Performance Analysis of Fast Reservation Protocols for ATM Networks

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Abstract

The future Broadband-ISDN based on the Asynchronous Transfer Mode (ATM) has to cope with a vast variety of services with different bitrate and Quality of Service (QoS) requirements. Consequently, traffic control is essential to guarantee the negotiated QoS while allowing a high network utilization. One possible traffic control scheme is the Fast Reservation Protocol (FRP) which introduces a dynamic traffic control at the burst level enhancing the capabilities of the network to increase its utilization for highly bursty traffic. In this paper we focus on the analysis of the two variants of the FRP. An analytical approach for an isolated switching node as well as for a whole reference connection is presented. The obtained results show a good agreement with simulation results. Finally, the analysis is used to compare the two variants of the FRP with respect to their key performance parameters.

Keyword Codes: C.2.2; C.4; G.3

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1. INTRODUCTION

The Asynchronous Transfer Mode has been standardized for the future Broadband-ISDN [I.121]. This packet-oriented technique supports statistical multiplexing to make efficient use of the network resources. However, this requires traffic control schemes in order to guarantee the QoS of the different connections negotiated at connection set-up [I.371].

For Variable Bitrate (VBR) sources peak bitrate allocation for the whole duration of the connection may result in low network utilization [Boye 90]. Moreover, for VBR services like data services which are very loss sensitive but may tolerate a certain delay, pure statistical multiplexing seems to be inadequate.

Fast resource management schemes, as standardized in [I.371] for the B-ISDN, address

this problem by introducing an access control on the time scale of the round-trip propagation delay of an ATM connection. The in-band signalling necessary for these schemes is supported by the payload type field in the ATM cell header [I.361].

One possible Fast Resource Management function is the FRP proposed and described in [Boye 90, BoTr 92]. The basic idea is to allocate network resources for a connection at the burst level for the transfer duration only. In order to minimize the time to allocate and deallocate the bitrate, the FRP has to be supported by special hardware. Hence, so called *reservation cells* are processed in the switching nodes “on the fly”. If the network is in a congestion state, the protocol will reattempt to allocate the bitrate after a certain time interval.

Boyer and Tranchier [BoTr 92] address the performance of an FRP variant called the Fast Reservation Protocol with Delayed Transmission. In this case, a source has to wait for an acknowledgement from the network before it can increase its bitrate. They consider identical on-off sources with negative exponentially distributed burst and silence periods and approximate the reservation blocking probability of an isolated switching node by the waiting probability of a Markovian queueing system with finite population and a finite number of servers. Doshi [DoDr 90] and Worster [WFD 93] have presented a similar analysis, where they use Erlang’s blocking formula to assess the reservation blocking probability. In contrast to [BoTr 92] they assume that the burst interarrival times are negative-exponentially distributed. Crosby [Cros 93] analyses a simple dynamic “renegotiation” protocol and compares it to static resource allocation. Bounds were derived on the performance of an optimal dynamic protocol.

In this paper we present a detailed analysis of the two variants of the FRP. A switching node model for on/off sources is presented that comprises the reattempts for blocked or lost bursts. Furthermore, the end-to-end performance of the FRP is evaluated for a reference connection.

The paper is organized as follows: In section 2. the two variants of the FRP are outlined. In section 3. the modelling assumptions are given. Section 4. is dedicated to the analysis of an isolated switching node and a whole reference connection running over several nodes. In section 5. the two variants of the FRP are compared using end-to-end performance measures.

2. THE FAST RESERVATION PROTOCOL

In our analysis we want to contrast the two fast resource management schemes called *Fast Reservation Protocol with Immediate Transmission* (FRP/IT) and *Fast Reservation Protocol with Delayed Transmission* (FRP/DT). These schemes described in [BoTr 92] are based upon variable peak bitrate reservation in the switching nodes. Here, only the main characteristics reflected in the analysis are outlined.

The FRP/DT is intended to be applied on Negotiated Stepwise Variable Bit Rate (NSVBR) sources, that may tolerate a variable delay of a bitrate request. Among such services are LAN-LAN interconnections. The FRP/IT may be used for sources that cannot wait for a network agreement before increasing their activity, for example multimedia

sources with real-time requirements including traffic from video codecs.

Figure 1. FRP reference configuration

Both protocols are run by the general network, make use of the same hardware functions in the switching nodes and may coexist. The allocated peak bitrate for a connection in the switching elements can be renegotiated upon request of the source using mono cell management messages. The allocation and release messages sent by a source are checked by a so-called FRP Control Unit at the ingress node of the network before being processed by the switching elements. Thus, the FRP is composed of a user-network protocol and a network internal protocol as depicted in Figure 1.

According to the FRP/DT, a source has to reserve the required bitrate in all switching nodes along its connection before increasing its activity. A *Reservation Requested Cell* is sent from the source to the FRP Control Unit to indicate a bitrate reservation request. The receipt of a *Reservation Requested Cell* is acknowledged by the FRP Control Unit and the *Reservation Requested Cell* is forwarded to the switching nodes along the connection. If the bitrate is available in all nodes, an acknowledgement is sent back from the last node to the FRP Control Unit and a *Reservation Accepted Cell* is returned by the FRP Control Unit to the source indicating the permission to increase its activity. During the reservation process the source may continue to transfer at the previous rate. If the reservation fails in any of the nodes, no reservation acknowledgement is sent from the last switching node to the FRP Control Unit. The reservation is timed out and will be reattempted by the FRP Control Unit after some time that may depend on the congestion state of the network. If no reservation is possible after several attempts, a *Reservation Denied Cell* is returned from the FRP Control Unit to the source. To release network resources, the source sends a *Release Requested Cell* to the FRP Control Unit that forwards it to the switching nodes.

When using the FRP/IT, a source can transfer the burst immediately after the *Reservation Requested Cell*. The source does not have to wait for an acknowledgement of the network. After the burst, it sends immediately a *Release Requested Cell*. If possible, the required bitrate is reserved at every switching node “on the fly” for the duration of the burst. When a reservation fails in any of the nodes, the whole burst will be discarded at

that node and has to be retransferred after some time. Since the FRP/IT is not entirely specified in [BoTr 92], there remain two possibilities to implement the generation of reattempts. Either the losses are “repaired” by retransmission in a higher layer or explicit acknowledgements are introduced from the last switching node to the FRP Control Unit and the source. For the analysis, presented in this paper, the latter alternative is chosen for comparison purposes. In this case the source will retransfer the whole burst after a certain time interval in case of congestion. Hence, the source has to buffer the burst until it receives a positive acknowledgement.

3. MODELLING

The ATM network can be represented by its switching nodes and the finite capacity links that connect them. Since the FRPs are connection-oriented protocols, the analysis will be performed for a reference connection that is modelled by a chain of n switching nodes as illustrated in Figure 2.

Figure 2. Reference connection

At any switching node connections may originate or terminate. Thus a connection is defined by the switching nodes where it joins and leaves the chain. For the analysis only the burst level behaviour is considered. According to the Fast Reservation Protocols bursts are not buffered within the network in case of congestion. Hence, a switching node can be modelled by a pure loss system with c servers corresponding to a maximum of c bursts that can be transferred simultaneously on its reference output link. This is similar to the model of a circuit-switched network at the connection level.

Figure 3. Burst level behaviour of a traffic source

The traffic sources used in the analysis are of the on/off-type (burst-silence model) with negative exponentially distributed burst and silence durations. Within a burst the bitrate of the source is given by Λ_{max} . During silence periods the source emits no information. If a bitrate reservation request is rejected by a node, the affected traffic source will be blocked for a certain time before trying again to reserve the bitrate. This behaviour is depicted in Figure 3.

The mean burst duration will be denoted by $t_b = E[T_b]$, the mean silence duration by $t_s = E[T_s]$ and the mean time between reattempts in case of congestion by $t_w = E[T_w]$. The burstiness b of the traffic sources is defined by the ratio of peak to mean bitrate given as $b = 1 + \frac{t_s}{t_b}$ for a source that does not experience blocking of its bitrate requests.

4. ANALYSIS

Within this section the analysis of the FRP/IT and FRP/DT will be presented. In principle, our model is very similar to that of a circuit-switched network at the connection level. In [Kell 86] it is shown that circuit-switched networks with an infinite number of customers satisfy the requirements for a product form solution. This approach may be extended to a finite number of customers. However, the product form solution is computationally infeasible for a realistic network size and it cannot incorporate the reattempts of a rejected burst. Since reattempts are an essential part of the FRP and burst blocking or loss probabilities may be much larger than the ATM cell loss probability, they cannot be neglected. The analysis presented in the following takes the reattempts into account and will consider the correlations among consecutive nodes along the reference connection. It will comprise two parts:

1. Analysis of an isolated queueing node of the reference connection including reattempts.
2. Node-by-node analysis of a reference connection based on the analysis of its isolated switching nodes taking into account the correlation of the traffic streams offered to the nodes along the reference connection.

4.1. Analysis of an Isolated Switching Node

For the analysis of an isolated switching node we presuppose that all characteristic time intervals are negative-exponentially distributed. Thus, assuming negative-exponentially distributed silence times and time intervals between reattempts, the activation rate α of a source being in a silence state is given by $\alpha = \frac{1}{(b-1)t_b}$ and the activation rate β for reattempts is given by $\beta = \frac{1}{t_w}$. For the FRP/IT the protocol overhead necessary to reserve the bitrate for a burst can be neglected. Since the burst duration T_b is negative-exponentially distributed, the termination rate ϵ is determined by $\epsilon = \frac{1}{t_b}$. In contrast, the FRP/DT reserves the bitrate for a connection at all participating nodes before transferring a burst. This results in a blind occupation equal to the roundtrip delay τ . Hence, in this case the termination rate ϵ is given by $\epsilon = \frac{1}{t_b + \tau}$ assuming that the sum of the burst

duration and the roundtrip delay is negative-exponentially distributed. Simulations with constant time intervals between reattempts and constant roundtrip delays were used to validate the assumptions of negative exponential distributions. They have been found to be in very good agreement with the analysis. Similar approximations have been used in [SBKT 93] and [YiHl 91]. Furthermore, the reference link has a capacity of simultaneously transferring c bursts.

Figure 4. State-transition diagram of an isolated node

With these assumptions an isolated node multiplexing $N > c$ sources can be described by a two-dimensional Markov chain with the state space $\{(i, j) : 0 \leq i \leq c, i \leq j \leq N - c + i\}$, where i is the number of active sources on the reference link and j is the number of active (transferring or blocked) sources that want to use the reference link. The corresponding state-transition diagram is depicted in Figure 4. The two-dimensional Markov chain comprises three types of state transitions. Suppose the node is in state $(1, 2)$, i.e. one source is successfully transferring and a reservation request of another source was rejected while the network was in a state of congestion. Thus, there remain $N-2$ sources that may want to start a burst transfer (rate $(N-2)\alpha_2$), the transferring source may terminate its burst transfer (rate ϵ) and the source with the rejected request may start a reattempt (rate β). For $c \geq N$, i.e. no blockings or losses occur, the two-dimensional state-space is reduced to a one-dimensional chain.

The parameters α_l are used to adapt the node model to the probability distribution of the number of active sources of the incoming traffic when the reference connection is considered (cf. section 4.2.3.). For N identical sources it is $\alpha_l = \alpha$ for $l = 0, 1, \dots, N-1$.

The structure of this Markov chain does not satisfy the requirements for a product

form solution, thus the stationary probabilities $q(i, j)$ have to be calculated from a set of $(c + 1)(N - c + 1)$ linear equations comprising the normalization equation

$$\sum_{i=0}^c \sum_{j=i}^{N-c+i} q(i, j) = 1 \quad (1)$$

using numerical algorithms.

Using the probabilities $q(i, j)$, the probability distribution $p(i)$ of having i bursts simultaneously transferred on the reference link is given by

$$p(i) = \sum_{j=i}^{N-c+i} q(i, j), \quad \text{for } i = 0, 1, \dots, c. \quad (2)$$

The model distinguishes between the first bitrate request for a burst and the reattempts. Hence, the blocking (FRP/DT) or loss (FRP/IT) probabilities B_{init} for the first attempt of a source to transfer a burst and B_{tot} for all attempts including the reattempts can be calculated using the state-transition diagram. The probabilities B_{init} and B_{tot} are given by the respective probability of an arriving burst that is blocked or lost divided by the probability of a burst arrival. Thus it is

$$B_{tot} = \frac{\sum_{j=c}^{N-1} [(N-j)q(c, j)\alpha_j] + \sum_{j=c+1}^N [(j-c)q(c, j)\beta]}{\sum_{i=0}^c \left[\sum_{j=i}^{N-c+i} [(N-j)q(i, j)\alpha_j] + \sum_{j=i+1}^{N-c+i} [(j-i)q(i, j)\beta] \right]} \quad (3)$$

and

$$B_{init} = \frac{\sum_{j=c}^{N-1} (N-j)q(c, j)\alpha_j}{\sum_{i=0}^c \sum_{j=i}^{N-c+i} (N-j)q(i, j)\alpha_j}. \quad (4)$$

The total blocking probability B_{tot} is also equal to the mean number of reservation rejects divided by the mean number of reservation attempts necessary to successfully transfer a burst. Thus, it can be derived that the mean number of attempts $\bar{v}$ needed to transfer a burst is given by

$$\bar{v} = \frac{1}{1 - B_{tot}}. \quad (5)$$

4.2. Analysis of a Reference Connection

Up to now, the focus of the analysis was on the performance of a single network node. Now the analysis will be extended to a reference connection over several nodes. In general, the states of the nodes of the reference connection are correlated. This has the following reasons:

1. The maximum number of active sources on the reference link between node k and node $k + 1$ is limited by the capacity of this link.

2. If some sources are simultaneously in a burst state at the first node, they will be simultaneously in a burst state at any intermediate node, as long as the bursts are not blocked or lost.

To evaluate the influence of the correlation on the overall performance of the reference connection, two approximation techniques will be presented. The results obtained by the approximation techniques will be compared to results obtained by simulation and by the independence assumption.

Figure 5. First two nodes of the reference connection

Figure 5 depicts the first two nodes of the reference connection with up to n nodes and its systematic notation. With the variable N we denote the total number of connections, with M the maximum number of sources that are able to transfer a burst at a time, with c the capacity of a reference link and with a the random variable for the number of active sources. The subscript k denotes the k^{th} node of the chain.

4.2.1. Independence Assumption

The first possibility to assess the overall blocking or loss probability is to assume, that the correlation between the network nodes is negligible for small loss or blocking probabilities. This means, that the characteristic measures of the nodes can be calculated independently as presented in section 4.1.. The number of sources N_k at the input of node k is the sum of the sources of the connections the node has to carry, i.e. no losses at previous nodes are considered. The blocking or loss probabilities of the reference connection are then estimated by

$$B_{tot}^{ref} \approx 1 - \prod_{k=1}^n (1 - B_{tot,k}) \quad \text{and} \quad (6)$$

$$B_{init}^{ref} \approx 1 - \prod_{k=1}^n (1 - B_{init,k}) \quad , \quad (7)$$

using the total and initial loss probabilities $B_{tot,k}$ and $B_{init,k}$ of each node.

4.2.2. Approximation by Reduction of the Offered Traffic

The bursts that are lost or blocked at node k decrease the traffic that is offered to node $k+1$. If the total traffic offered at node k is denoted by A_k , then A_k can be approximated by

$$A_k \approx \frac{N_k^{ref}}{N_{k-1,k}^{ref}} A_{k-1} (1 - B_{tot,k-1}) + \frac{N_k^{in}}{b} \quad \text{for } k = 2, 3, \dots, n \quad (8)$$

with $A_1 = \frac{N_1}{b}$. In order to take into account the reduction of the offered traffic, the burstiness of the sources at the reference node k , $k = 2, 3, \dots, n$, is adapted according to

$$b_k = \frac{N_k}{A_k} \quad \text{for } k = 2, 3, \dots, n. \quad (9)$$

Hence, for this approach the mean offered traffic is taken into consideration. The burst transmission times are maintained, but the distributions of the incoming traffic streams are approximated by Binomial distributions. The blocking or loss probabilities $B_{tot,k}$ and $B_{init,k}$ of the nodes are again calculated using the single node analysis. Finally, the blocking or loss probabilities of the reference connection are obtained from the equations 6 and 7.

4.2.3. Approximation by Adaptation of the Input Distribution

For the performance of a switching node, not just the mean of the incoming traffic is essential, but to an even greater extent the probability distribution of the bitrate requirements of the incoming traffic. This distribution changes due to the fact that the maximum number of bursts being simultaneously transferred over the reference link from node k to node $k+1$ is limited to $c_{k,k+1}$. In addition, the number of sources active at different nodes are correlated (cf. page 8). Therefore, if node k is congested, the probability of node $k+1$ to be in a state of congestion is more likely, than if independence of the nodes is assumed. These two observations have motivated an approach, which uses the results of node k to calculate the performance parameters of node $k+1$. The approach will take three steps that are explained exemplarily for the first two nodes (cf. Figure 5) and the initial blocking or loss probability.

In the first step, the first node is analysed using the two-dimensional Markov chain approach for an isolated node. This leads to the initial blocking or loss probability $B_{init,1}^{ref}$ and to the probability of $a_{1,2}^{ref}$ active sources on the link to node 2 given by $p(a_{1,2}^{ref})$, $0 \leq a_{1,2}^{ref} \leq c_{1,2}^{ref}$.

In order to obtain the overall blocking or loss probability $B_{init,1-2}^{ref}$ of the first two nodes it is necessary to approximate the conditional probability $B_{init,2/\bar{1}}^{ref}$ that a new reservation attempt will be rejected by node 2 given that it is successful in node 1. Then $B_{init,1-2}^{ref}$ can be calculated by

$$B_{init,1-2}^{ref} = B_{init,1}^{ref} + (1 - B_{init,1}^{ref}) B_{init,2/\bar{1}}^{ref}. \quad (10)$$

Note, that node 1 will reject a new reservation only if $a_{1,2}^{ref} = c_{1,2}^{ref}$, i.e. if the link to node 2 is fully utilized at that moment. Hence, to assess the conditional probability $B_{init,2/\bar{1}}^{ref}$ this case has to be excluded. This is done by setting the probabilities $p_{1,2}(a_{1,2}^{ref})$ of active sources at the input of node 2 to

$$p_{1,2}(a_{1,2}^{ref}) = \begin{cases} p(a_{1,2}^{ref}) & 0 \leq a_{1,2}^{ref} < c_{1,2}^{ref} \\ 0 & a_{1,2}^{ref} \geq c_{1,2}^{ref} \end{cases} . \quad (11)$$

In the second step these probabilities are used to calculate the probability $p_2(a_2)$ of having a_2 active sources that will be multiplexed on the reference output link of node 2. This procedure is similar to that described in [Krön 92]. The selection of a_2^{ref} active sources, that remain on the reference link is a combinatorial problem. The conditional probability that a_2^{ref} active sources remain on the reference link given that $a_{1,2}^{ref}$ sources are active at the input of node 2 can be described by the following hypergeometric distribution:

$$p_{2/1,2}^{ref}(a_2^{ref} | a_{1,2}^{ref}) = \frac{\binom{N_2^{ref}}{a_2^{ref}} \binom{N_{1,2}^{ref} - N_2^{ref}}{a_{1,2}^{ref} - a_2^{ref}}}{\binom{N_{1,2}^{ref}}{a_{1,2}^{ref}}} \quad (12)$$

for $\begin{cases} a_{1,2}^{ref} = 0, 1, \dots, \min(c_{1,2}^{ref} - 1, N_{1,2}^{ref}) \\ a_2^{ref} = 0, 1, \dots, \min(a_{1,2}^{ref}, N_2^{ref}) \end{cases}$.

Using the theorem of the total probability, the probability $p_2^{ref}(a_2^{ref})$ of a_2^{ref} active sources remaining on the reference link is given by:

$$p_2^{ref}(a_2^{ref}) = \sum_{a_{1,2}^{ref}=a_2^{ref}}^{\min(c_{1,2}^{ref}-1, N_{1,2}^{ref})} p_{2/1,2}^{ref}(a_2^{ref} | a_{1,2}^{ref}) p_{1,2}(a_{1,2}^{ref}) \quad (13)$$

for $a_2^{ref} = 0, 1, \dots, \min(c_{1,2}^{ref} - 1, N_2^{ref})$

The probability distribution $p_2^{in}(a_2^{in})$ of the incoming traffic is described by the Binomial distribution

$$p_2^{in}(a_2^{in}) = \binom{N_2^{in}}{a_2^{in}} \left(\frac{\alpha}{\alpha + \epsilon} \right)^{a_2^{in}} \left(\frac{\epsilon}{\alpha + \epsilon} \right)^{N_2^{in} - a_2^{in}} \quad \text{for } a_2^{in} = 0, 1, \dots, N_2^{in} . \quad (14)$$

Since the reference and cross traffics are statistically independent, the probability $p_2(a_2)$ of a_2 active sources which are multiplexed in node 2 is given by the convolution

$$p_2(a_2) = \sum_{a_2^{ref}=\max(0, a_2 - N_2^{in})}^{\min(a_2, c_{1,2}^{ref}-1, N_2^{ref})} p_2^{ref}(a_2^{ref}) p_2^{in}(a_2 - a_2^{ref}) \quad \text{for } a_2 = 0, \dots, M_2 , \quad (15)$$

where M_2 is given by $M_2 = \min(c_{1,2}^{ref} - 1, N_2^{ref}) + N_2^{in}$.

Figure 6. Input distribution

In the third step, a one-dimensional Markov process as depicted in Figure 6 is used to model the burst level behaviour of the sources that have to be multiplexed on the reference output link of node 2.

The termination rate ϵ is chosen to be equal to the mean burst duration and the FRP protocol overhead as described at the beginning of section 4.1.. The Markov chain can be matched to any probabilities $p_2(a_2)$ by the state dependent activation rates α_l that are calculated according to

$$\alpha_l = \frac{(l+1) p_2(l+1)}{(M_2-l) p_2(l)} \epsilon \quad \text{for } l = 0, 1, \dots, M_2 - 1. \quad (16)$$

Now, the α_l , $l = 0, 1, \dots, M_2$, are used instead of α to adapt the two-dimensional state-transition diagram of a single node (cf. Figure 4) to the probabilities $p_2(a_2)$ of a_2 active sources at node 2. The maximum number of active sources N is substituted by M_2 . Note, that M_2 and the α_l were obtained under the condition that node 1 would not reject a new reservation. Thus, the conditional probability $B_{init,2/\bar{1}}^{ref}$ of a new reservation request to be rejected at node 2 when being admitted at node 1 can be obtained from the two-dimensional state-transition diagram of node 2 according to equation 4. Again, N is substituted by M_2 . Similarly, the probabilities of i active sources on the reference output link of node 2 under the condition that node 1 would not reject a new reservation can be obtained using equation 2. From this distribution the probabilities $p_{2,3}(a_{2,3}^{ref})$ of active sources at the input of node 3 under the condition that neither node 1 nor node 2 would reject a new reservation can be derived similarly as presented for node 2 in equation 11. Next, the steps 2 and 3 are applied to node 3. The whole procedure is carried out for the successive nodes up to node n to determine the conditional blocking or loss probabilities $B_{init,3/\bar{2},\bar{1}}^{ref}, \dots, B_{init,n/\bar{n-1},\dots,\bar{1}}^{ref}$.

Finally, the overall initial blocking or loss probability B_{init}^{ref} of the reference connection is approximated by:

$$\begin{aligned} B_{init}^{ref} &\approx B_{init,1}^{ref} + (1 - B_{init,1}^{ref}) B_{init,2/\bar{1}}^{ref} + (1 - B_{init,1}^{ref})(1 - B_{init,2/\bar{1}}^{ref}) B_{init,3/\bar{2},\bar{1}}^{ref} \\ &\quad + \dots + (1 - B_{init,1}^{ref}) \cdot \dots \cdot (1 - B_{init,n-1/\bar{n-2},\dots,\bar{1}}^{ref}) B_{init,n/\bar{n-1},\dots,\bar{1}}^{ref} \\ &= 1 - (1 - B_{init,1}^{ref}) \prod_{k=2}^n (1 - B_{init,k/\bar{k-1},\dots,\bar{1}}^{ref}) \end{aligned} \quad (17)$$

5. RESULTS

Within this section the performance of the FRP/IT will be compared to that of the FRP/DT considering a single switching node. Then we extend the reference connection to several switching nodes with cross traffic. The approximations of section 4.2. will be validated by simulation results.

The parameters of the sources are given by a mean bitrate of 0.5Mbit/s, a mean on-off cycle duration of 2s and a mean time interval between two consecutive reattempts of $t_w = \tau + 20\text{ms}$ in case of congestion. The mean information contents of a burst is fixed to 1Mbit. For all the results the capacity of the reference links is chosen to 150Mbit/s ($c_i^{ref} = 15$).

5.1. Single Switching Node

Figure 7 illustrates the admissible load that can be carried by a single reference link, when the maximum initial burst blocking or loss probability in the node is set to $2.36 \cdot 10^{-3}$. This value corresponds to an ATM cell loss probability of about 10^{-6} assuming independent cell losses. The roundtrip delay is chosen to 10ms which may be representative for a connection within Europe and to 50ms that may stand for a US coast-to-coast connection. The performance of the FRP/IT and FRP/DT is compared to peak bitrate allocation

Figure 7. Comparison of admissible loads for roundtrip delays of 10ms (a) and 50ms (b)

and ideal statistical multiplexing at a cell loss probability of 10^{-6} . The curve for ideal statistical multiplexing is calculated using a convolution approximation. The probability of the cumulative bitrate required by all sources is given by a binomial distribution. The cell loss probability can be approximated by the information loss probability calculated

Figure 8. Influence of roundtrip delay on admissible load ($B_{init} < 2.36 \cdot 10^{-3}$, $t_b = 100\text{ms}$, $\Lambda_{max} = 10\text{Mbit/s}$)

Figure 9. Influence of total blocking or loss probability, respectively, on the mean transfer time ($t_b = 100\text{ms}$, $\Lambda_{max} = 10\text{Mbit/s}$)

from the differences of the overload bitrates and the link capacity divided by the mean offered bitrate.

The gain of the multiplexing methods over peak bitrate allocation is obvious. The FRP performs better than pure statistical multiplexing, since the less severe specification of the tolerable burst losses or blockings overcompensates the overhead that is introduced by the roundtrip delay and the additional load caused by the reattempts. These results confirm the observations of [Tran 91]. A comparison of Figure 7 (a) and (b) already indicates that the performance of the FRP/DT depends upon the roundtrip delay, whereas the performance of the FRP/IT can be considered independent of it. This fact is confirmed by Figure 8. For the results presented here, the mean burst duration is set to $t_b = 100\text{ms}$, the burstiness to $b = 20$ and the peak bitrate to $\Lambda_{max} = 10\text{Mbit/s}$. The curve for the FRP/DT shows a considerable degradation of the admissible load for high roundtrip delays. This is caused by the reservation procedure, because the required bitrate has to be reserved in the switching nodes not just for the burst duration but in addition for the roundtrip delay.

5.2. Reference Connection

In the following, the mean network transfer time T_{trans} and the mean network response time T_{resp} for a reference connection are examined. The mean network transfer time is defined as the time that is necessary to successfully transfer a burst from a source to its destination. The mean network response time is the time interval that passes until the source knows that its burst is (FRP/IT) or will be (FRP/DT) transferred successfully. Hence, this is the time the source is blocked due to an incomplete data transfer. These times comprise three components: The mean burst transmission time itself, an un-

avoidable constant protocol overhead and a variable component due to blocking or loss of bursts. The response times are identical for the FRP/DT and the FRP/IT, since for the FRP/IT it also takes the time τ for a source to get an acknowledgement for a successful burst transfer, if no congestion occurs. The mean transfer time of the FRP/DT comprises an additional constant overhead of τ compared to the FRP/IT. Thus, we get as lower bounds (without considering processing overheads):

$$T_{resp,DT} = T_{resp,IT} = \tau + (\bar{v} - 1)t_w \quad (18)$$

$$T_{trans,DT} = T_{trans,IT} + \tau = t_b + 1.5\tau + (\bar{v} - 1)t_w \quad (19)$$

The mean transfer times are depicted in Figure 9. For low blocking or loss probabilities the mean burst transmission time and the constant protocol overhead determine the transfer and response times. Only for high blocking or loss probabilities they are affected significantly by the retransmissions.

Table 1

Initial blocking probabilities $B_{ref,init}$ obtained by the different approximation techniques ($\tau = 10\text{ms}$, 50% cross traffic)

Number of nodes	Simulation	Distribution adaptation	Traffic reduction	Independence assumption
Number of sources/node = 123 (load = 0.41)				
1	$2.22 \cdot 10^{-3}$ $\pm 1.9 \cdot 10^{-4}$	$2.19 \cdot 10^{-3}$	$2.19 \cdot 10^{-3}$	$2.19 \cdot 10^{-3}$
2	$4.10 \cdot 10^{-3}$ $\pm 1.7 \cdot 10^{-4}$	$4.11 \cdot 10^{-3}$	$4.36 \cdot 10^{-3}$	$4.38 \cdot 10^{-3}$
3	$6.14 \cdot 10^{-3}$ $\pm 3.8 \cdot 10^{-4}$	$6.00 \cdot 10^{-3}$	$6.51 \cdot 10^{-3}$	$6.56 \cdot 10^{-3}$
4	$7.63 \cdot 10^{-3}$ $\pm 5.3 \cdot 10^{-4}$	$7.89 \cdot 10^{-3}$	$8.65 \cdot 10^{-3}$	$8.73 \cdot 10^{-3}$
number of sources/node = 150 (load = 0.50)				
1	$1.31 \cdot 10^{-2}$ $\pm 4.5 \cdot 10^{-4}$	$1.31 \cdot 10^{-2}$	$1.31 \cdot 10^{-2}$	$1.31 \cdot 10^{-2}$
2	$2.35 \cdot 10^{-2}$ $\pm 1.3 \cdot 10^{-3}$	$2.35 \cdot 10^{-2}$	$2.54 \cdot 10^{-2}$	$2.60 \cdot 10^{-2}$
3	$3.33 \cdot 10^{-2}$ $\pm 1.6 \cdot 10^{-3}$	$3.35 \cdot 10^{-2}$	$3.71 \cdot 10^{-2}$	$3.88 \cdot 10^{-2}$
4	$4.21 \cdot 10^{-2}$ $\pm 1.4 \cdot 10^{-3}$	$4.34 \cdot 10^{-2}$	$4.87 \cdot 10^{-2}$	$5.13 \cdot 10^{-2}$

To examine the influence of the cross traffic, we exemplarily use the FRP/DT. For the FRP/IT we have obtained similar results. According to Figure 9, blocking probabilities up to 10^{-1} seem to be reasonable for a connection with low quality of service requirements. Table 1 gives the results for a reference connection running over 1 to 4 nodes

with 50% cross traffic joining the path at every node and leaving at the next one. The approximation techniques presented in section 4.2. are validated by a simulation using a constant delay t_w for reattempts. The results of the simulations are given in Table 1 with 95% confidence intervals. The similarity of the results for one node justifies the use of negative exponentially distributed roundtrip delays for the analysis. The analyses using the independence assumption or the approximation by reduction of the offered traffic overestimate the blocking probabilities for a connection over several nodes, whereas the results obtained by the analysis based on the adaptation of the input distributions are in accordance with the simulation results. The independence assumption is reasonable to give an upper bound for small blocking probabilities and a reference connection running over a few nodes only. But since the computation expense for the distribution adaptation is only a fraction of the expense to solve the system of linear simultaneous equations of the node model, this technique gives better results for little additional cost.

6. CONCLUSIONS

A burst level analysis of the Fast Resource Management schemes FRP/IT and FRP/DT has been presented. The analysis was split into the detailed analysis of an isolated switching node and into the approximate analysis of a reference connection. The analysis of a single node takes into account that sources may be blocked due to bitrate reservation rejects and will reattempt to transfer rejected burst. To analyse a reference connection over several switching nodes with cross traffic, approximation techniques were proposed to take the paths of the connections and thus the correlation of successive nodes into account. The validation by simulations reveals that the approach to consider conditional blocking or loss probabilities of consecutive nodes while adapting the node models to their actual input distributions performs best and yields very accurate results.

The results confirm that a considerable gain in the admissible load of a node is achievable when using the FRP compared to peak bitrate allocation. The FRP may even perform better than ideal statistical multiplexing due to less restrictive maximum loss or blocking probabilities at the burst level. For a small ratio of roundtrip delay to burst duration the two variants of the FRP perform similar, but for higher ratios the FRP/IT is superior. The effect that is imposed by cross traffic on a reference connection depends on the volumes of the traffic streams and the switching nodes cannot generally be considered as independent. However, if the traffic volume of the reference connection is small compared to that of the cross traffic that does not run over several nodes and blocking or loss probabilities are low, an approximation using the independence assumption gives reasonable upper bounds.

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REFERENCES

- [Boye 90] P. Boyer, *A Congestion Control for the ATM*, Proceedings of the 7th ITC Specialist Seminar, Morristown, Oct. 1990, paper 4.3.
- [BoTr 92] P. Boyer, D. Tranchier, *A Reservation Principle with Applications to the ATM Traffic Control*, Computer Networks and ISDN Systems 24, North Holland, 1992, pp. 321–334.
- [Brie 92] U. Briem, *Modellierung des Fast Reservation Protocols für einen Netzknoten*, Internal Report, Institute of Communications Switching and Data Technics, University of Stuttgart, 1992.
- [Cros 93] S. Crosby, *In-call Renegotiation of Traffic Parameters*, Proceedings of IEEE INFOCOM '93, San Francisco, 1993, pp. 638–646.
- [DoDr 90] B. Doshi, S. Dravida, *Congestion Control in High Speed Wide Area Packet Networks: In-Call Parameter Negotiations*, Proceedings of the 7th ITC Specialist Seminar, Morristown, Oct. 1990, paper 12.5.
- [I.121] ITU-TSS, *Recommendation I.121: Broadband Aspects of ISDN*, Geneva, 1991.
- [I.361] ITU-TSS, *Recommendation I.361: B-ISDN ATM layer specification (Proposed revision)*.
- [I.371] ITU-TSS, *Recommendation I.371: Traffic control and congestion control in B-ISDN*, Geneva, 1992.
- [Kell 86] F. Kelly, *Blocking Probabilities in Large Circuit-Switched Networks*, Adv. Appl. Prob. 18, 1986, pp. 473–505.
- [Krön 92] H. Kröner, M. Eberspächer, T. H. Theimer, P. J. Kühn, U. Briem, *Approximate Analysis of the End-to-End Delay in ATM Networks*, Proceedings of IEEE INFOCOM '92, Florence, 1992, pp. 978–986.
- [SBKT 93] W. Schödl, U. Briem, H. Kröner, T. Theimer, *Bandwidth Allocation Mechanism for LAN/MAN Interworking with an ATM Network*, Computer Communications, Vol. 16, No. 2, 1993, pp. 93–99.
- [Tran 91] D. Tranchier, *The Fast Reservation Protocol*, 1st IEEE Broadband ISDN Technical Workshop, Phoenix, March 1991.
- [WFD 93] T. Worster, W. Fischer, S. Davis, *Resource Allocation for Packet Data Traffic on ATM: Problems and Solutions*, ITG/GI Fachtagung Kommunikation in Verteilten Systemen, 1993, pp. 100–113.
- [YiHl 91] N. Yin, M. G. Hluchyj, *A Dynamic Rate Control Mechanism for Source Coded Traffic in a Fast Packet Network*, IEEE JSAC, Vol. 9, No. 7, 1991, pp. 1003–1012.