Performance of Centralized Bandwidth Reservation Protocol in AVPNs

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Abstract

ATM based Virtual Private Networks(AVPNs) are embedded in public ATM network to provide an efficient transport service to a multisite customer using virtual levels of ATM. In this paper we propose a centralized protocol for resource allocation in AVPNs and compare its performance with that of the previously proposed strategies. We analyze the protocol to get average burst delay and burst loss probability in case of finite buffering at the customer sites.
Keywords : *AVPN, on-off model, burstiness, internal node congestion*

1 Introduction

A Virtual Private Network(VPN) [9] is a service offering that provides customers with private network capabilities, although the service is realized through using public network resources. The customer perceives a private network based on logical communication resources. In the near future, as the networking needs are increasing rapidly, the corporate customers will be subscribing the broadband services offered by globally operating service providers to replace most of their leased line services used earlier. The main benefit of the VPNs is to achieve cost saving by sharing same public network resources between several customers combined with the features of a private network. For customers with a dynamic traffic pattern, this results in lower cost since it is based on usage and for the service provider it means increased income due to better utilization of the resources.

1.1 ATM based Virtual Private Networks

AVPNs use the virtual levels of ATM [1], *i.e.*, VPs(Virtual Paths) and VCs(Virtual Circuits), to operate as a backbone to interconnect various sites of a corporate customer. Various schemes have been proposed for resource allocation in AVPNs. In end to end approach, a virtual path is established between each pair of customer sites. The customer can multiplex any number of VCs in a single VP without any bandwidth associated with an individual VC. The only constraint is that the sum of bandwidth of all the VCs should not exceed the VP bandwidth(see figure 1). This can be given as follows:

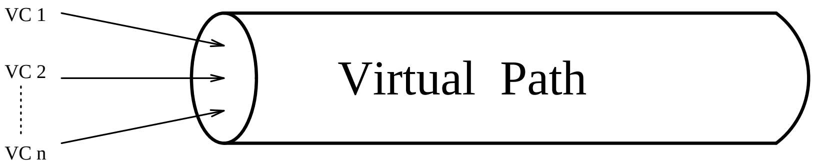

Figure 1: End to End VP Approach

$$B_{VC_1} + B_{VC_2} + \ldots + B_{VC_n} <= B_{VP}$$

Where B_x denotes the bandwidth allocated to x, where x may be a VP or a VC.

In [1], a new concept of Broadband Virtual Private Networks(BVPNs) has been introduced. Under this concept, customer's reservation is based only on VP links. So the VCs are not confined to only one VP but instead may traverse several VP links. The main advantage of this approach is that the customer can multiplex different source/destination traffic streams on the VP links thus achieving statistical gain. However, since bandwidth is reserved only on VP links, we require input as well as output policing on the VP links. In addition to that, another problem of *internal node congestion* in BVPNs is addressed in [1, 2]. To understand this, consider the situation given in figure 2. There are two incoming and two outgoing VP links to an ATM XC(Cross Connect) which have their policing parameters set for normal traffic pattern. Now at a particular time, the traffic pattern can change in such a way that all the traffic, entering from VP 1 and VP 2, goes to VP 3. In this case, we can not prevent the ATM XC from internal congestion, for example some of its internal buffers may overflow, by just policing VP 3.

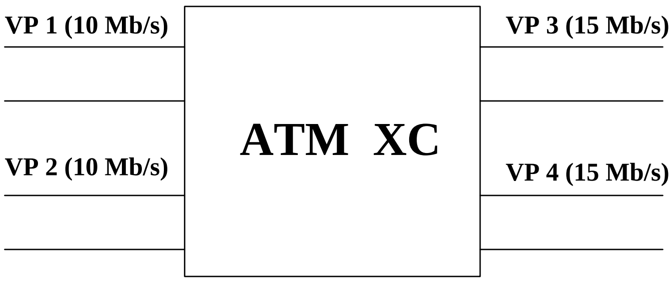

Figure 2: Internal Node Congestion

Two strategies have been proposed in [2] to solve this problem. One of them, called Fast Resource Management(FRM), uses burst level reservation for resource allocation while the other, called Intra Node Policing(INP), puts a limit on resource utilization to avoid internal node congestion. These schemes will be briefly described in subsequent sections.

In this paper, we present a centralized protocol for resource allocation in AVPNs. This succeeds to eliminate most of the drawbacks of the two schemes proposed in [2]. We present analysis of a buffering strategy at customer sites and compare its performance with the previous schemes. Rest of the paper is organized as follows. In section 2, we discuss the existing schemes for AVPNs. In section 3, we present CBR(Centralized Bandwidth Reservation) protocol and its functioning. The performance of the CBR protocol is compared with that of the existing schemes in section 4. Section 5 gives the analysis of the CBR protocol. In section 6, analytical and simulation results are discussed. Finally we conclude with a brief discussion regarding implementation of the scheme.

2 Bandwidth allocation strategies for AVPNs

Several schemes have been proposed for resource allocation in AVPNs. All of them make use of the VPs in ATM network, but in different ways. While End to End VPNs make use of End to End VPs, the other two strategies extend this concept to VP Links.

2.1 End to End Virtual Private Networks

In this scheme [1], an end to end virtual path is established for every pair of customer sites. As already explained, there is no bandwidth associated with an individual VC. Any VC can enjoy upto full VP bandwidth at a particular time. This strategy is totally transparent to public ATM network. It assigns a peak bandwidth to each end to end VP and polices its bandwidth without considering the VCs inside.

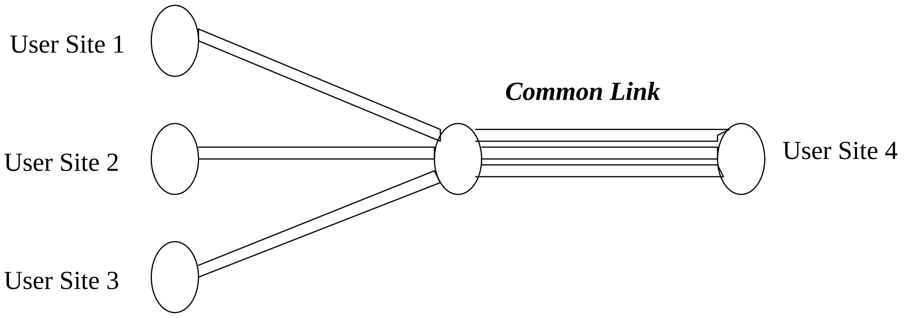

Figure 3: Bandwidth Fragmentation

A drawback of this scheme is *bandwidth fragmentation* between traffic streams, belonging to different source/destination pairs. If we consider the topology given in figure 3, the given traffic streams can not be statistically multiplexed on the common link since we have to maintain separate *end to end VPs* for every source/destination pair. This results in an inefficient utilization of network resources and hence increased cost to the customer. In addition to that, the customer has to dynamically change the VP bandwidth allocations in order to accommodate the changes in traffic pattern between its various locations.

2.2 Fast Resource Management

This strategy uses burst level reservation for resource allocation in AVPNs [2]. Each customer site has a LCM(Local Control Manager). Whenever the LCM at a customer site receives a burst from a source, it sends a reservation cell to the first ATM node, called ingress node, along the path. This node processes the reservation cell and checks whether the reservation can be supported on the proper outgoing VP. If sufficient bandwidth is available on the VP, it reserves the requested bandwidth and forwards the reservation cell to the next node along the path which in turn processes it and so on. If the reservation is successful on every node along the path, the last node sends an acknowledgment to the LCM which then transmits the burst. If the bandwidth is not available on the proper outgoing VP, it simply discards the reservation cell. This scheme allows full statistical multiplexing of different traffic streams whenever they have a common path, no matter which source/destination pair they belong to. It also prevents the ATM XC from internal congestion since each VC is individually monitored.

This scheme, however, has following drawbacks :

1. Additional intelligence is required for the ATM XC in the form of hardware and software as it has to store the present user allocation in order to process the reservation cell. This results in increased cost and complexity of the switch.

2. In FRM, the resources are reserved additionally for a round trip delay due to the reservation procedure. Hence, the offered load to the network, ρ_{offered}, differs from the load which is actually reserved by the network, ρ_{reserved}, as follows.

$$\rho_{\text{reserved}} = \rho_{\text{offered}} * (1 + \frac{\text{ERT}}{\text{EA}}) \tag{1}$$

   where ERT is the mean round trip delay of a connection and EA is mean burst duration. The transmission inefficiency can be defined as the ratio ERT/EA. We see that the transmission inefficiency increases with the round trip delay of the connection.

3. Since the implementation of this strategy requires special ATM switches, extension of AVPN is not easy. Public ATM network has to be involved in the operation and the extension of the AVPN.

2.3 Intra Node Policing

This strategy [2] puts a limit to the statistical multiplexing in order to achieve transparency to the public ATM network. It introduces the concept of I-VPs(Intra Node Virtual Paths), *i.e.*, the VPs inside an ATM XC. Each incoming VP to the ATM XC is partitioned into as many number of I-VPs as the number of outgoing VPs. Now each I-VP inside a VP is policed separately in such a way that sum of bandwidth of all the I-VPs, going into a particular outgoing VP, does not exceed the allocated VP bandwidth.

This scheme avoids internal node congestion in the ATM XC by policing each I-VP separately. The involvement of the public ATM network is less as compared to FRM since the ATM XC does not need to keep track of present user allocation. But the drawback of this scheme is that the I-VPs, heading for the same outgoing VP, can not be statistically multiplexed. So it offers less statistical multiplexing as compared to FRM. In addition to that, if the traffic pattern in an AVPN changes, the bandwidth allocated to the I-VPs must also be changed in order to get optimum utilization of the resources. For that, the customer should be allowed to change the policing parameter of the I-VPs dynamically. This requires complex signaling procedure to be implemented in the ATM network.

3 Centralized Bandwidth Reservation Protocol

Here we propose a new protocol which enjoys the advantages of both FRM and INP and is tuned to reduce most of their drawbacks. It makes use of the burst level reservation for resource allocation as in FRM, but in a different manner. We call this protocol as **Centralized Bandwidth Reservation(CBR)** protocol.

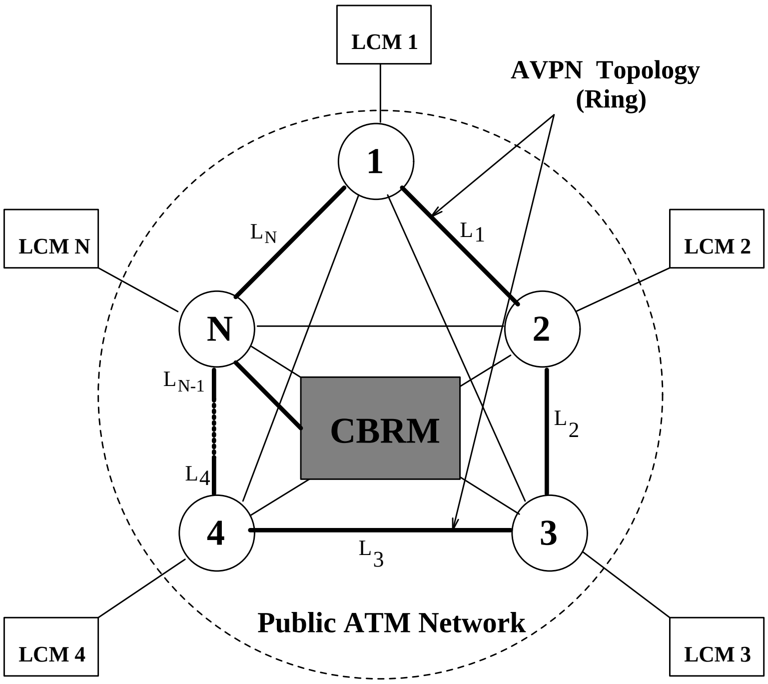

Figure 4: Centralized Bandwidth Reservation

CBR incorporates a central manager, we call it as CBR Manager(CBRM), to reserve the resources at the burst level. The reservation cells are processed only at the CBRM which keeps all the information necessary to decide whether a particular reservation request can be supported or not. The ATM nodes, therefore, do not have to keep track of the present user allocation thus making CBR completely transparent to the public ATM network. In addition to that, average response time per connection request is reduced because the reservation cells do not have to pass through all the nodes along the path, but only up to the CBRM. A ring topology is shown in figure 4 for the CBR protocol.

3.1 Functioning of CBR

Functioning of the CBR protocol can be divided into two procedures. One is *User to Network* procedure and the other is *Network to Network* procedure. In the user to network procedure, we talk about functions which take place between a source and the LCM at the customer site. The network to network procedure defines functions between the LCM and CBRM.

3.2 *User to Network Procedure*

These functions are defined to create an interface between users of the given AVPN and resources of the public network. LCM does the work of this interface. It checks that the public network resources are accessed by the user in a proper and secure way so that any extra burden on CBRM is avoided. For example, it checks that no more than one reservation request per connection at a time is sent to the CBRM and also that the connections maintain their stipulated transmission rate.

When a source at a customer site generates a burst, destined for some other site, it sends a *Reservation Request Cell* to its LCM. As an acknowledgment, it gets a *Reservation Received Cell* from the LCM. Then it waits for acceptance of the reservation request. On getting the acceptance from the LCM it transmits the burst. Until the burst is transmitted, it is buffered at the customer site. UN - Algorithm, that is to be run on LCMs, describes the functions of the user to network interface.

UN - Algorithm

1. `If a Reservation Request Cell is received from a user`
   (a) `send a Reservation Received Cell to the user`
   (b) `When Reservation Accepted Cell is received from the CBRM`
      i. `Adjust the policing parameters for that connection to` C_{req}
      ii. `Send a Reservation Accepted Cell to the user`
2. `If a Release Request Cell is received from a user`
   (a) `Adjust the policing parameters for that connection`
   (b) `send a Release Received Cell to the user`

3.3 *Network to Network Procedure*

CBR requires a central station, called CBRM, which stores the values of C_is and h_is, *viz.*, the capacity reserved on link L_i and the bandwidth presently allocated to the AVPN applications on link L_i respectively. It also stores the AVPN topology, which it requires to decide the route of a connection. The LCM at each customer site maintains a policing parameter for each VC originating from the site.

The network to network procedure consists of two parts. First part, NN-Algorithm(I), is to be run on the LCM when it receives a reservation cell from a source and the second part, NN-Algorithm(II), is to be run on the CBRM to process the reservation cells.

The LCM, after sending the *Reservation Received Cell* to the source, communicates with CBRM and tries to reserve the requested bit rate. If the reservation is denied by CBRM, it requests the reservation again upto a configurable number of times with an interval γ between successive requests. On receiving the acceptance from the CBRM it informs the source so that it can transmit the burst.

NN - Algorithm(I)

1. If a Reservation Request Cell is received from a user
   (a) Send a Reservation Request Cell to CBRM indicating value of the requested bit rate C_{req}
   (b) Wait for the response from CBRM
   (c) If a Reservation Accepted Cell is received from CBRM
      i. Adjust the policing parameters for that connection to $\mathbf{C_{req}}$
      ii. Send a Reservation Accepted Cell to the user
   (d) If a Reservation Failed Cell is received from CBRM, restart after a delay γ
2. If a Release Request Cell is received from a user, send a Release Request Cell to CBRM

On receiving a *Reservation Request Cell* CBRM checks for the possibility of supporting the requested bit rate on the connection route. If the requested bit rate can be supported, it updates the values of the presently allocated bandwidth on various links involved and informs the LCM about the acceptance. If the request can not be supported, it informs the LCM by sending it a *Reservation Failed Cell* . The algorithm, to be run on CBRM, can be given as follows.

NN - Algorithm(II)

1. If a Reservation Request Cell is received from a LCM
   (a) Get the value of C_{req} from the Reservation Request Cell
   (b) For each link L_i, involved in the connection, check the condition
   $$(h_i + C_{req}) \leq C_i$$
   (c) If the condition is satisfied for every concerned link
      i. Update the values of h_i's
      $$h_i = h_i + C_{req}$$
      ii. Send a Reservation Accepted Cell to the LCM
   (d) Otherwise Send a Reservation Failed Cell to the LCM
2. If a Release Request Cell is received from a LCM
   (a) Get the value of C_{req} from the Release Request Cell
   (b) For each link envolved in the connection, update the values of h_i's
   $$h_i = h_i - C_{req}$$

(c) `Send a Release Accepted Cell to the LCM.`

In the above description of various functions, it has been assumed that there is no loss of *Reservation Request/Accepted/Failed Cells* or *Release Request/Accepted Cells* . These losses can be taken into account by provisioning different timers in the LCM and the source which can time out after a specified period.

4 Performance Considerations

To compare performance of the CBR protocol with that of the FRM and INP schemes, we consider response time, cost of implementation, and involvement of the public ATM network as performance criteria.

Public Network Involvement : We note that in CBR ATM XC does not have any additional functions to perform. The CBR protocol, therefore, can be implemented on simple ATM switches. In FRM, each ATM XC has to keep track of the present user bandwidth allocation and in INP scheme, if user is allowed to change the I-VP policing parameters dynamically, complex signaling procedures are required in the ATM network.

Response Time : Average response time for the reservation procedure is also reduced in the CBR protocol as compared to FRM. The *Reservation Request Cell* now does not need to go through each concerned node along the path but only upto CBRM. The location of the CBRM in the AVPN topology can be determined to get an optimal value of the average response time. The average response time for FRM and CBR in case of ring and linear topologies are given below. It has been assumed here that a session exists between each pair of nodes with uniform traffic between the nodes. Location of CBRM in the linear topology is assumed to be at the central node.

- Ring Topology

$$\text{for FRM} \qquad \mathrm{t_R} = \frac{\mathrm{N}+1}{2}(\mathrm{t_{avg}} + \mathrm{t_p})$$
$$\text{for CBR} \qquad \mathrm{t_R} = \frac{\mathrm{N}^2-1}{2\mathrm{N}} * \mathrm{t_{avg}} + \mathrm{T_s}$$

- Linear Topology

$$\text{for FRM} \qquad \mathrm{t_R} = \frac{2(\mathrm{N}+1)}{3}(\mathrm{t_{avg}} + \mathrm{t_p})$$
$$\text{for CBR} \qquad \mathrm{t_R} = \frac{\mathrm{N}^2-1}{2\mathrm{N}} * \mathrm{t_{avg}} + \mathrm{T_s}$$

where $\mathrm{t_R}$ is the response time of the reservation procedure, $\mathrm{t_{avg}}$ is the average propagation delay on a link, $\mathrm{t_p}$ is the processing delay of a reservation cell on an ATM XC, $\mathrm{T_s}$ is the processing delay of the reservation cell at CBRM, and N is the number of nodes in the AVPN. We see that for linear topology the reduction in response time is quite appreciable. In any case, however, it will not exceed that of the FRM.

Transmission Inefficiency : In case of FRM, even if the reservation request can not be accepted due to insufficient resources at some of the nodes, the resources are reserved for a round trip delay on the previous nodes through which the reservation cell has been cleared. This results in the waste of resources. CBR is not affected by this drawback because the resources are reserved only when all the concerned nodes can support the reservation request. Furthermore,

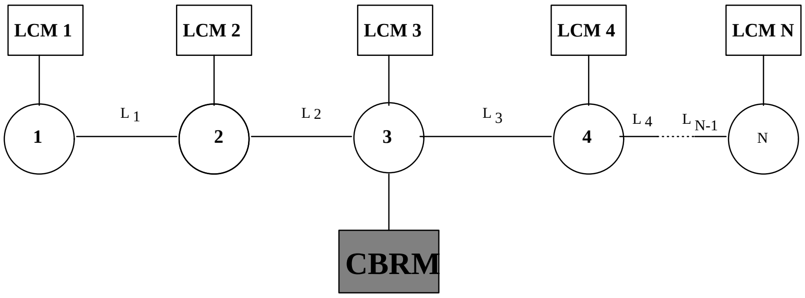

Figure 5: Linear Topology

in case of successful reservation, the resources are reserved for only half of the round trip delay in addition to the actual burst duration. So the equation 1 is modified as follows.

$$\rho_{\text{reserved}} = \rho_{\text{offered}} * (1 + \frac{\text{ERT}}{2 * \text{EA}}) \tag{2}$$

Therefore, the transmission inefficiency is given by ERT/(2∗EA). Please note that the average value of ERT here is itself low as compared to the average value of the round trip delay in FRM.

Phase-In : CBR protocol can be implemented on simple ATM switches as it does not require any special function from them. Hence the gradual phase-in of the AVPN is easy in this case as compared to FRM and INP. The only thing that requires up gradation is the AVPN topology and the values of C_i's at CBRM. The cost of special hardware and software in case of FRM has now been shifted to CBRM.

Problems In Large Network : If number of nodes in an AVPN increases, FRM continues to work well without being affected. But in case of CBR, it becomes difficult to maintain huge database at a single place. In this case, more than one bandwidth managers are needed and the database has to be synchronized among these managers. This results in additional complexity in the AVPN.

5 Analysis of CBR

AVPN is expected to support all types of traffic between geographically spread sites of a customer. Some of the applications like real time video and voice may not tolerate large delays while some other classes like data and still images can tolerate. So we can put a limit on maximum number of bursts that can be queued at the customer site depending on the delay requirements. Burst loss probability and average delay of a burst can then be calculated by preparing a mathematical model.

Let N be the number of nodes in an AVPN. A session is defined between each unordered node pair with uniform traffic between the nodes. The peak bit rate of the source is R. The number of sessions passing through link L_i is n_i. Two virtual topologies, ring and linear, are considered here for the model.

5.1 Ring Topology

In case of ring topology, the number of sessions n_i on each link will be equal due to symmetry of the ring.

$$\mathrm{n}_1 = \mathrm{n}_2 = \ldots = \mathrm{n}$$

where n is given by[1]

$$\mathrm{n} = \frac{(\frac{\mathrm{N}-1}{2})(\frac{\mathrm{N}-1}{2}+1)}{2} \tag{3}$$

Let C be the capacity reserved on each link for the AVPN. The maximum number of sessions m, therefore, that can be simultaneously supported on the link, is given as

$$\mathrm{m} = \frac{\mathrm{C}}{\mathrm{R}} \tag{4}$$

Each link, therefore, can be modeled as m servers, which are common to n session queues. Here we assume that each link behaves independently and the arrival rate of bursts, belonging to a particular session, is equal on all the concerned links. The effect of other links can be taken into account by using reduced load approximation.

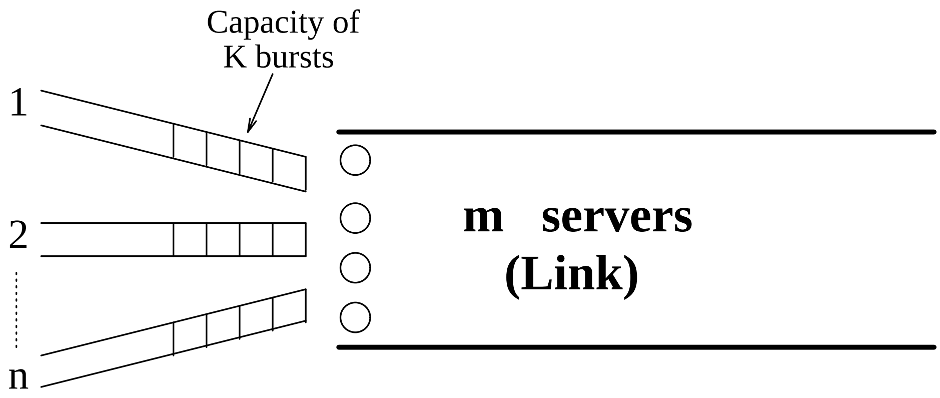

Figure 6: Link Model

Let the maximum number of bursts, for a session, that can be queued at the customer site is K. Therefore, each session queue can have 0 to K bursts at a given time. The total number of bursts that are being served may vary between 0 to m. This system can be modeled as an $\mathbf{n+1}$ **Dimensional Continuous Time Markov Chain**. The $(\mathrm{n}+1)$ th dimension shows the number of bursts being served.

The state space of the system is represented by set of states $\mathbf{S} = \{\mathbf{s_1},\ \mathbf{s_2},\ \ldots\}$. Each element of the state space $\mathbf{S}$ represents a unique state $\mathbf{s}_i$, given by $1 \times (\mathrm{n}+1)$ vector

$$\mathbf{s}_i = [x_{i,1}, x_{i,2}, \ldots, x_{i,n+1}] \tag{5}$$

values of various $x_{i,j}$ are given by

$$x_{i,j} = \begin{cases} \text{Number of bursts queued for session } j \text{ in state } \mathbf{s_i} & 1 \le j \le \mathrm{n} \\ (\textit{not including those bursts which are in service}) & \\ & \\ \text{Total number of bursts presently being served} & j = \mathrm{n}+1 \end{cases}$$

[1] Shortest path routing has been assumed

Each of the $x_{i,j}$'s $(1 \leq j \leq \mathrm{n})$ may take any value between 0 to K. The values of $x_{i,\mathrm{n}+1}$ can vary between 0 to m. Note that $x_{i,\mathrm{n}+1}$ can be less than m only if all the session queues are empty. This is because as soon as a server becomes free it takes a burst from any one of the non-empty queues with equal probability.

The total number of states is thus given by,

$$\|\mathbf{S}\| = (\mathrm{K}+1)^{\mathrm{n}} + \mathrm{m} \tag{6}$$

5.1.1 Formulation of generator matrix Q

Each element $\mathrm{q_{ij}}$ of the generator matrix $\mathbf{Q}$ will denote the transition rate from state $\mathbf{s_i}$ to state $\mathbf{s_j}$. The arrival rate of bursts for each session is equal to λ. The mean service time of a burst is $1/\mu$. Total number of bursts in the system can differ by at most one in any one of the transitions. The various transitions of the states can be classified as follows:

- **Arrival of a burst**

  1. If all queues are empty and at least one of the servers is free, the incoming burst will directly go to a free server. So the rate at which the number of bursts being served increases, is equal to the summation of arrival rate of all the sessions, i.e., $\mathrm{n}\lambda$.
  2. If all the servers are busy, an incoming burst will be queued in its session queue. In this case, the arrival rate of the session queue is λ.

- **Departure of a burst**

  1. If at least one of the queues is non-empty, as soon as a burst completes its service, a new burst is taken by that server from one of the non-empty queues with equal probability. So the rate at which the number of bursts, queued in a particular session queue, decreases is equal to the total service rate divided by number of the non-empty queues. The number of bursts being served in this case is unchanged.
  2. If all the session queues are empty, when a burst completes its service, the number of bursts being served gets decreased by one. The rate of this transition is given by present service rate.

The various values of $\mathrm{q_{ij}}$ are thus given as follows:

$$\mathop{\mathrm{q_{ij}}}_{\mathrm{i}\neq\mathrm{j}} = \begin{cases} \lambda & \text{if} \quad x_{j,\ell} = x_{i,\ell} + 1 \\ & \text{for one and only one value of } \ell \text{ where } 1 \leq \ell \leq \mathrm{n} \\ \mathrm{n} * \lambda & \text{if} \quad x_{j,\mathrm{n}+1} = x_{i,\mathrm{n}+1} + 1 \\ \mathrm{m} * \mu/\mathrm{p} & \text{if} \quad x_{j,\ell} = x_{i,\ell} - 1 \\ & \text{for one and only one value of } \ell \text{ where } 1 \leq \ell \leq \mathrm{n} \\ & \text{p is number of the non-empty session queues} \\ x_{i,\mathrm{n}+1} * \mu & \text{if} \quad x_{j,\mathrm{n}+1} = x_{i,\mathrm{n}+1} - 1 \\ 0 & \text{otherwise} \end{cases}$$

and

$$q_{ii} = -\sum_{\substack{j=1 \\ j\neq i}}^{||\mathbf{S}||} q_{ij}$$

5.1.2 Calculation of Burst Loss Probability

After getting the generator matrix $\mathbf{Q}$, the steady state probability vector $\mathbf{\Pi}$ can be found by solving the following set of equations

$$\begin{aligned} \mathbf{\Pi Q} &= \mathbf{0} \\ \sum_{i=1}^{||\mathbf{S}||} \pi_i &= \mathbf{1} \end{aligned} \tag{7}$$

Burst loss probability for session j $(1 \leq j \leq \mathrm{n})$ is given by

$$\mathrm{P_b}(j) = \sum_{\mathbf{s}_i \in \mathbf{U}} \pi_i \tag{8}$$

where $\mathbf{U} \subset \mathbf{S}$ such that

$$\forall \quad \mathbf{s}_i \in \mathbf{U} \quad ; \quad x_{i,j} = \mathrm{K} \tag{9}$$

Due to symmetry[2] the average probability of burst loss

$$\mathrm{P_b} = \mathrm{P_b}(1) = \mathrm{P_b}(2) = \ldots = \mathrm{P_b}(\mathrm{n}) \tag{10}$$

5.1.3 Calculation of Delays

Average delay of a burst can be calculated with the help of Little's theorem

$$\overline{\mathrm{N}} = \lambda \mathrm{T} \tag{11}$$

Where $\overline{\mathrm{N}}$ is the average number of bursts given by

$$\overline{\mathrm{N}} = \sum_i i * \pi_i \tag{12}$$

In the present case, value of $\overline{\mathrm{N}}$ for a given session will be determined by the average number of bursts in the session queue and those, belonging to the given session, which are in service.

Each burst which is in service, belongs to a particular session with the probability 1/n. If at a given time, there are a total of α bursts in service, the probability that out of them β bursts belong to a given session, $\mathrm{p}_\alpha(\beta)$, will be given by simple binomial distribution

$$\mathrm{p}_\alpha(\beta) = {}^{\alpha}\mathrm{C}_\beta * (1/\mathrm{n})^\beta * (1 - 1/\mathrm{n})^{\alpha-\beta} \tag{13}$$

where ${}^{\alpha}C_\beta$ is given by $\frac{\alpha!}{\beta!(\alpha-\beta)!}$.

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[2] The values of K and λ are equal for all user sites

For a session i ($1 \leq i \leq$ n), therefore, the average number of bursts $\overline{\mathrm{N}}_i$ will be given by

$$\overline{\mathrm{N}}_i = \sum_{\mathbf{s}_\ell \in \mathbf{S}} \sum_{j=0}^{x_{\ell,\mathrm{n}+1}} (x_{\ell,i} + j) * \mathrm{p}_{x_{\ell,\mathrm{n}+1}}(j) * \pi_\ell \tag{14}$$

T is the average delay of a burst, which is composed of the service time $\mathrm{T_t}$ and the queuing delay $\mathrm{T_q}$

$$\mathrm{T} = \mathrm{T_t} + \mathrm{T_q} \tag{15}$$

The average service time of a burst is given by $1/\mu$.

5.2 Linear Topology

In case of linear topology, number of sessions on the link L_i, as shown in Figure 5, is given by

$$\mathrm{n}_i = i * (\mathrm{N} - i) \tag{16}$$

For each session the burst loss probability can then be calculated from equation 8. Now the average burst loss probability can be calculated by taking the average of the burst loss probabilities over all the links.

$$\mathrm{P_b} = \frac{\mathrm{P_{b,1}} + \mathrm{P_{b,2}} + \ldots + \mathrm{P_{b,N-1}}}{\mathrm{N} - 1} \tag{17}$$

Here, $\mathrm{P_{b,i}}$ denotes the burst loss probability on the link $\mathrm{L_i}$. The average delay of a burst in this case is obtained by taking the average of the delays over all links.

5.3 Numerical Example

Here an example is given to show the various steps involved in the analysis. The topology considered is a ring.

- The number of nodes in the AVPN N = 5
- The reserved capacity on each link C = 10 Mb/s
- The peak bit rate of the source R = 10 Mb/s
- The value of K = 1

The number of session on each link by equation 3

$$\begin{aligned} \mathrm{n} &= \frac{(\frac{5-1}{2})(\frac{5-1}{2}+1)}{2} \\ &= 3 \end{aligned}$$

The total number of states are given by equation 6

$$\begin{aligned} \|\mathbf{S}\| &= (1+1)^3 + 1 \\ &= 9 \end{aligned}$$

So this comes out to be a four dimensional Markov Chain. All the states of the system are given as follows:

$$\begin{array}{ll} \mathbf{S_1}: 0000 & \mathbf{S_6}: 1001 \\ \mathbf{S_2}: 0001 & \mathbf{S_7}: 1011 \\ \mathbf{S_3}: 0011 & \mathbf{S_8}: 1101 \\ \mathbf{S_4}: 0101 & \mathbf{S_9}: 1111 \\ \mathbf{S_5}: 0111 & \end{array}$$

The representation of the states is such that each digit shows the number of bursts queued for that session except for the last digit which represents the total number of bursts being served. The last digit can be zero only if all the other digits are zeros since a server can not be idle if there is a burst queued.

The generator matrix $\mathbf{Q}$ of the system is given below.

$$\mathbf{Q} = \begin{bmatrix} -3\lambda & 3\lambda & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \mu & -\mu-3\lambda & \lambda & \lambda & 0 & \lambda & 0 & 0 & 0 \\ 0 & \mu & -\mu-2\lambda & 0 & \lambda & 0 & \lambda & 0 & 0 \\ 0 & \mu & 0 & -\mu-2\lambda & \lambda & 0 & 0 & \lambda & 0 \\ 0 & 0 & \mu/2 & \mu/2 & -\mu-\lambda & 0 & 0 & 0 & \lambda \\ 0 & \mu & 0 & 0 & 0 & -\mu-2\lambda & \lambda & \lambda & 0 \\ 0 & 0 & \mu/2 & 0 & 0 & \mu/2 & -\mu-\lambda & 0 & \lambda \\ 0 & 0 & 0 & \mu/2 & 0 & \mu/2 & 0 & -\mu-\lambda & \lambda \\ 0 & 0 & 0 & 0 & \mu/3 & 0 & \mu/3 & \mu/3 & -\mu \end{bmatrix}$$

Where λ is the arrival rate of the bursts for each session and μ is the service rate of the bursts. By solving the set of equations 7, we get the steady state probabilities $\pi_i's$ for the corresponding states $\mathbf{s}_i$'s. Now the burst loss probability can be calculated as follows.

Burst Loss Probability : The burst loss probability of a session is given by equation 8

$$\mathrm{P_b}(1) = \pi_6 + \pi_7 + \pi_8 + \pi_9$$

similarly,

$$\mathrm{P_b}(2) = \pi_4 + \pi_5 + \pi_8 + \pi_9$$
$$\mathrm{P_b}(3) = \pi_3 + \pi_5 + \pi_7 + \pi_9$$

So the average probability of burst loss is

$$\mathrm{P_b} = \frac{\mathrm{P_b}(1) + \mathrm{P_b}(2) + \mathrm{P_b}(3)}{3}$$

Due to symmetry

$$\mathrm{P_b} = \mathrm{P_b}(1) = \mathrm{P_b}(2) = \mathrm{P_b}(3)$$

Average Delay : The probabilities that whether a burst being served belongs to a particular session queue or not, are given by equation 13

$$\mathrm{p_1}(1) = 1/3 \qquad \mathrm{p_1}(0) = 2/3$$

So the average number of bursts in session 1 equals

$$\begin{aligned}
\overline{\mathrm{N}}_1 &= 1 * 1/3(\pi_2 + \pi_3 + \pi_4 + \pi_5) \;+\; 1 * 2/3(\pi_6 + \pi_7 + \pi_8 + \pi_9) \\
&\quad + 2 * 1/3(\pi_6 + \pi_7 + \pi_8 + \pi_9) \\
\overline{\mathrm{N}}_1 &= 1/3(\pi_2 + \pi_3 + \pi_4 + \pi_5) \;+\; 4/3(\pi_6 + \pi_7 + \pi_8 + \pi_9)
\end{aligned}$$

Now the average delay of a burst in session 1 is given as

$$\mathrm{T}_1 = \overline{\mathrm{N}}_1/\lambda$$

Due to symmetry, the average delay T of a burst will be given by

$$\mathrm{T} = \mathrm{T}_1 = \mathrm{T}_2 = \mathrm{T}_3$$

The analytical results are presented in section 6, in comparison with the simulation results of the CBR protocol.

5.4 Reduced Load Approximation

Here we remove the assumption made in the beginning of the analysis. We now consider effect of the other links on the burst loss probability at a particular link by using Reduced Load Approximation [4]. Here an iterative procedure is given which takes into account the effect of the other links by reducing the total arrival rate on the link.

We take λ_i as the effective arrival rate of session i on that link and H_i is the number of links involved in that session. ${\mathrm{P_b}}^j(i)$ is the value of $\mathrm{P_b}(i)$ after j iterations.

5.4.1 *Iterative Procedure*

- **Step 1:**
  - Set $\;\;$ j=1
  - For i = 1 to n $\quad \lambda_\mathrm{i} = \lambda$
  - Calculate the values of various $\quad \mathrm{P^j_b(i)}$
- **Step 2:**
  - Increment j
  - For i = 1 to n $\quad \lambda_\mathrm{i} = \lambda * (1 - \mathrm{P^{j-1}_b(i)})^{\mathrm{H_i}-1}$
  - Calculate the values of various $\quad \mathrm{P^j_b(i)}$
- **Step 3:**
  - If $\quad \sum_{\mathrm{i}=1}^{\mathrm{n}} \mid \mathrm{P^j_b(i)} - \mathrm{P^{j-1}_b(i)} \mid \;\leq\; \epsilon \quad$ Stop
  - Else $\qquad$ Go to Step 2

The value of ϵ can be taken arbitrary small depending upon the value of the desired burst loss probability. However, it has been observed that the above procedure results in total convergent value of burst loss probability.

6 Simulation

Simulation results have been obtained using *on-off model* [5] for the source. In this model the source is always in one of the two states, *viz.*, On state and Off state. During On state the source transmits at peak bit rate and during Off state it remains idle. The length of both On and Off periods are assumed to be exponentially distributed. The burstiness of the source can be calculated as follows.

R is the peak bit rate with which the source transmits in On state. T_{On} and T_{Off} are mean On and mean Off periods of the source respectively. Considering r as the average bit rate of the source,

$$\begin{aligned} \mathrm{R.T_{On}} &= \mathrm{r.(T_{On} + T_{Off})} \\ \text{burstiness} \quad \mathrm{b} &= \frac{\text{peak bit rate}}{\text{mean bit rate}} \\ \mathrm{b} &= \frac{\mathrm{R}}{\mathrm{r}} \\ \mathrm{b} &= \frac{\mathrm{T_{On} + T_{Off}}}{\mathrm{T_{On}}} \end{aligned}$$

6.1 Analytical and Simulation Results

Here we present analytical and simulation results for both the topologies, *i.e.*, ring and linear. In all the followings plots in this section the mean burst length is taken as 1000 cells. The peak bit rate of the source in the On state is taken as 10 Mb/s. Average delay of a burst is calculated assuming 53 bytes ATM cells. Analytical results are obtained without using reduced load approximation for simplicity.

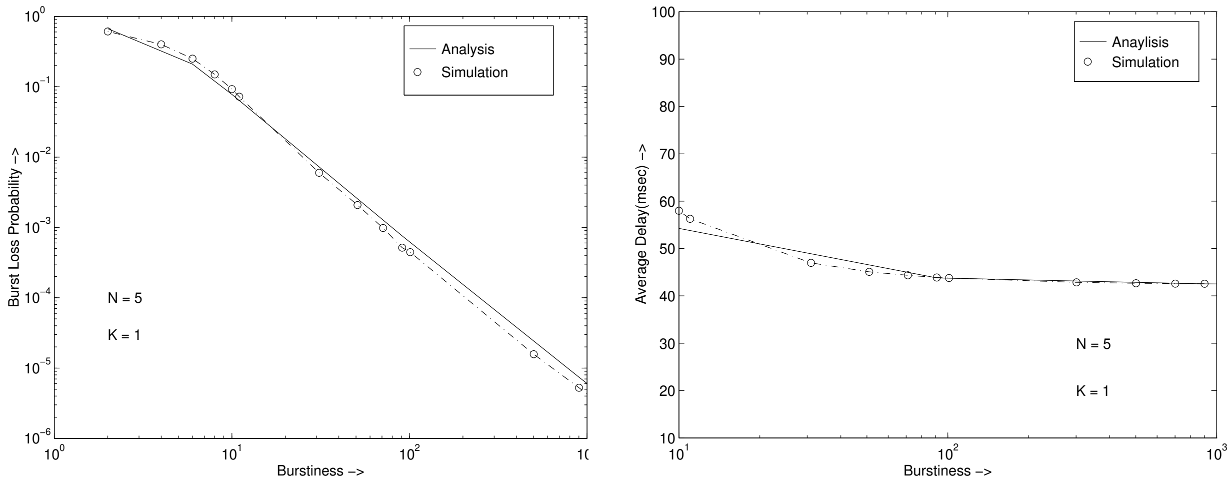

Figure 7: Burst Loss Probability and Average Delay versus Burstiness

In Figure 7, burst loss probability and average delay of a burst are plotted against the burstiness of the source for a ring of 5 nodes. As the burstiness is increased, keeping the mean burst length constant, the bursts come less frequently and buffer becomes empty quite often. Thus both the burst loss probability and the average delay decrease monotonically.

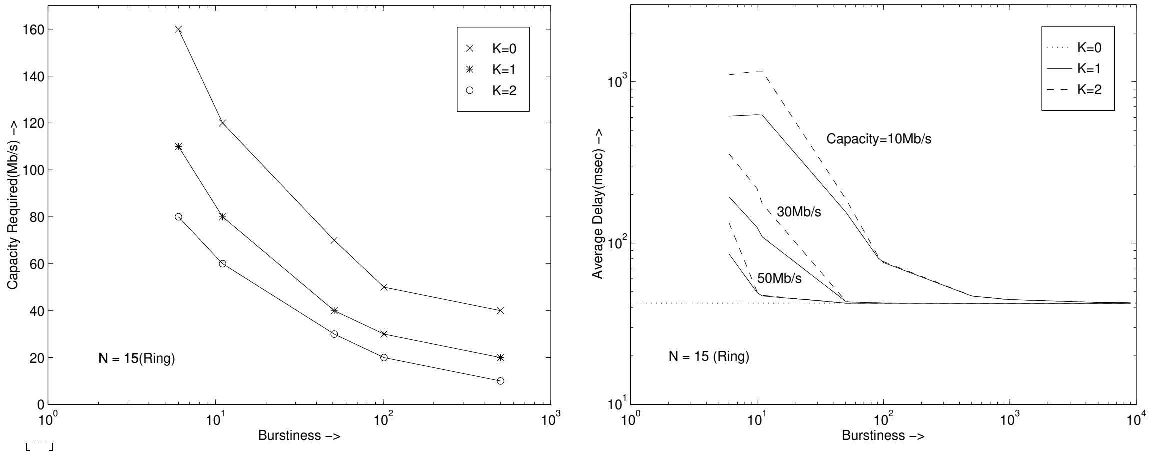

Figure 8: Link Capacity and Average Delay versus Burstiness

In Figure 8, capacity required on the links and average delay of a burst are plotted against burstiness for various values of permissible queue length K. Here the QOS(Quality of Service) parameter is taken as the burst loss probability which is less than 10^{-4} for all the plots in the figure. We see that as the burstiness is increased, the effect of queuing at customer site decreases. This is because of the fact that since the bursts are coming less frequently, there are less chances of them to be queued at the user site. When the burstiness is too high, there is no queuing delay for the bursts and average delay of a burst reduces to average transmission delay.

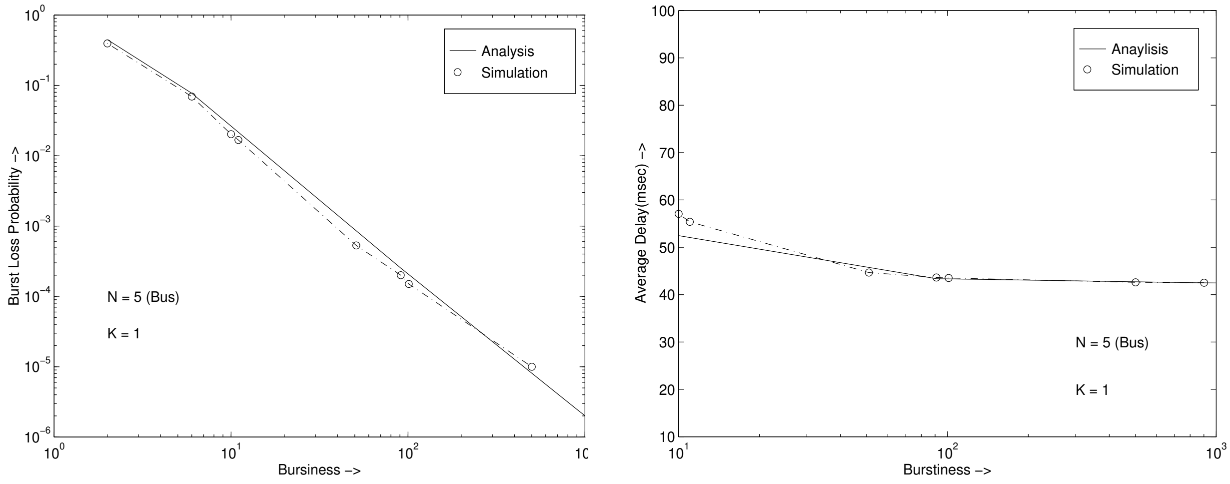

Figure 9: Burst Loss Probability and Average Delay versus Burstiness

Figure 9 and 10 show the results obtained for linear topology, as given in figure 5. In this topology, since the number of sessions on a link varies according to its position from the center, the capacity reserved on various links are assumed to be in the same ratio as given by equation 16. The capacity reserved on the links shown in the figure is for link L_1. The capacity reserved on the other links can be found with the help of equation 16.

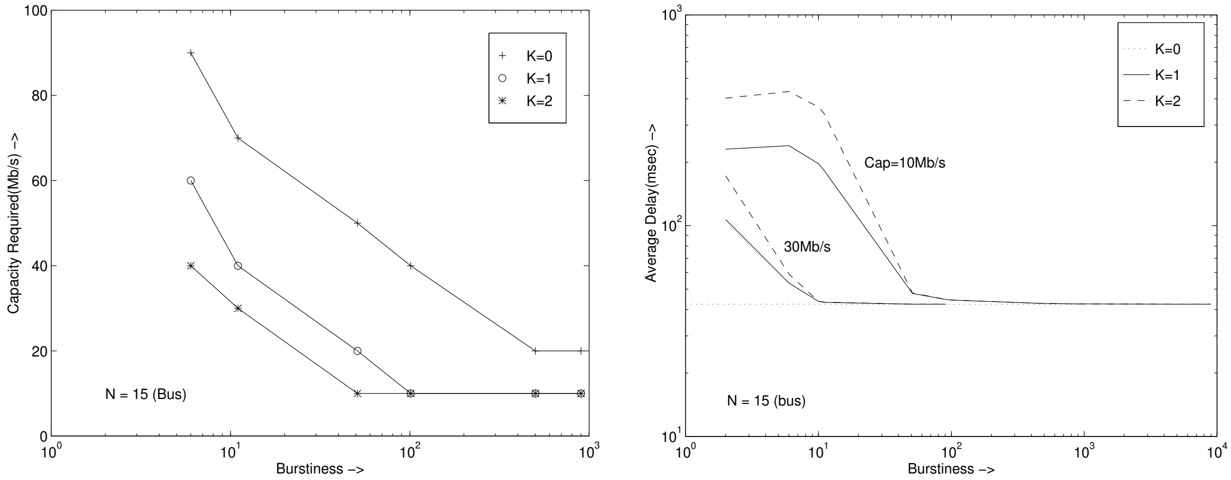

Figure 10: Link Capacity and Average Delay versus Burstiness

Conclusion

It can be concluded from the results and discussions in this paper that the centralized approach for bandwidth allocation in AVPNs offers several advantages as compared to FRM and INP schemes. It reduces the involvement of the public ATM network as compared to FRM, and offers better statistical multiplexing as compared to INP strategy. So it takes the good features of both the schemes and does not suffer from their drawbacks. But in order to get these advantages, the reliability of CBRM must be extremely high since whole AVPN functionality is dependent on it. We can try to avoid this problem by having more than one such managers but in that case the issues of database synchronization will arise. Further research is needed in this field to explore these issues.

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