m)\}, & e>0 \ \&\ f=0 \\ Pr\{X_n^{-} + x \le A_{n+1} = Y_n^{-} + y - f, C_n^{+} = n | B_{ij}(k,l,m)\}, & e=0 \ \&\ f>0 \\ Pr\{X_n^{-} + x \le A_{n+1} = Y_n^{-} + y \le A_{n+1}, C_n^{+} = n | B_{ij}(k,l,m)\}, & e=0 \ \&\ f=0 \end{cases} \tag{22}$$

$$= \begin{cases} Pr\{A_{n+1} = k+x-e = l+y-f, C_n^+ = m+\alpha = n | B_{ij}(k,l,m)\}, & e>0 \ \& \ f>0 \\ Pr\{A_{n+1} = k+x-e \geq l+y, C_n^+ = m+\alpha = n | B_{ij}(k,l,m)\}, & e>0 \ \& \ f=0 \\ Pr\{k+x \leq A_{n+1} = l+y-f, C_n^+ = n | B_{ij}(k,l,m)\}, & e=0 \ \& \ f>0 \\ Pr\{k+x \leq A_{n+1}, l+y \leq A_{n+1}, C_n^+ = n | B_{ij}(k,l,m)\}, & e=0 \ \& \ f=0. \end{cases} \tag{23}$$

By letting $f_{ij} = Pr\{A_{n+1} = t | S_{n+1} = j, S_n = i\}$, we can obtain

$$Pr\{Z_{n+1}^- = (e,f), C_{n+1}^- = n | B_{ij}(k,l,m)\}$$
$$= \begin{cases} \delta(k+x-e-l-y+f) \cdot \delta(m+\alpha-n) \cdot f_{ij}(k+x-e), & e>0 \ \& \ f>0 \\ u(k+x-e-l-y) \cdot \delta(m+\alpha-n) \cdot f_{ij}(k+x-e), & e>0 \ \& \ f=0 \\ u(l+y-f-k-x) \cdot \delta(m+\alpha-n) \cdot f_{ij}(l+y-f), & e=0 \ \& \ f>0 \\ (\sum_{t=max(k+x,l+y)}^{\infty} f_{ij}(t)) \cdot \delta(m+\alpha-n) & e=0 \ \& \ f=0, \end{cases} \tag{24}$$

where

$$u(t) = \begin{cases} 1 & \text{if } t \geq 0 \\ 0 & \text{otherwise} \end{cases} \tag{25}$$

$$\delta(t) = \begin{cases} 1 & \text{if } t = 0 \\ 0 & \text{otherwise.} \end{cases} \tag{26}$$

By putting (24) into (20), the iterative equation for (16) can be obtained.
Finally, the equilibrium distribution may be written as

$$Pr\{S = j, Z^- = (e,f), C = n\} = \lim_{n \to \infty} Pr\{S_{n+1}^- = j, Z_{n+1}^- = (e,f), C_{n+1}^- = n\}. \tag{27}$$

2. Cell Discarding Probability

In order to determine the cell discarding probabilities with respect to CLP = 0 and CLP = 0+1 cells, we define the following measures.

$$P_d(0) = \Pr\{\text{Cell discarded} | \text{CLP} = 0 \ \text{ cell arrives}\}$$
$$P_d(0+1) = \Pr\{\text{Cell discarded} | \text{CLP} = 0+1 \ \text{ cell arrives}\}$$

The performance measures can be obtained after some algebraic manipulation.

i) No cell tagging case

$$P_d(0) = \frac{Pr\{S=0, X^- > \tau_0\}}{Pr\{S=0\}} = \frac{\sum_{m\in W}\sum_{k\in L_0}\sum_{l\in E_{0+1}} Pr\{S=0, Z^- = (k,l), C^- = m\}}{Pr\{S=0\}} \tag{28}$$

$$\begin{aligned} P_d(0+1) &= Pr\{S=0, X^- > \tau_0\} + Pr\{S=1, Y^- > \tau_{0+1}\} + Pr\{S=1, Y^- < \tau_{0+1}, C^- > 0\} \\ &= \sum_{m\in W}\sum_{k\in L_0}\sum_{l\in E_{0+1}} Pr\{S=0, Z^- = (k,l), C^- = m\} \\ &\quad + \sum_{m\in W}\sum_{k\in E_0}\sum_{l\in L_{0+1}} Pr\{S=1, Z^- = (k,l), C^- = m\} \\ &\quad + \sum_{m\in W, m\neq 0}\sum_{k\in E_0}\sum_{l\in R_{0+1}} Pr\{S=1, Z^- = (k,l), C^- = m\}. \end{aligned} \tag{29}$$

ii) Cell tagging case

$$P_d(0) = \frac{Pr\{S=0, X^- > \tau_0\}}{Pr\{S=0\}} = \frac{\sum_{m\in W}\sum_{k\in L_0}\sum_{l\in E_{0+1}} Pr\{S=0, Z^- = (k,l), C^- = m\}}{Pr\{S=0\}} \tag{30}$$

$$\begin{aligned} P_d(0+1) &= Pr\{S=0, X^- > \tau_0, Y^- > \tau_{0+1}\} + Pr\{S=0, X^- > \tau_0, Y^- \leq \tau_{0+1}, C^- > 0\} \\ &\quad + Pr\{S=1, Y^- < \tau_{0+1}, C^- > 0\} + Pr\{S=1, Y^- > \tau_{0+1}\} \\ &= \sum_{m\in W}\sum_{k\in L_0}\sum_{l\in L_{0+1}} Pr\{S=0, Z^- = (k,l), C^- = m\} \\ &\quad + \sum_{m\in W, m\neq 0}\sum_{k\in L_0}\sum_{l\in R_{0+1}} Pr\{S=0, Z^- = (k,l), C^- = m\} \\ &\quad + \sum_{m\in W, m\neq 0}\sum_{k\in E_0}\sum_{l\in R_{0+1}} Pr\{S=1, Z^- = (k,l), C^- = m\} \\ &\quad + \sum_{m\in W}\sum_{k\in E_0}\sum_{l\in L_{0+1}} Pr\{S=1, Z^- = (k,l), C^- = m\}. \end{aligned} \tag{31}$$

These $Pr\{S=0\}$ and $Pr\{S=1\}$ are obtained as follows. Let p_i be the stationary probability when the input DSMP process is in the state i: $p_i = Pr\{S=i\}$. Let π denote the vector $[p_0,\ p_1]$, and the state transition matrix be $\mathbf{P} = [\mathbf{p_{ij}}]$. Then, the π can be determined from $p_0 + p_1 = 1$ and $\pi \cdot \mathbf{P} = \pi$ equations where

$$p_0 = \frac{p_{10}}{1 + p_{10} - p_{00}} \tag{32}$$

$$p_1 = \frac{1 - p_{00}}{1 + p_{10} - p_{00}}. \tag{33}$$

3. Numerical Results and Discussion

For a numerical example, the discrete-time Markov arrival process (DMAP) is used as an input process. The DMAP is a special case of the DSMP. It is a stochastic process which is based on an irreducible discrete-time Markov chain. The state space comprises of two states (i.e., 0 and 1) in the context of this analysis. If the process is in state i at slot k, it moves to state j at slot $(k+1)$ with probability $p_{ij} = c_{ij} + d_{ij}$, where c_{ij} is defined as the probability that the transition from state i to state j occurs without an arrival, and d_{ij} is the probability that the same transition occurs with an arrival. Therefore, the DMAP process is defined by two matrices $\mathbf{C}$ and $\mathbf{D}$, where $\mathbf{C} = [c_{ij}]$ and $\mathbf{D} = [d_{ij}]$. The transition matrix of the underlying Markov chain is $\mathbf{P} = \mathbf{C} + \mathbf{D}$, and we have $\sum_{j=0}^{1}(c_{ij} + d_{ij}) = 1$, for all i. For the analysis and simulation, we use the same input parameters as those defined by *Do* [13]:

$$\mathbf{C} = \begin{bmatrix} 0.3 & 0.55 \\ 0.6 & 0.35 \end{bmatrix}, \tag{34}$$

$$\mathbf{D} = \begin{bmatrix} 0.1 & 0.05 \\ 0.024 & 0.026 \end{bmatrix}. \tag{35}$$

In this case, we obtain the following probabilities: $p_0 = 0.509804$, $p_1 = 0.490196$. The mean interarrival time of cells is 9.902913 slots, and the mean interarrival time of two consecutive CLP = 0 cells equals 19.615385 slots.

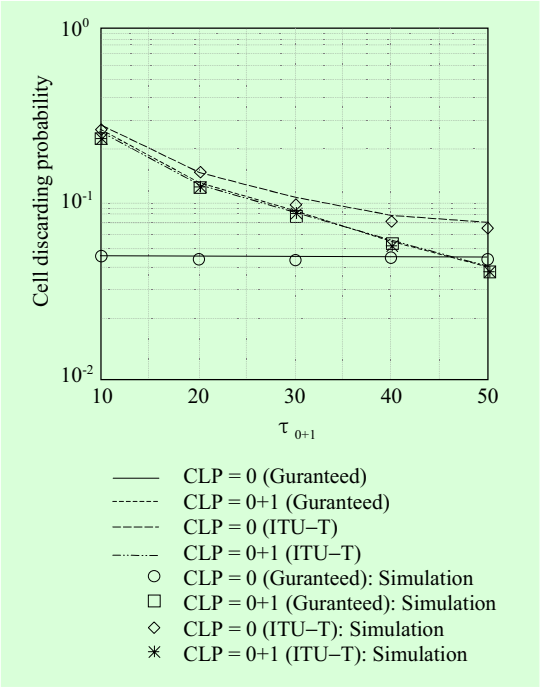

Fig. 5. Cell discarding probability versus τ_{0+1}: $T_0 = 10$, $\tau_0 = 30$, and $T_{0+1} = 8$ with tagging option.

From Fig. 5 to Fig. 8, we present a cell discarding probability (CDP) versus the value of τ_{0+1} with different parameter values. In Fig. 5, we compare the QoS guaranteed UPC/NPC with the UPC/NPC defined by ITU–T for CDPs, where the parameter values are $T_0 = 10$, $\tau_0 = 30$, and $T_{0+1} = 8$ in a cell slot time with tagging option. The CDP of CLP = 0 cell stream in the UPC/NPC defined by ITU–T decreases as the value of τ_{0+1} increases because the dependency of CLP = 0 cells on P_{0+1} test decreases, and converges to the value of 0.0466. However, the probability remains constant at the value of 0.0466 because it is independent of P_{0+1} text in the QoS guaranteed UPC/NPC. We consider a tagged cell

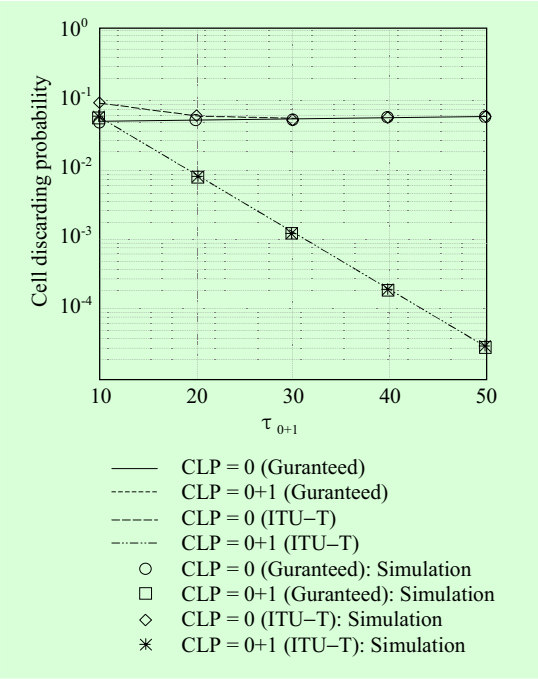

Fig. 6. Cell discarding probability versus τ_{0+1}: $T_0 = 10$, $\tau_0 = 30$, and $T_{0+1} = 5$ with tagging option.

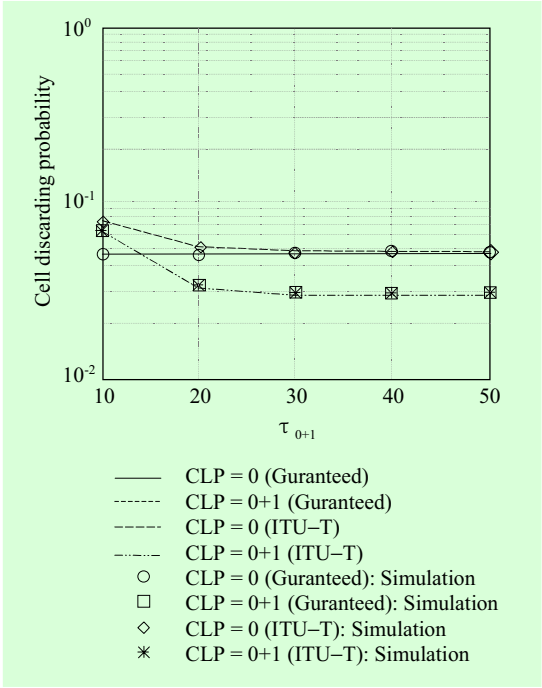

Fig. 7. Cell discarding probability versus τ_{0+1}: $T_0 = 10$, $\tau_0 = 30$, and $T_{0+1} = 5$ with tagging option.

which becomes a CLP = 1 cell and is lost in the case of CLP = 0 cell stream. Compared to Fig. 5, the parameter value of T_{0+1} in Fig. 6 is changed to $T_{0+1} = 5$, which means the PCR of CLP = 0+1 cell stream is increased. When the PCR is increased, the CDP of a CLP = 0 cell stream in the QoS guaranteed UPC/NPC is not changed but the value converges more rapidly to the constant value of 0.0466 in the UPC/NPC defined by ITU–T. The CDPs of CLP = 0+1 cell streams decrease fast as the value of τ_{0+1} increases. As the value of τ_{0+1} becomes very large, the CDPs of $CLP = 0 + 1$ cell streams converge to zero because all tagged cells pass P_{0+1} test as CLP = 1 cells. The CDPs of CLP = 0+1 cell streams in both UPC/NPC functions are the same.

In Fig. 7, the same parameter values to Fig. 6 are used but the tagging option is not used. In the case, the cell discarding probabilities of CLP = 0 cell stream is the same as the values of Fig. 6. While the values converge to zero when the tagging option is used, the values of CLP = 0+1 cell streams converge to 0.029 because of the cell discarding of CLP = 0 cells. Compared to Fig. 7, the parameter value of T_{0+1} in Fig. 8 is changed to $T_{0+1} = 8$. In that case, the CDPs of CLP = 0 cell stream is the same as the values in Fig. 7 in the QoS guaranteed UPC/NPC, but the values are

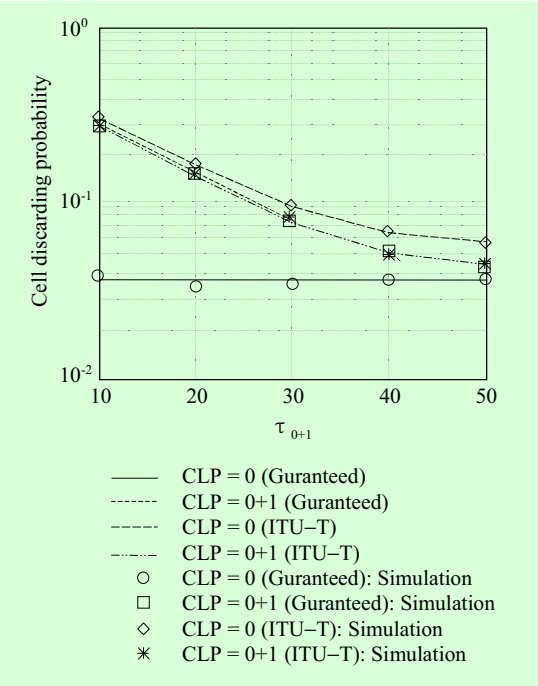

Fig. 8. Cell discarding probability versus τ_{0+1}; $T_0 = 10$, $\tau_0 = 30$, and $T_{0+1} = 8$ without tagging option.

relatively large in the UPC/NPC defined by ITU–T, and converges to the constant value more slowly. Compared to Fig. 5, where the same parameter values are used with the tagging option, the CDPs of CLP = 0+1 cell stream are relatively large in Fig. 8.

In all cases, the CDP of a CLP = 0 cell stream in the QoS guaranteed UPC/NPC remains constant with the value of 0.0466 independent of values of τ_{0+1} because it is independent of the P_{0+1} test. The CDP of a CLP = 0 cell stream in the UPC/NPC defined by ITU–T is always larger than the constant value, and converges to the constant value as the value of τ_{0+1} converges to infinity. Also, if the same parameters and the same tagging option are used, the CDPs of CLP = 0+1 cell streams in both UPC/NPC are the same.

The simulation was event driven. The criterion for stopping the simulation is that the width of the 95% confidence interval should be less than 1% of the estimated cell loss probability.

VI. CONCLUSION

In this paper, we have proposed a QoS guaranteed UPC/NPC algorithm to commit the cell loss ratio of CLP = 0 and CLP = 0+1 cell streams without the measurement phasing problem when a cell loss priority scheme is used. By using the UPC/NPC algorithm, we can define the cell loss ratios for CLP = 0 and CLP = 0+1 cell streams when non-conforming cells exist. We can also guarantee the cell loss ratios while admitting the maximum number of CLP = 0 cells. As the CLP = 0 traffic is more important than the CLP = 1 traffic, the admittance of the maximum number of CLP = 0 cells in a given number of CLP = 0+1 cells is another advantage. Nevertheless, one disadvantage of using the QoS guaranteed UPC/NPC algorithm is that the admitted cell pattern can be more bursty compared to the cell pattern admitted by the ideal UPC/NPC function based on the cell conformance test. In practice, however, the traffic flows sent across ATM

links controlled by UPC/NPC can sometimes be shaped using a leaky bucket algorithm. In this case the disadvantage can be resolved.

By using the QoS guaranteed UPC/NPC algorithm, the network may admit more CLP = 0 cells in the transient state compared to the ideal UPC/NPC function. The difference of the numbers of admitted CLP = 0 cells depending on the starting point is bound by $[\tau_0/T_0]$, where [x] represents the integer part of x. The disadvantage would be some waste of resources. But this possible waste of resources is the price to pay to support a cell loss priority control scheme and to admit the maximum number of CLP = 0 cells.

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