MASTER

Medium access protocols for ATM based passive optical networks

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Medium Access Control Protocols
for
ATM based Passive Optical Networks

by F.M. Ploumen

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Summary

The main function of a shared medium access network is to multiplex the upstream traffic from several customers and offer it to the core network. In the context of networked applications over ATM, this involves the multiplexing of ATM connections. The end-to-end performance of a broadband shared-medium access network will be determined by the combination of the adopted multiplexing policy and the behaviour of network elements assuming to quality of service policy. This policy should be optimized for end-to-end delays which are as constant as possible, and maximum troughput. Clearly, in the case of broadband shared-medium access networks, the (shared) Medium Access Control protocol will be one of the determining factors for the end-to-end performance.

In this thesis a general simulation model for the performance evaluation of MAC protocols was developed with the software simulation tool OPNET. After developing this model, several MAC protocols were studied and new proposals were made. An essential choice for the performance of the shared medium access control mechanism is the question whether the MAC protocol is based on a static or dynamic mechanism. In contrast with the static protocols the dynamic protocols can react on traffic fluctuations. They are also more robust for changing loads or burstiness.

Analyzing the simulation results with the passive optical access network, it is concluded that all dynamic MAC protocols perform quite similar. Although more complex grant generation mechanisms might be able to outperform the others for certain scenario's, it is on this moment not possible to identify a MAC protocol which is the best performing over a wide range of traffic scenario's. Especially mechanisms used to reduce cell delay variation, like spacing, should be dimensioned very conservative since they can disturb the throughput under heavy loads. Therefore it must be concluded that the performance of a MAC protocol should be analyzed with several, well chosen traffic scenarios.

CONTENTS

1. INTRODUCTION

The Asynchronous Transfer Mode (ATM) is now widely accepted as the standard transport technology for the forthcoming high speed telecommunication age. It is known as the Broadband Integrated Services Digital Network (B-ISDN). The superiority of ATM is based upon its flexibility to support a wide diversity of services and applications within a single networking infrastructure. To this end, ATM has matured into a multi-service technology since the early nineteen-eighties. This integration is illustrated by the standardization of various ATM transfer capabilities (ITU-T terminology) and the specification of ATM service categories (ATM Forum denomination).

The wide range of Quality of Service (QoS) performance associated with different ATM Transfer Capabilities imposes a need for network elements with more intelligent scheduling strategies that go beyond the traditional First In First Out (FIFO) buffering discipline. Similarly, the wide variety in traffic characterizations imposes the need for a performing Medium Access Control (MAC) protocol for an ATM-based shared-medium access network.

The main function of a shared medium access network is to multiplex the upstream traffic from several customers and offer it to the core network, and to distribute the downstream traffic from the core network to the relevant customers. In the context of networked applications over ATM, this involves the multiplexing and demultiplexing of ATM connections. The end-to-end performance of a broadband shared-medium access network will be determined by the combination of the adopted multiplexing policy and the behaviour of network elements assumed to QoS policy. The challenge is the definition of a QoS policy which introduces end-to-end delays which are as constant as possible, and hence reduce jitter. Clearly, in the case of broadband shared-medium access networks, the MAC protocol will be one of the determining factors for the end-to-end performance.

The objective of this thesis is to develop a general simulation model in the OPNET tool for the performance evaluation of MAC protocols. After developing this model, several MAC protocols are studied and a new proposal is made. The performance of these protocols is evaluated with the OPNET model using the ATM based Passive Optical Network (APON) access network characteristics.

The thesis report is structured in three parts. The first part “Shared Medium Access Control” (chapter 2 and 3) handles the structure of the access network and gives an overview of MAC protocols. The performance metrics for the MAC protocol evaluation are also specified.

In chapter 4 (second part), the basic structure of the developed OPNET model for MAC performance evaluation is discussed. Special attention was paid to the development of traffic sources (chapter 5), since the traffic characteristics can have great influence on the performance of the MAC protocol.

The results of the simulations done with the developed model are discussed in the third part (chapter 6 and 7). The APON simulations were performed and evaluated first and the results of this evaluation were used in the design of the MAC protocols for SuperPON.

This report will end with a section containing several conclusions and recommendations. It must be noted that this section is divided in conclusions and recommendations for the design of new MAC protocols and with recommendations for the further development of the OPNET simulation model.

2. PROPERTIES OF THE ATM BASED ACCESS NETWORK

2.1 ACCESS NETWORK ARCHITECTURE

The ATM-based access network is based on a point-multipoint configuration. This means that several terminals are connected to one central point. This central point is called Line Termination (LT) and it connects the ATM backbone link (V-interface) with all terminals. Since the link between a terminal and the LT is (partly) shared with the other terminals, a control mechanism for the usage of this link is necessary in order to avoid collisions in the upstream direction. For the downstream traffic no link control is needed, since it is broadcasted from the LT to all connected terminals. The upstream link control will be handled by the Medium Access Control (MAC) protocol. This protocol specifies the behaviour of the terminals concerning the usage of the upstream link. Figure 1 shows this ATM based access network configuration.

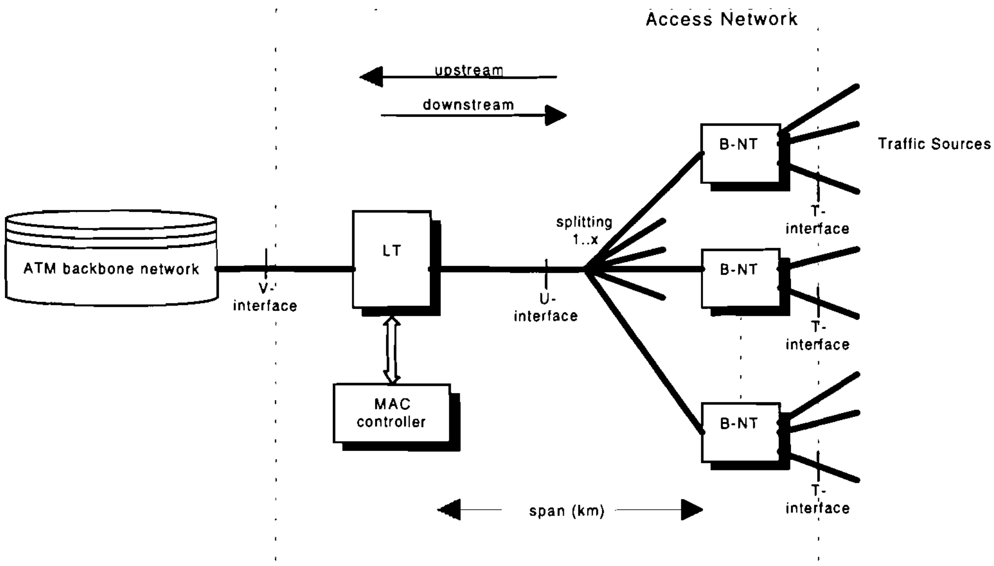

Figure 1: ATM-based access network architecture

The MAC protocol is situated in the Medium Access Control sub-layer which is part of the second layer of the OSI model [25,26] called "Data Link Layer". The terminals which are called Broadband Network Termination (B-NT) are further discussed in section 2.3, the LT in section 2.4.

2.2 TRANSMISSION CONVERGENCE LAYER CHARACTERISTICS

Since the frame structure of the Hibrid Fiber Coax (HFC) system differs from the Passive Optical Network (PON) system, it is not possible to define general Transmision Convergence (TC) layer characteristics. The characteristics discussed in this section are used to develop the PON simulation model. They are based on the TC layer specification of the Gx-FSAN OAN group [12].

The downstream transmission consists of a continuous stream of time slots, each time slot containing 53 octets of an ATM cell or a Physical Layer Operation And Maintenance (PLOAM) cell. Every 28 time slots a PLOAM cell is inserted. A downstream frame contains 2 such PLOAM cells and is 56 slots long (Figure 2). This results in a downstream ATM data cell load of 155.52Mbps * 54/56 = 149.97Mbps.

In the upstream direction the frame contains 53 time slots of 56 bytes (Figure 2). Most of these time slots carry one ATM data cell of 53 bytes preceded by a 3 bytes Physical Layer Preamble. The LT requests a B-NT to transmit an ATM cell via grants conveyed in downstream PLOAM cells. In section 2.2.1 the contents of the downstream PLOAM cell is discussed. In each downstream frame of 56 cells, the first PLOAM cell will contain 27 grants while the second one will only contain 26 grants. In the simulation model each downstream PLOAM cell carries 27 grants. This simplification results from the fact that the duration of one upstream time slot is considered as one time unit in the simulation model.

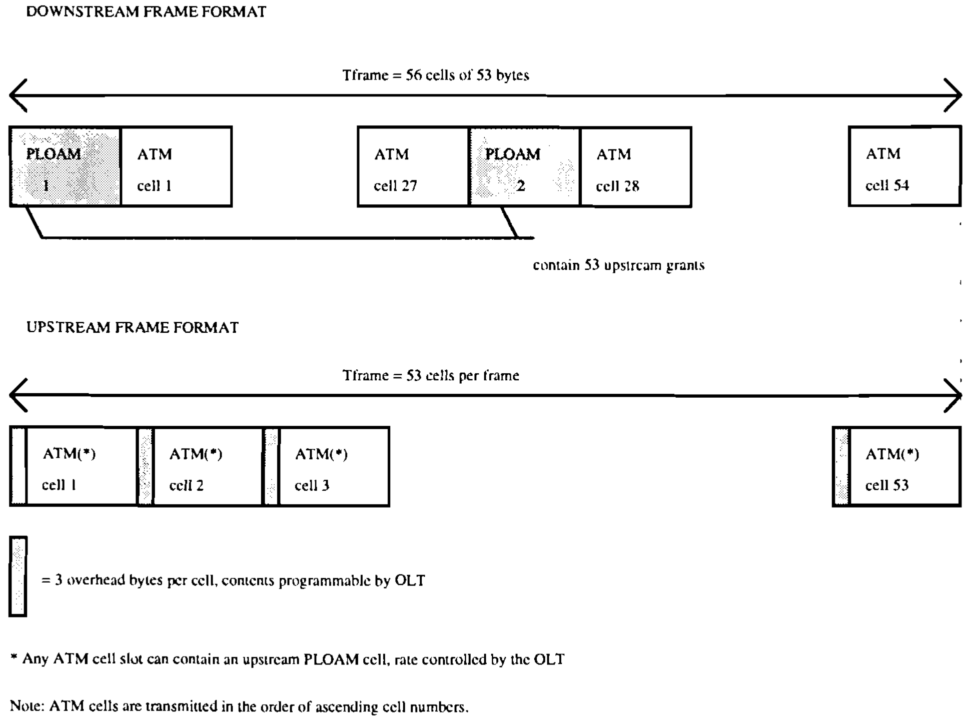

Figure 2: Frame format for 155.52/155.52 Mbps PON

At a programmable rate, the LT can also request a B-NT to transmit a PLOAM cell or a minislot frame. The upstream PLOAM rate depends on the required functionality contained in these PLOAM cells. In the simulations, it is assumed that no upstream PLOAM cells had to be inserted.

2.2.1 PLOAM cells

As already explained, the downstream PLOAM cells are used to specify the usage of the upstream timeslots. Therefore the LT will broadcast the PLOAM cells to all B-NTs. Figure 3 shows the payload content of the PLOAM cell. Just like an ordinary ATM cell, it is preceded by a 5 byte header.

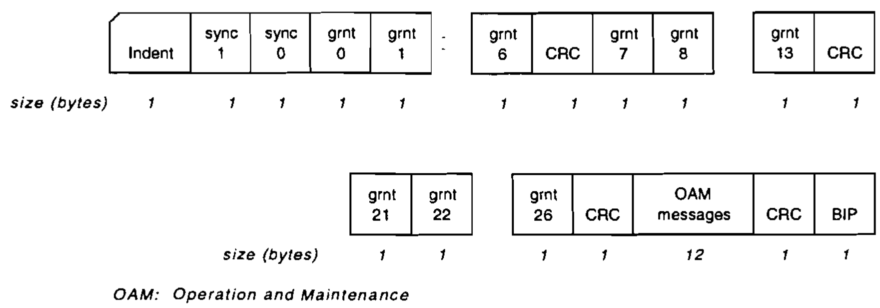

Figure 3: Payload content of the downstream PLOAM cell

2.2.2 Minislot Frame

The minislot frame consists of 8 minislots and allows multiple B-NTs to be polled in the duration of one upstream time slot. The minislot frame has the same size as a conventional upstream time slot (56 bytes) The structure of a minislot frame is given in Figure 4.

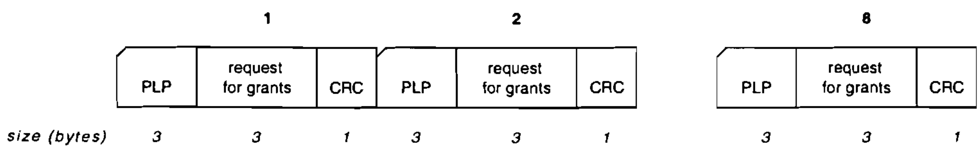

Figure 4: Minislot frame structure

In order to know which B-NTs can send its requests, minislot groups have to be made. The structure of these groups (made by the LT) will be broadcasted to all B-NTs. So every B-NT knows in which minislot frame and on what position it can send its data. Since up to 8 B-NTs can be polled with one minislot frame, the number of minislot frames has to be at least 1/8 of all connected connected B-NTs. The minislot coding will be discussed in Section 2.3.

2.2.3 Piggybacking

Another mechanism to provide a MAC communication channel is piggybacking. In this mechanism the MAC information which has to sent from the B-NTs to the LT is built in the upstream data frame of 56 bytes. This can be done by reducing the physical layer preamble size. Figure 5 shows the upstream frame with piggybacking field.

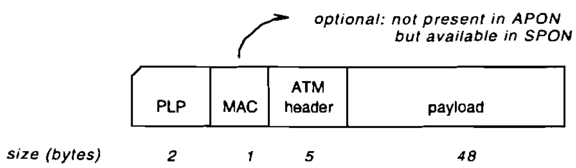

Figure 5: Upstream frame containing an ATM cell and a piggybacking field

Comparing the piggybacking mechanism with ordinary or minislot polling, it can be concluded that it has many advantages. First of all the overhead is relatively small (one byte on a 56 byte frame) which makes an efficient usage of the limited upstream capacity possible. Second the fact that every transmitted cell generates an update of the queue status is an important advantage. The update frequency while using polling is by definition much lower. However the piggybacking mechanism has also some disadvantages. While the piggybacking mechanism can only send information with an upstream frame, only the status of the active B-NTs will be updated. In order to detect whether a B-NT has become active, additional polling of the inactive B-NTs is needed besides the piggybacking mechanism. The piggyback coding is depending on the information, the MAC protocol needs. It is not specified yet.

2.3 B-NT CHARACTERISTICS

The home networks are connected to the (PON) access network by means of a Broadband Network Termination (B-NT). This B-NT can be either integrated (B-iNT) or modular (B-mNT). A modular B-NT usually consists of a multiplexing module (MUX) and one or more Line Interface Modules (LIMs). Figure 8 in section 2.5 shows both the B-iNT as well as B-mNT implemented in the access network. The motivation for a modular B-NT in the form of a service multiplexer rises from the desire to concentrate traffic better and more economically. Moreover, a modular B-NT also provides the flexibility to offer different types of network interfaces to different users. The SuperPON Optical Network Unit (ONU) under development at the research center is an example of an integrated B-NT. Modular B-NTs can be found in Fiber To The Block (FTTB), Fiber to the Curb (FTTC) and Fiber to the Cabinet (FTTCab) configurations. In FTTC and FTTCab configurations, an Asymmetric Digital Subscriber Line (ADSL) delivery system will be used between the Customer Premises Network (CPN) and the B-NT.

While the ATM strategy has to support several Quality of Services (QoS), a B-NT architecture which implements a strict QoS segregation has been considered. The B-NTs are equipped with different buffers (also called queues) grouping ATM cells with similar QoS requirements. The B-NT model implements four First In First Out (FIFO) queues, reserved for Constant Bit Rate (CBR), Variable Bit Rate (VBR), Avaiable Bit Rate (ABR) and Unspecified Bit Rate (UBR) respectively, as indicated in Figure 6. The mentioned QoS are specified in appendix B.

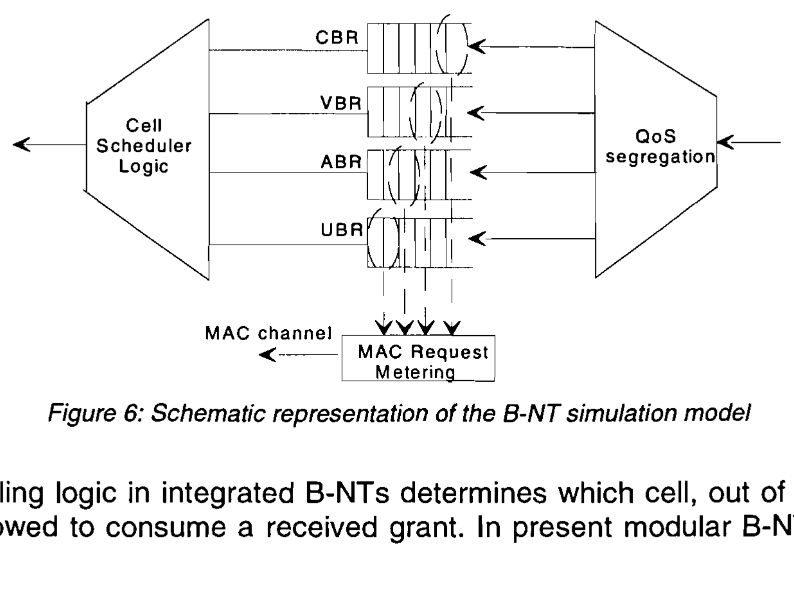

Figure 6: Schematic representation of the B-NT simulation model

The cell scheduling logic in integrated B-NTs determines which cell, out of a set of queued cells, will be allowed to consume a received grant. In present modular B-NTs, a distributed queuing architecture is adopted whereby buffering capacity is provided on each of the Line Interface Module (LIM) in stead of considering centralized queues on the multiplexer module (MUX). In such an architecture, the bus arbitration protocol operates as a work-conserving cell scheduler. Naturally, the operation of this cell scheduling logic or internal bus arbitration logic will also be significant factors in determining the end-to-end performance of the access network.

In the B-NT simulation model, the behaviour of the B-iNT as well as the B-mNT assumes FIFO queuing per QoS class and per B-NT. As such, an output queuing architecture is assumed whereby buffering capacity is provided on the multiplexing module in stead of on the LIMs. The internal B-mNT bus capacity is assumed to be high enough to allow transfer of all traffic carried by the LIMs to the MUX without contention.

Another important property of B-NTs will be the supported permit granularity, i.e. the targeted traffic stream of the transmission grants. Several options have been studied and compared in the literature. The optimum choice is again coupled with the constraints introduced by the profile and QoS requirements of the traffic that will have to be supported. The three main options based on logical queues which cover aggregation of connections are grants per B-NT, grants per QoS class (i.e. aggregation of connections per B-NT with similar QoS requirements) and grants per connection. The choice of the target has an important impact on the system complexity and on the shaping imposed by the access network. A MAC protocol generating permits to a particular connection is likely to be more complex than a MAC protocol targeting a network termination. However, it would allow the MAC protocol to impose shaping at connection level, and thus it would allow to control the CDV of individual connections.

In the simulation model, all request based MAC protocols generate grants directed to a specific QoS class. In this case, the grant consists of the network termination identifier combined with a queue (or QoS) discriminator. The queue discriminator field encapsulated in the permits determines which FIFO will be serviced. For the HFC and PON configurations, it is assumed that a permit can only be consumed by cells buffered in the targeted FIFO. If the targeted FIFO is empty, the permit is lost (an idle cell is inserted by the B-NT). More intelligent consuming of permits will be studied for the sPON system.

It is also possible to give so-called colourless grants which only contain an identifier for the network termination. The B-NT implements a Static Priority Scheduling Discipline (SPSD), whereby cells from a lower priority FIFO are only allowed to consume an allocated time slot if all higher priority queues are empty when the permit is serviced. The main drawback of this option is that it can not discriminate between different connections from the same terminal with different QoS requirements and different traffic characteristics. The cell scheduling logic (B-iNT) or bus arbitration logic (B-mNT) will autonomously determine which cell should be serviced next.

Related to the problem of permit granularity is of course the ability to generated MAC requests with the same granularity. When grants are targeted to a specific QoS class on a specific network termination, and considering that a request-based MAC protocol is implemented, the MAC Controller needs to be informed of the transmission requirements per targeted queue.

The Gx-FSAN OAN group TC-layer specification [12] does not define the minislot frame content. In our simulations we assume that the B-NT is able to measure the growth of each of the four queuing points. When the B-NT receives a grant for a MAC minislot, it will forward the queue growth information as indicated in Figure 7.

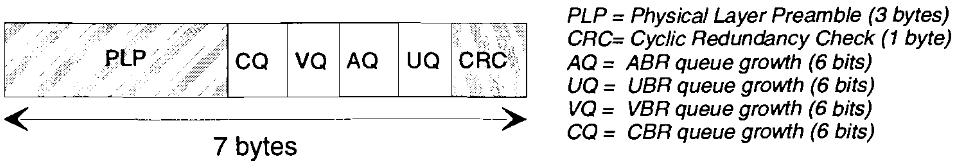

Figure 7: MAC minislot coding

The coding of the request fields is linear. As such, a polled B-NT can indicate a queue growth per QoS class which ranges from 0 to a maximum of 63 cells. Upon receipt of this information, the LT can determine the number of cells received in each of the B-NT queuing point during the previous polling interval.

2.4 LT CHARACTERISTICS

The Line Termination (LT) or head-end of the access tree implements the MAC controller function. The MAC controller function generates the transmission grants. For request based MAC protocols (like CPP, GF, EGF, SP), the grant generating process is based on requests issued from the B-NTs. In order to obtain these requests a MAC cornmunication channel (like minislots or piggybacking) is needed.

Some protocols combine the information from the MAC channel with connection profile information (GF and EGF). The non-request based MAC protocols (AAM) generate permits solely based on connection profile information. The connection profile information is automatically generated by every B-NT and it contains PCR SCR and MCR per QoS. The B-NT creates these data by summarizing the specifications of all aggregated sources.

In the simulations, it is assumed that the MAC controller generates one permit during every upstream time slot. These permits are queued. A downstream PLOAM cell is filled with 27 of these queued permits. The B-NTs use these PLOAM cells to derive the grants for the next 27 upstream time slots. This usage of PLOAM cells generates an additional constant delay of 27 slots distributed in a delay before the generated grant will be sent via the PLOAM cell and an delay before the received grant in the PLOAM cell is allowed to use an upstream time slot.

2.5 PERFORMANCE METRICS

When developing broadband shared-medium MAC protocols, it is important to limit the scope of the performance evaluation to well-defined segments. In Figure 8, the evaluation segments is defined.

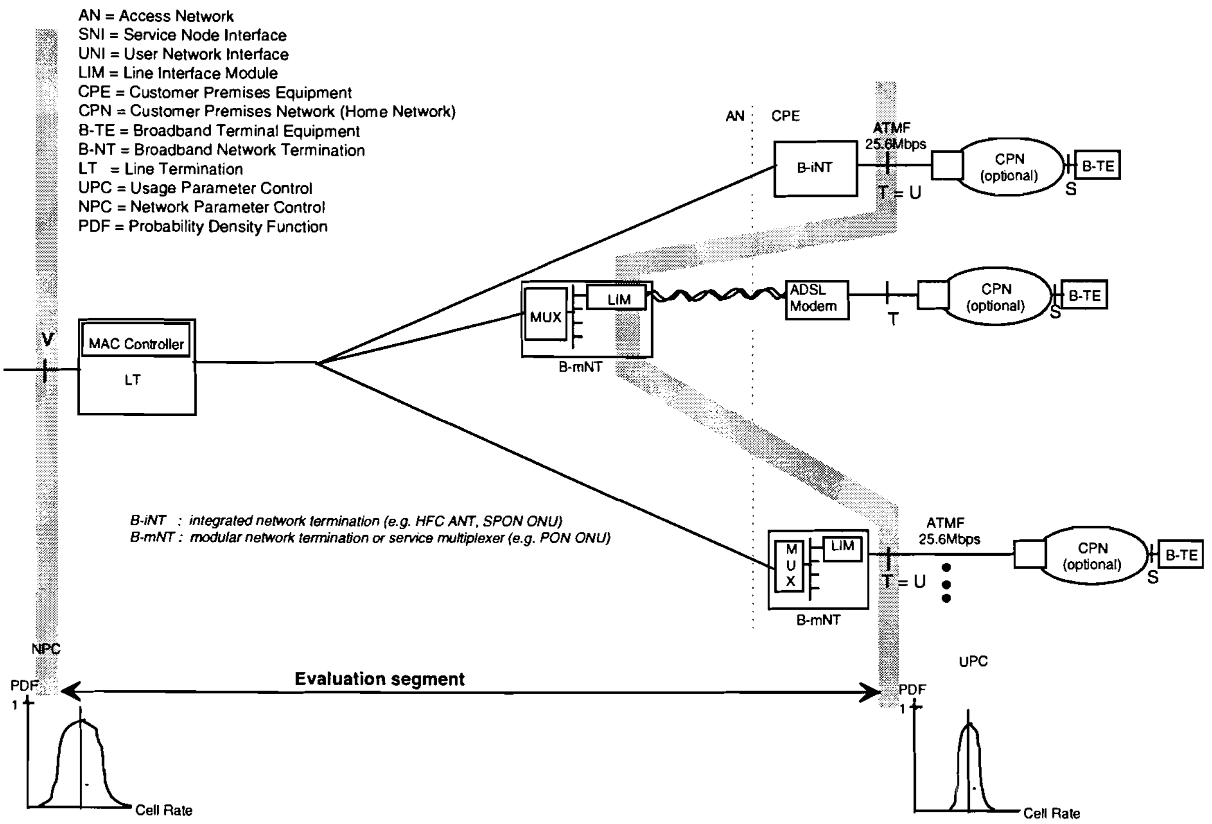

Figure 8: Reference Configuration

The private or home Network called Customer Premises Network (CPN) is characterized by its bit rate in upstream and downstream direction, the number of Broadband Terminals (B-TE) per residence, the number of ports on the home network side, the type of broadband User Network Interface (UNI), the type of physical medium and the distance on the home network side.

It is not the responsibility of the access network QoS policy to correct traffic distortions introduced outside the examined evaluation segment. Indeed, the traffic generated by a B-TE might for instance pass through a multiplexer inside the private network (CPN), or over an ADSL delivery segment, before it reaches the border of the defined evaluation segment. Although the source traffic may be conforming to the declared traffic contract, the Cell Delay Variation (CDV) introduced between the source and the ingress of the evaluation segment can be considerable. Explicitly the assumption is made that all traffic streams are well-behaved (i.e. compliant to their traffic contract) when they enter the evaluation segment. The QoS policies applied to the CPN and to the xDSL delivery segment should minimize these distortions, or their presence should be taken into account when determining the Cell Delay Variation Tolerance (CDVT) parameter for a connection.

The distortions introduced by the access network are dependent on the characteristics of the traffic, the access network topology, the network element behaviour, the used MAC protocol, and the load of the access network. The access network QoS policy as specified in the MAC protocol and the behaviour of network elements like B-NT and LT should bring these distortions to acceptable levels.

In this thesis report the performance of several MAC protocols for a given architecture of the involved network elements is evaluated. In a multiservice environment the MAC protocol should aim at good:

- flexibility: the MAC protocol should be able to support the whole spectrum of ATM service categories.

- performance: the delay and delay variation introduced by the MAC protocol should be kept within certain bounds, particularly for delay sensitive services. Also, cell loss must be as low as possible. Other performance characteristics are the obtainable load and multiplexing gain. Note however that QoS guarantees are considered as more important than link load efficiency. It is considered better to give QoS guarantees in a less load-efficient manner than to try to optimize the link load efficiency at the cost of the delivered QoS.

- fairness: none of the terminals should be arbitrarily favored or discriminated with respect to delay, delay variation and throughput.

- upgradability: the MAC protocol should be adaptable to upgrades of the network it serves (for instance, higher transmission speeds, higher splitting factor, increased span, ...)

- complexity: the MAC protocol should be realizable. This doesn't necessarily mean that it should be kept as simple as possible. The ability of the access network to efficiently operate in a multiservice environment is crucial for a high utilization of the costly infrastructure. The additional cost penalty for a complex MAC design will be marginal compared to the system cost. Moreover, because of the higher obtainable link load, the revenues for the PONs are increased.

- robustness: when errors occur, introduced by the medium itself or elsewhere, the MAC should be able to recover from this error.

- connectivity: the MAC should provide access to a large number of terminals simultaneously.

- efficiency: the overhead introduced by the MAC protocol should be low.

This thesis will focus on the MAC protocol performance metrics. To this end, the end-to-end delay, the cell delay variation of the queue length at the B-NTs will be evaluated in a multiservice environment. Constant bit rate (CBR), variable bit rate (VBR) and unspecified bit rate (UBR) traffic are considered. CBR and rt-VBR are the most important service categories intended for real-time applications. They require tight constraints with respect to Cell Tranfer Delay (CTD) and CDV. They are often referred to as ATM Transfer Capabilities for services sensitive to (variations in) delay. Cells which are delayed beyond some specific value can be considered as being lost. As such, real-time services require a fast reaction time of the MAC protocol. However, studies show that the performance of the MAC protocol with respect to real-time services is mainly characterized by the introduced Cell Delay Variation. UBR services then 'fill-up' the remaining transmission capacity (e.g. Internet applications). An important performance metric for these services will be the required queue length on the B-NTs to guarantee a zero cell loss.

2.5.1 End-to-End (ETE) delay

The ETE delay is specified as the time between the moment an ATM-cell enters a (sub)-queue in the B-NT, and the time that the same ATM-cell arrives on the LT and is ready to be retransmitted through the ATM backbone network. This delay is mainly caused by:

- a variable queuing delay caused by the buffering of cells at the B-NT also called Cell Transfer Delay (CTD),
- propagation delay through the access network, and
- processing delays at the LT and B-NTs

When request-based MAC protocols are used, the ETE-delay will increase because of the propagation delays of the requests, the processing time to convert requests into permits and the propagation delay of the permits to reach the B-NT again. ETE delays as well as the delay variations are quite important for real-time services.

2.5.2 1-Point Cell Delay Variation (CDV1)

The 1-point cell delay variation is defined as the variance in the inter-arrival time between consecutive cells belonging to the same connection.

The variable queuing delay on the B-NTs experienced by ATM cells entering the access network explains the introduction of cell delay variation. Moreover, the multiplexing of permits in the downstream MAC channel and the multiplexing of ATM cells belonging to different connections towards the head-end of the access tree may also introduce CDV.

In order to analyze the performance of the access network the 1-point cell delay variation can be measured on the LT.

CDV is an important performance metric for real-time services. In audio applications for example CDV could cause unacceptable performance decrease. Controlling CDV is also needed for correct timing assumed to the read and write cycli in receive and transmit buffers. Another reason to evaluate the CDV is the fact that policing devices in the ATM network are based on 1-point CDV measurements.

2.5.3 2-Point Cell Delay Variation (CDV2)

From 1-point CDV measurements it cannot be derived how much CDV was introduced by the access network, unless the inter-arrival times of the ATM cells before they entered the B-NT are known.

When CBR sources are used, this is quite trivial because of the constant inter-arrival time at the entrance of the access network. However, when bursty or variable bit rate traffic sources are evaluated the 1-point CDV should be measured twice, once before the cell enters the queue on the B-NT and once when the cell leaves the LT. By subtracting these 1-point CDVs from each other, the 2-point CDV (CDV2) is calculated. In formula this looks like:

$$CDV2 = CDV1_{before\ NT} - CDV1_{after\ LT} = \Delta t_{before\ MAC} - \Delta t_{after\ MAC} \qquad (1)$$

In the simulations, the 2-point CDV for all ATM cell streams will be measured. By collecting all measured CDVs a Probability Density Function (PDF) can be generated. It is obvious that the measured CDVs can only be multiples of the upstream slot time of the access network

2.5.4 QUEUE LENGTH

The length of the Queues on the B-NT is evaluated in ATM cells. When the protocol serves bursty traffic efficiently, it doesn't need large queues. Smaller queue sizes means the B-NT needs less RAM. In order to evaluate the efficiency of the MAC protocol, the queue sizes of all specified (sub-) queues are measured during the simulations.

3. MAC PROTOCOLS

3.1 OVERVIEW

As already mentioned the main task of the MAC protocol is to control the usage of the upstream link of the access network. Since the access network consists of a medium which is shared by several users it is most likely to contol the usage of this shared medium in the access network centrally.

There are several access networks in which terminals share the medium. In these typical configurations the upstream traffic is sent from terminals to the central point, while the downstream traffic is broadcasted from the central point to all terminals. The most famous example of this configuration is perhaps the satellite communication. The satellite can be considered as the central office which is however controlled by a (special) ground station. The other ground stations act like terminals. In order to avoid collisions, the control station has to broadcast information about the usage of the upstream link.

There are several ways to organize the control of the link. In general multiplexing traffic can be done by using frequency-, time-, or code- multiplexing (FDMA, TDMA or CDMA). In this context only the TDMA strategy will be used. This means that the medium can only be used by one terminal at a time.

In general there are two ways for controlling the medium: reservation based and collision feedback control. When using the collision feedback approach, every terminal can send a packet when it is available. Whenever two or more terminals have sent packets in the same upstream timeslot the packets will collide. The central point detects the collision and gives feedback information to the terminals whether the transmission was succesfull or not. The unsuccessfull transmitted packets have to be sent again. Therefor the terminal waits a (pseudo) random time and retransmits the same packet again. The waiting time can not be specified deterministic otherwise the retransmitted packet would collide again since all terminals behave the same. Examples of this access control are the Ethernet and the (slotted-) ALOHA protocol. When using the slotted-ALOHA protocol, the terminal has to start the transmission of a packet at the beginning of the slot while in a normal ALOHA protocol, the terminal can start sending at random times. Using slotted-ALOHA the chance packets will collide is reduced compared to normal ALOHA. This means the slotted-ALOHA protocol can realize a higher throughput compared to normal ALOHA.

The collision feedback approach has a limited efficiency. The maximum throughput of slotted-Aloha is 37% [26]. Another disadvantage is the delay between central point and the terminals. When this delay is quite large, the terminal has to wait very long before it receives feedback about possible collisions. This results in large access delays and large CDV.

In the reservation based mechanisms the upstream slots are reserved for one specific terminal. The reservation scheme is broadcasted by the central point to all terminals. By using the reservation scheme it is not possible that two terminals send packets in the same timeslot. This means there is no chance of collision, assuming the medium is error free. Consequently, the maximum throughput of a reservation based mechanism can approach

100% ignoring the needed bandwidth for additional overhead. Therefore the PON and HFC access networks will use reservation based mechanisms.

The reservation based mechanisms differ in the way the reservation scheme is created. In static protocols the central point uses the connection profile information from the signaling channel while in request based protocols terminals ask for upstream slots (requests) based on the waiting packets in their queue. In the next sections the static and reservation based mechanisms are studied further.

3.2 STATIC MAC PROTOCOLS

Static protocols produce grants for all (active) terminals based on the average needed bandwidth of the terminals. This average bandwidth or sustainable cell rate (SCR) can be derived from the signaling information which is generated with the setup of the connection.

The main disadvantage of generating grants by using the static information of the connection is the fact there is no feedback from the terminal to the central point, resulting in a rather poor performance for bursty traffic. The static allocation of bandwidth will result in either a poor utilisation of the available upstream bandwidth or serious quality degradation of the service (Figure 9). The most well known implementations of the static bandwidth allocation are based on the usage of a table or the usage of count-down counters.

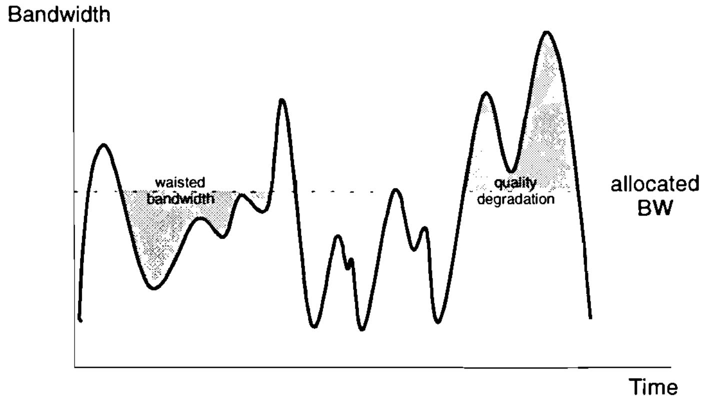

Figure 9: Static BW allocation for bursty traffic

Once the table is written it can be read cyclic. The allocated bandwidth can be derived from the number of entries in this table. By spacing the entries over the whole table clumps of cells are avoided and CDV is limited. For static traffic patterns the table can be optimized for minimal CDV resulting in a better performance than a counter based static protocol. Whenever new connections are made or others are released the table must be updated. This update takes relative a lot of time. So this system is not very performant for fast changing traffic.

As already mentioned, the static bandwidth allocation can also be realized using count-down counters. The usage of this system is quite easy. The counters are initiated on the desired interarrival times of cells. Every upstream slot all counters are decreased by one. Whenever a counter becomes zero, a grant is generated for the corresponding terminal and the counter is resetted to its initial value. This system has some major advantages compared to the usage of a table. First of all, there is no need to fill a table with entries. The update when creating or releasing new connections is also much faster because only the corresponding count-down counter has to be updated instead of a complete table. Another advantage is the fact that this system can be translated easily to a request based structure.

A disadvantage of the counter implementation is the continuous need of a downstream channel in order to send the grants for the upstream channel. When using a table it is possible to send only the table-updates to the terminals in stead of every generated grant. It must be noted that sending table updates is only performing for quite static traffic patterns.

3.3 REQUEST BASED PROTOCOLS

Request based protocols differ from the static protocols in the sense they send requests for grants based on the amount of packets arrived on the terminal. Although it takes some time before the request is transmitted from terminal to LT, converted into a grant and this grant is transmitted back to the terminal again, this approach has some major advantages. The most important advantage is the fact that the terminals will not waste any grants so the upstream efficiency is only limited by the overhead introduced by the necessary MAC communication channels.

The terminals can sent their updates by sending the current value of the queue sizes or by sending the queue growth. Sending the current queue sizes means more overhead since it includes a lot of redundant information. In general, the dynamic range of the queue sizes will be larger than the queue growth in a certain interval. Sending the queue sizes also means the LT still has to calculate the queue growth in order to derive the number of new requests. When sending the queue growth this can be avoided however there are some additional facilities needed to guarantee robustness when requests get lost.

3.4 MAC PROTOCOLS FOR HFC

Although the development of a MAC protocol for HFC is not within the context of this project anymore, this section will handle the currently implemented MAC protocol. It can be seen as an example of a static protocol based on a table.

Obviously the HFC access network has quite some different characteristics than the PON. The upstream physical layer is a 3.04 Mbps ATM-based QPSK channel. Its upstream slots are 68 bytes containing a full ATM cell (53 bytes), with preamble (4 bytes) FEC (3 bytes) and a 7 bytes gap. This results in a ATM bitrate of 2.37 Mbps serving a maximum cell payload of 2.15 Mbps.

The downstream channel is 41.6 Mbps ATM based 64-QAM. It consists of a superframe containing 126 ATM cells. The first ATM cell of the superframe (TGT-cell) contains the downstream MAC information. This information is used to specify for each upstream slot which terminal is allowed to use it. It can be compared with the PLOAM cells for the PON configuration.

The MAC controller for ATHOC step 1 [22] is based on a 512 entries long static terminal. The upstream grants are generated by a cyclically polling of the table. Once the grants are generated they are sent to the terminals with the TGF cells in groups of seven or eight.

In ATHOC step 1, the table, which is called "TEAL" is configured with a static number of entries, proportionate to a predefined bandwidth. The way by which the entries for a certain terminal (TEA) are distributed over the TEAL is such that the distance between the same TEA entries in the TEAL is as equal as possible. This is obtained in the following way:

- The list of active TEAs and their bandwidth is predefined. The bandwidth is determined in number of entries. Each entry stands for (53/68)*(3.04Mbps/512)=4.63kbps.
- a "mute" TEA is defined to consume the unused upstream bandwidth. The bandwidth allocated to this "mute" TEA is derived from the total upstream bandwidth minus the sum of all bandwidth allocated to the active TEAs.
- For each TEA, active and "mute", the ideal step-size between consecutive entries is calculated : step size = (53/68)*3.04Mbps/upstream bandwidth
- Given these step sizes for each TEA the ideal position is given by:

  next_position = current_position+ step_size
- Then the TEAL is filled for index 0 to 511 according to these criterions:
  - All TEAs start from index= step_size/2
  - Entries are filled in the TEA as densely as possible: the next entry in the TEAL is allocated to the TEA with the lowest value of "next_position", even if this value is lower than the theoretically calculated value.
  - Then for this TEA the value of the "current_position" is replaced by that of "next_position".

The algorithm always allows full occupation of the needed bandwidth. So no entries will go lost because of competition between two TEAs. It also provides a fairly good equal distribution. A main this advantage is the fact that this algorithm sometimes places the permits on an entry earlier then the ideal one. This can be important for CBR connections because the cell to transmit may not be ready resulting in a lost permit.

Obviously the ATHOC step 1 MAC protocol is a static protocol. This means it is not able to respond to traffic fluctuations like the bursty traffic generated by internet applications. Therefore in the extensions made to the implemented MAC protocol for ATHOC step 1 a piggybacking field will be used as upstream MAC channel. This channel is needed to provide regular and accurate updates of the queue status on the terminals to a more dynamic grant generation mechanism.

In order to guarantee the different QoS parameters for several services an extension should also be made to the QoS policy. The weaknesses of ATHOC step 1 have been used in the definition of ATHOC step 2. Since the MAC protocol for HFC is not within the context of this thesis report no further analyses will be made on the MAC protocol for ATHOC step 2.

3.5 MAC PROTOCOLS FOR APON

This paragraph describes the evaluated MAC protocols for the APON configuration. An overview of the main characteristics can be found in appendix A.

3.5.1 Alcatel APON MAC (AAM)

This semi-static protocol produces permits at equal intervals according to the inverse of the total peak-rate of connections established at each termination. The head-end contains a counter associated with each network termination for which suitable reload values are recalculated at the establishment of each semi-permanent connection. No requests are used.

The rate at which permits are emitted is updated with every call establishment and release. However, it is not possible to respond to burst level fluctuations created by the aggregation of bursty services. Thus, the benefits of the concentration and multiplexing gain can only be exploited down to call level. It is a simple and predictable method for the introductory phase of PONs when small upstream traffic loads are expected. In current Alcatel PON implementations, the AAM protocol allocates bandwidth for B-NT[i] according to:

$$BW_{all}[i] = \sum_{\substack{active\\ sources}} PCR \tag{2}$$

This bandwidth allocation scheme can only be used for CBR services. Using for instance VBR traffic sources with PCR 10 times the SCR would cause an extreme low efficiency, resulting in a very low number of connected sources (or equivalently, a high call blocking propability).

In this proposal, bandwidth for VBR services is allocated based on the SCR. The bandwidth allocation for ABR and UBR services takes the MCR guarantees into account. The sum of this allocated bandwidth is called the minimum Guaranteed BandWidth (GBW_{min}) defined as:

$$GBW_{\min}[i] = \sum_{\substack{active\ CBR\\ sources}} PCR + \sum_{\substack{active\ VBR\\ sources}} SCR + \sum_{\substack{active\ ABR,\\ UBR\ sources}} MCR \tag{3}$$

The remaining bandwidth is allocated proportional to the SCR for VBR services and to (PCR-MCR) for ABR and UBR services. In formula the total bandwidth allocation is given by:

$$BW_{all}[i] = GBW_{\min}[i] + BW_{rest} \cdot FairShare[i] \tag{4}$$

In our proposal, the remaining (or rest) bandwidth is defined as the total bandwidth subtracted by the guaranteed minimum bandwidth of all B-NTs and is given by:

$$BW_{rest} = TBW - \sum_{\substack{active\\ B-NTs}} \left(GBW_{\min}[i]\right) \tag{5}$$

The Fair Share for B-NT[i] is defined as:

$$FairShare[i] = \frac{\left\{ \sum_{\substack{active\ VBR \\ sources}} SCR + \sum_{\substack{active\ ABR; \\ UBR\ sources}} (PCR - MCR) \right\}_{B-NT[i]}}{\sum_{\substack{active \\ B-NTs}} \left\{ \sum_{\substack{active\ VBR \\ sources}} SCR + \sum_{\substack{active\ ABR; \\ UBR\ sources}} (PCR - MCR) \right\}} \tag{6}$$

The MAC controller implements one spacer per B-NT. The bandwidth allocation is implemented by programming an initial spacer value for each of the B-NTs. During every upstream time slot the value of all spacers is decreased by 1. When the value of a spacer reaches zero, a permit is generated for the associated B-NT and the spacer is reset to its initial value. The initial value of the spacer can easily be calculated as follows:

$$AAM\_spacer(NTnr) = \frac{TBW}{BW_{all}(NTnr)} \tag{7}$$

In the currently implemented AAM protocol the mean interarrival time of grants on a B-NT is calculated by dividing the upstream ATM bitrate by the allocated bandwidth for this Network Termination. Whenever the outcome of the calculation is not an integer number of upstream timeslots, it will be rounded downwards to the closest lower integer, in order to guarantee enough bandwidth. This rounding causes a frequency mismatch between the arrival of grants and the arrival of cells at the B-NT.

The simulated AAM protocol will approximate the calculated mean interarrival rate. This can be done by using floating point values for the spacer countdown counters. When the value of a countdown counter becomes less than zero, a grant will be generated and the counter will be increased with its initial (floating point) value. Assuming that the mean interarrival time of the grants is a value between ‘n’ and ‘n+1’, this mechanism will generate grants every ‘n’ or ‘n+1’ slots.

3.5.2 Static Priority (SP)

The static priority MAC protocol is one of the simplest request based MAC protocols. This protocol generates grants to the B-NTs using a static priority permit scheduling discipline. The priority mechanism distinguishes between the four QoS classes (resp. CBR, VBR, ABR and UBR).

The MAC controller maintains 4 counters per B-NT, indicating the number of pending CBR, VBR, ABR and UBR respectively. The protocol will first serve all CBR requests from all B-NTs before it generates grants for VBR services. In the same way, grants for ABR services will only be generated after all CBR and VBR requests are served. UBR services have the lowest priority.

Within each priority level, all B-NTs are treated equal. A “Round Robin” scheduling discipline is used. This means the MAC controller will generate requests by serving the B-NTs one by one in a cyclic way until all pending requests are consumed.

Although the SP protocol is a request based MAC protocol, it has some major limitations, for instance:

- No Minimum Cell Rate guaranties for ABR and UBR traffic
- No Peak Cell Rate policing
- No mechanisms in order to reduce CDV of real time services.

3.5.3 Global FIFO (GF)

The simulated GF protocol was described by F. Panken [23]. It focuses on minimising delays for real time services. The GF MAC protocol only considers 3 types of requests, namely requests for ABR cells and requests for CBR and VBR cells. In our simulations we still consider that only 6 bits are available per QoS class for MAC requests. The UBR request field (UQ) is not used. As such, a request based MAC protocol is used for CBR, VBR and ABR traffic, while pre-arbitrated permits are used for UBR services.

In the original proposal, the MAC requests were based on a combination of piggybacking (request field prepending each upstream timeslot) and minislot polling. In our simulations, we only use the MAC channel defined by the Gx-FSAN OAN group, called minislot polling.

The GF protocol considers grants per B-NT and per QoS class. Each of the four traffic classes (CBR, VBR, ABR and UBR) has dedicated grants.

The MAC controller enforces Minimum Cell Rate guarantees for ABR traffic per B-NT. It maintains two counters per B-NT: a CountDown Counter (CDC) and a Request Counter (RC). The MAC controller also maintains 2 Global Counters (GC) for cyclic order selection between B-NT, when serving UBR and ABR traffic under special conditions: GC1 and GC2.

The implemented MAC protocol can be summarised as follows: all requests received related to real-time traffic (CBR, VBR) are immediately translated in permits to the associated B-NT and queued in the global permit FIFO. CBR and VBR permits are however differentiated by their colour.

CDC[i] is initialised at M[i], a value reflecting the MCR for ABR connections, and counts down during each upstream timeslot. CDC[i] stops counting down as soon as it reaches zero. RC[i] is increased for every new ABR cell request received from B-NT[i] (this is derived from the MAC information carried in the MAC minislots). If CDC[i] is zero and RC[i] > 0, an ABR permit to NT[i] is inserted in the global permit FIFO, RC[i] is decreased by one, CDC[i] is reset to M[i].

Whenever the global permit FIFO is empty, and ABR requests are still pending (some of the RCi > 0), ABR requests are generated to these B-NTs until all RCi's reach zero. Selection between NTs is cyclic (GC1) Whenever the global FIFO is empty and all RCi's are zero, UBR permits are generated to all NTs in a cyclic order (GC2).

3.5.4 Enhanced Global FIFO (EGF)

The GF MAC protocol has some mayor limitations in reducing CDV for bursty real-time services and the upstream bandwidth efficiency. In order to reduce these limitations, a enhancement on this protocol has been designed. The EGF MAC-protocol is based on the GF protocol. The most important differences are:

- EGF considers 4 types of requests (resp. CBR, VBR, ABR and UBR) instead of the 3 types in GF. The main advantage is the more efficient upstream bandwidth allocation for UBR services.
- EGF uses spacers like the AAM protocol, in order to allocate bandwidth for B-NTs. This is done for all QoS classes. The spacer enforce PCR spacing for real-time services (CBR and VBR) and provide MCR guarantees for ABR and UBR services.
- The spacers all use the bounded period rule (described below).
- The empty slots are used for additional ABR and UBR requests using "Round Robin" scheduling.

The Bounded period Rule

As already described, the spacing mechanism in *EGF* creates a minimum distance between two consecutive cells from one QoS class on the same B-NT in order to force a more regular traffic pattern from each B-NT entering the core network. Normally, this minimum inter-arrival time is derived from the sum of all peak cell rates of all connections sharing the considered QoS queue.

In case this spacing rate equals the (mean) cell rate of the targetted services, classical queuing theory proves that the load of the B-NT buffer will be very large. This heavy load on B-NT buffers will result in unacceptable large access delays. In order to prevent this situation, the Bounded Period Rule (BPR) was introduced [24]. It controls the values of the spacer timers, knowing the following impacts:

- The spacer may introduce both high transfer delays and CDVs for individual VCs in case a superposition of low bit rate sources is offered to the NT-buffer. Therefore space as little as possible.
- The spacer avoids clumps of cells in the case high bit connections are offered to the NT-buffer. It also provides a protection mechanism for the access network. Therefore space as strictly as possible.
- The values of spacer timers can be derived, using the following formula [24]:

$$T_{sp}[i] = \min\left\{\varepsilon \cdot \left\lfloor \frac{TBW}{\sum PCRs\ on\ NT_i} \right\rfloor, T_{\max}\right\} \qquad 0 < \varepsilon \le 1 \tag{8}$$

where T_{max} is the maximum spacing value and ε is called the bundle spacing tolerance. From [24] it is known that an ε equal to 0.8 and a T_{max} equal to 50 slots or 36 μs generates good performance of the bounded period rule when using 622 Mbps upstream. In our simulations we considered a symmetrical 155.52/155.52Mbps PON. As such the value of T_{max} was set equal to 13 slots.

3.5.5 Circular Permit Programming (CPP)

The Circular Permit Programming MAC protocol, designed by Angelopolos [1,2,3], mainly focusses on reducing the CDV. The focal point of the permit distribution algorithm are four CPP Random Access Memories (RAM). Each RAM contains a number of entries, which is exactly an integer times the number of upstream timeslot between two polling instances of one B-NT (in our case, 128 entries). Figure 10 depicts the configuration. Each of the four CPP RAMs is associated with one specific QoS class.

Requests are carried in strictly periodic fashion using minislot polling. The B-NTs issue four types of requests: requests for CBR and VBR services, requests for ABR services and requests for UBR services. In the CPP protocol, transmission requests are expressed as the number of cells that have arrived at each B-NT since the network termination contributed to the previous minislot (thus, the queue growth).

Every time a minislot arrives at the LT, the requests are read and the address of the requesting B-NT is written into the CPP RAM a number of times equal to the number of requests. The QoS-class of the requests determines which CPP RAM is used. The requests are written into the CPP RAM, nicely spaced over the polling interval and starting from the first empty position after the current location. When a position is already occupied the next free one is used. Angelopoulos argues that the delay jitter introduced by this is insignificant considering that the rough spacing as described is done without connection information.

The CPP RAMs are read cyclically and continuously and the contents of each successive location is copied into the grant field in downstream PLOAM cells. CPP RAM1 (CBR) has strict priority over CPP RAMs 2 (VBR), 3 (ABR) and 4 (UBR). A backlog FIFO is used for CPP RAMs 2, 3 and 4. Grants are directed to a dedicated QoS-class located on a specified B-NT.

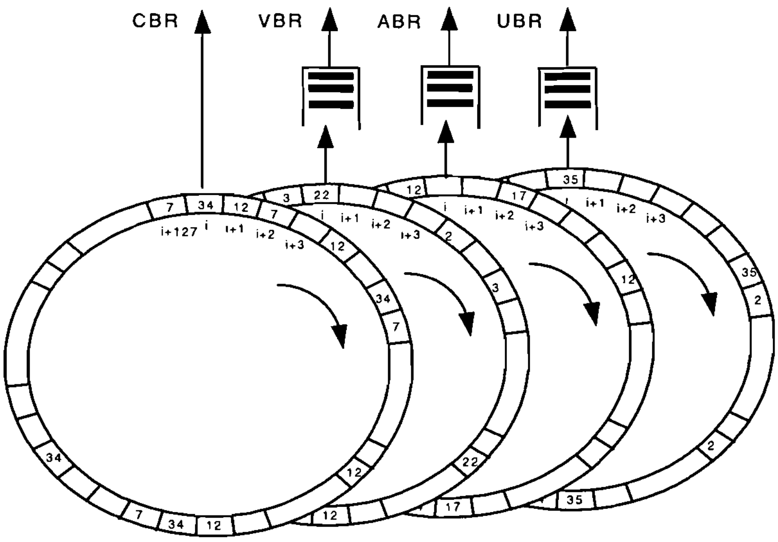

Figure 10: CPP configuration

At low load a lot of locations will be empty in the CPP RAMs. At high loads, although the Connection Admission Control function (CAC) guarantees no long term overload by call blocking, momentary overloads are expected when statistical multiplexing gain is pursued. At such overloads the protocol is well behaved without extra measures. Most places will be already occupied particularly near the current location and therefore the B-NT addresses may be written several locations later than wished, so zero permits will seldom be emitted. At higher loads it will not even be possible to write all the necessary permits to satisfy all requests. It must be stressed that no attempt is made to write beyond address i+Tpoll where Tpoll represents the number of entries associated with the B-NT polling interval. Whatever requests remain unsatisfied at this point are kept in the request buffer to be added to the next request from that same termination. This only occurs during momentary overload situations and most of the time the writes represent only new arrivals during the polling period.

When not all requests are satisfied in one circular round, adding unsatisfied requests to the new requests comes into play allowing a reflection of backlog. Regardless of whether it will be even more unlikely to satisfy them on the next round, it is imperative to keep track of arrivals and turn the distribution policy proportional to queue length contributing to robustness and loss avoidance. Quicker recovery is also served by the buffering of unsatisfied requests hence indicating which terminations suffer more from the overload. Of course spacing and CDV inescapably suffer but that is expected in an overload situation. By the preventive CAC action the duration of overload will not last long to cause buffer overflows above tolerable levels.

3.6 MAC PROTOCOLS FOR SUPERPON

The new generation PON network called SuperPON, is designed for Fiber to the home (FTTH) and Fiber to the Cab (FTTC) configurations. This means that the Network Termination point will be closer to the end user. The main consequences for the access network characteristics are the larger number of B-NTs and less traffic aggregation per B-NT. The maximum distance between terminals and LT (span) is increased from 10km to 100km resulting in a larger round trip delay.

However the MAC protocols empoyed in regular PONs are not suitable for the SuperPON, the evaluation of these protocols can and will be used for the design of SuperPON protocol. The round trip delay for a request-permit exchange approaches 1ms in SuperPON access network, which brings delay sensitive services to their tolerance limits. Consequently differentiating the support of delay sensitive and delay tolerant services is unavoidable.

3.6.1 SPON1

The design of the SPON1 MAC protocol is based on the evalution of the MAC protocols for APON. It supports four Quality of Services. The grant generation algorithm depends on the QoS. For CBR traffic the traffic profile will be used to generate a static pattern of unsollisted grants for every B-NT. The queuing delay for CBR traffic depends on the phase synchronisation. Assuming fully frequency synchronisation between grants arrival and cell arrival on the B-NT the maximum queuing delay caused by phase mismatch will be the interarrival time between two cells. This delay is unacceptable for services like POTS. Therefor the POTS service will synchronize both phase and frequency of the grants arriving on the B-NT. Phase synchronisation for other CBR services is for further study.

The VBR grant generation mechanism is a hibride mechanism of unsollisted grants and request based grants. Basically the VBR traffic receives unsollisted grants with a rate between SCR and PCR. Since the queuing delay for bursty traffic served with a static MAC protocol can reach large values when the burstiness increases, a request based mechanism will be used to limit the maximum queuinig delay. When the real-time FIFO is empty and more than "n" VBR-requests for one B-NT are pending, the request based mechanism will generate extra grants besides the unsollisted grants. This makes a faster troughput of long bursts possible. It must be noted that this hibride system is only effective when the bursts last longer than one round trip delay.

For ABR and UBR traffic a fully request based mechanism like the EGF will be used. The mechanism uses spacers in order to give MCR guarantees. The remaining grants will be given to ABR or UBR in a Round Robin fashion using static priority.

For the implementation of the SPON1 MAC protocol, two FIFO's are used. In the first FIFO, called "real-time FIFO", the unsollisted grants for the real time services are queued. When the real time FIFO is empty the request based mechanism of the hibride VBR grant generation is approached. If this meganism doesn't generate a grant the second FIFO which collects grants for ABR and UBR services based on MCR are queued is used. Whenever both FIFOs are empty, the Round Robin engine is activated. In Figure 11 a global view of the SPON1 protocol is given.

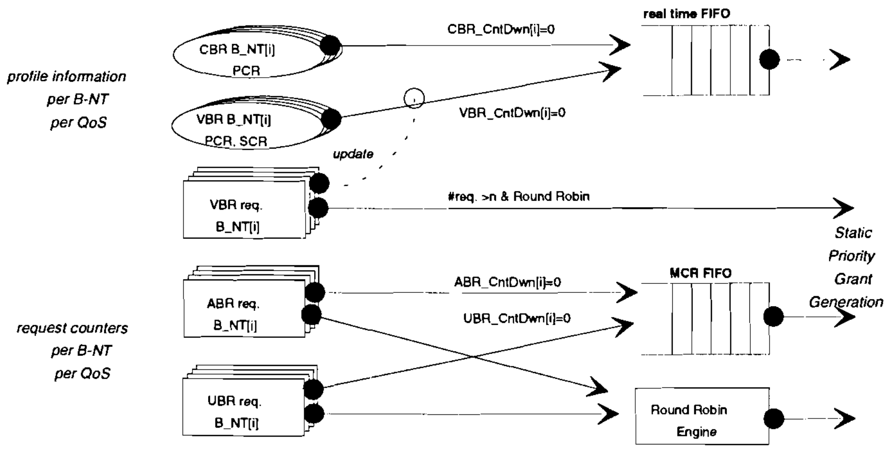

Figure 11: SPON1 configuration

3.6.2 PLANET

Since the definition of the SuperPON access network is quite recent, there are not many MAC protocols for this configuration described in literature. In this section the MAC protocol designed for the field trial of the ATM SuperPON access system PLANET is described. The protocol is simply called PLANET and it is designed by Angelopoulos [5].

PLANET is based on unsollisted grants issued on the basis of arrival rates known from call set-up information in case of CBR connections. A dynamic reservation mechanism is adopted for bursty services in order to increase efficiency.

4. THE OPNET MODEL FOR MAC PERFORMANCE ANALYSES

4.1 INTRODUCTION IN OPNET

OPtimized **N**etwork **E**ngineering **T**ools (OPNET) is a workstation-based environment for the modeling and simulation of communication systems, protocols and networks. This event-driven program is very useful for simulations of packet-switching networks. The user-interface is graphically oriented and divided in three levels. These levels are called:

- Network level,
- Node level,
- Process level.

In this section, the usage and functionality of these hierarchical levels is further discussed. For the performance evaluation of alternative MAC protocols an generic simulation model of the ATM based access network has been developed. In appendix E the features and limitations of this network are summarized. The rest of this chapter (section 4.2 until section 4.6) will analyze the basic structure of the developed model.

4.1.1 Network Level

The network level is the highest hierarchical level in OPNET. In this level, the network is designed by connecting routers, switches etc. using links. Specifications of the link include Bit Error Rate (BER), Delay, Maximum Bit Rate etc and can be done by using the Parameter Editor. The other network elements can be specified on the Node Level. On the network level, the topology of the access network is modeled. An example of an access network topology is given in Figure 12.

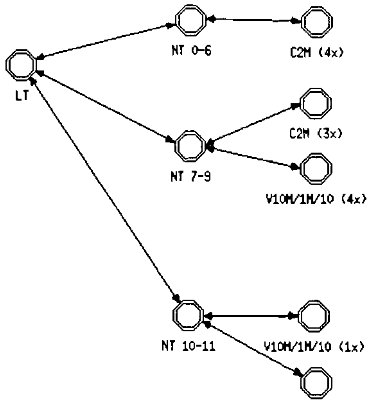

Figure 12: OPNET model for the Access Network (Network Level)

4.1.2 Node Level

The 'Node level' specifies the architecture of a network element. At this level one can use standard building blocks such as transmitters, receivers, queues traffic generators, etc. These building blocks are connected by "packet streams" which transfer the packets. All streams connected to a node have a unique identifier, called "stream index". It is also possible to connect the nodes using so-called statistical wires which can only be used to transmit status information. The design of new building blocks can be done by using a 'processor' node or 'queue' node. In section 4.3 and 4.4 the design of the LT and the B-NT on node level is further discussed.

4.1.3 Process Level

The behaviour of a "processor" or "queue" node is characterised by a finite state machine which is developed at the 'Process Level'. This is the lowest level in OPNET. The finite state machine is constructed with the "Process editor" by states and state transitions as shown in Figure 15 in section 4.3.

With ANSI-C code, the behaviour of the states can be specified. The functionality of the code is increased by 275 predefined OPNET procedures, called 'Kernel Procedures'. For every state can be specified what should be done during the entering of the state, and what should be done when leaving the state. Two different kind of states are distinguished:

- **Forced** States (black) and
- **Unforced** States (white).

In the forced states the system can not hold. The unforced states are only left when an interrupt occures. The state transitions are based on interrupts generated by other processes, however a process can also generate interrupts for its own purpose. Since forced states do not need interrupts for a state transition it is also possible to use booleans to indicate in which direction the state should be left. It must be noted that the finite state machine must be designed in a way that one of the transitions from a forced state is always true, since the system is not allowed to hold here.

4.2 MODELING THE ATM BASED ACCESS NETWORK

In order to evaluate the performance of a MAC protocol a model of the access network is needed. For several physical implementations the access network can differ in characteristics like the maximum number of terminals (splitting), the maximum (upstream) bitrate, and the maximum distance between terminals and central point. The topology of the access network can also differ. This means the model has to be configurable in network characteristics and topology.

These demands had a large influence on the structure of the model. The definition of a clock based on the upstream timeslots makes the model independent of the upstream bandwidth. All calculations are done in upstream timeslots.

The configurable network topology can be achieved by modeling all used "building blocks" of the ATM-based access network. The topology of the network can be specified easily by connecting the building blocks in the correct order. The most important building blocks are:

- the central point which has to control the usage of the link called Line Termination (LT),
- terminals which have to share the link called Broadband Network Terminations (B-NT),
- traffic sources: In order to generate realistic traffic for the terminals, and
- policer: In order to evaluate the performance of the MAC protocol.

For all these building blocks OPNET models are developed. In the next sections the behaviour of the models will be specified. For the traffic sources several models are develloped, for the most important Quality of Services in ATM.

The behaviour of the MAC grant generation algorithm can be specified in external C-code. So one does not have to know the structure of the OPET model in order to specify a new MAC algorithm. Obviously the code has to be compatible with the interface unit which is also written is external C-code. The interface is based on four functions as specified in section 4.3.1. The global structure of the model is shown in Figure 13.

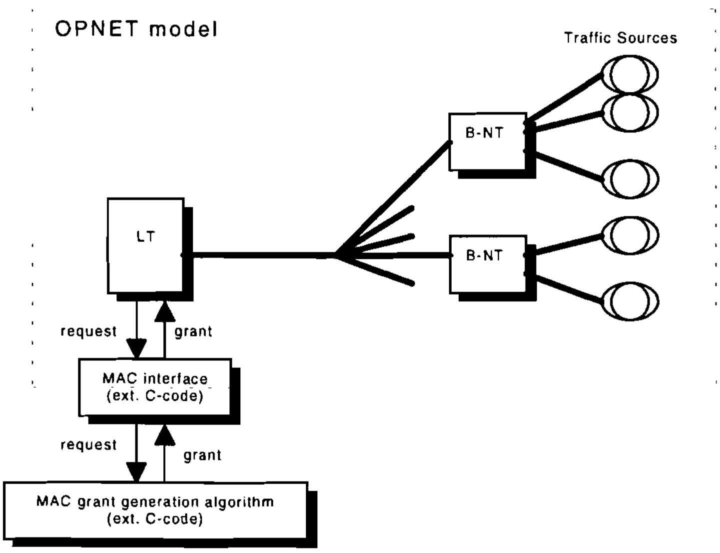

Figure 13: Structure of the OPNET model for MAC perfomance analyse

4.3 LINE TERMINATION (LT)

In Figure 14 the node model of the Line termination was already shown. On the left side several receiver and transmitter pairs are connected to a switch. These "transceivers" will be connected to the B-NTs on network level.

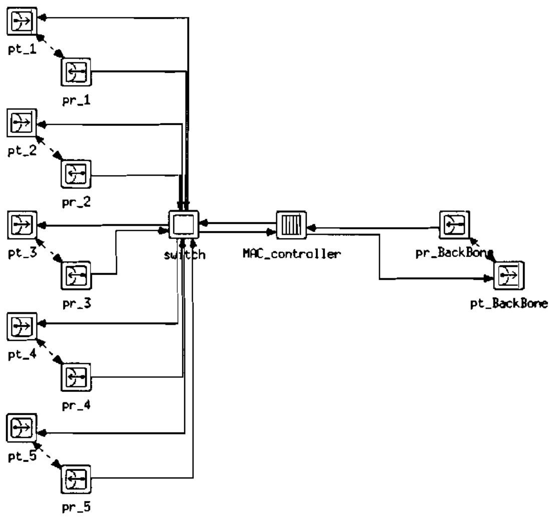

Figure 14: OPNET model for the LT (Node Level)

While OPNET has no standard model for point-to-multipoint links, the switch in the LT model is created. This switch will broadcast all downstream traffic to all connected transceiver pairs. In upstream direction the switch behaves transparantly. The question whether the incoming traffic is upstream or downstream can be determined by the input “stream-index”. If the index is zero, the traffic comes from the MAC controller and has to be downstream. All other indices are used for upstream traffic. The input stream index determines also the destination stream index.

The other element in the LT is the MAC controller. Most of the MAC functionality is situated in this controller. The MAC controller is connected to a backbone transceiver in order to do further analyses on the generated traffic. In the next section the MAC controller is further analyzed.

4.3.1 The MAC controller

The behaviour of the MAC controller is specified by the finite state machine as shown in Figure 15. The “Init” state is entered at the beginning of the simulation since the “begin_sim” interrupt is used to start the process. In this init state all specified values on node or network level are read, the minislot structure is build and it is send downstream by a “minislot_init” packets.

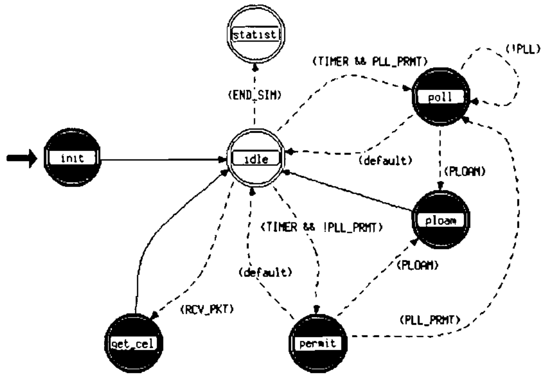

Figure 15: OPNET model for the MAC controller (Process Level)

It must be noted that the MAC controller has facilities to generate ETE-delay and CDV statistics per connection. A maximum of 50 connections specified by VPI and VCI labels can be monitored with this option. While the statistics can only be generated when the arrival time in the B-NT queuing point is known, each ATM cell carries a timestamp with this time. Obviously this facility is only available in simulation environment. When real measurements are done it is quite complex to generate 2-point CDV statistics.

While the MAC controller is the central process in the simulation model, it is also used to specify several general options like the number of connected B-NTs and the usage of MAC communication channels (Piggybacking and Minislots). The option “Polling sequence” specifies the polling frequuency while the option “Using empty slots for polling?” enables extra polling grants. When the upstream traffic has to be sent further to the backbone interface for further analyses, the option “BackBone” must be enabled otherwise the traffic will be destroyed.

The most important funtionality of the MAC controller is the conversion from requests to grants. Therefor several function interfaces are standarized. The communication between the OPNET MAC controller and the grant generation algorithm is realized using the following functions:

- **MAC_get_permit,** generates a grant by specifying the nurnber of the B-NT (permit) and the QoS (pri). These values are converted in a code which also specifies the expected behaviour of the B-NT about optional Piggybacking and QoS feedback.

- **MAC_place_permit(#req, nt_id, pri)** generates “#req” new requests for B-NT “nt_id” with QoS “pri”. In the (extern) algorithm can be specified how the new requests for grants should be processed

- **MAC_init_nt(nt_id, CBR_CR, VBR_MCR, VBR_SCR, VBR_PCR, ABR....)** tenders the traffic specification of the aggregated traffic of B-NT “nt_id” per QoS to the grant generation algorithm. This function is called when an “nt_init” cell enters the LT. These cells are generated by the B-NTs and sent to the LT in order to initialize the terminal.

- **MAC_init_process(prot_id, #NTs, xx)** initializes the MAC grant generation algorithm. By the parameter “prot_id” is specified which algorithm should be used. The number of connected B-NTs is specified by “#Nts”. The parameter “xx” can be used as a algorithm dependent initialisation parameter.

In appendix F the MAC grant generation library with the links to several algorithms is specified.

4.4 BROADBAND-NETWORK-TERMINATION (B-NT)

The B-NT model can be used as a general model for the queuing point at the network termination as described in chapter 2. In this model (Figure 16) five transceiver pairs are reserved for connections with traffic sources. Unless the restricted number of transceivers, it must be noted that the maximum number of sources can be larger than five since the traffic source models can act like aggregation of several sources. The switch will find out whether a transceiver is connected or not. It also detects which sources (VCI, VPI) are connected to the transceiver. This can be useful for routing the downstream traffic. The "queues" node specifies the behaviour of the queuing point.

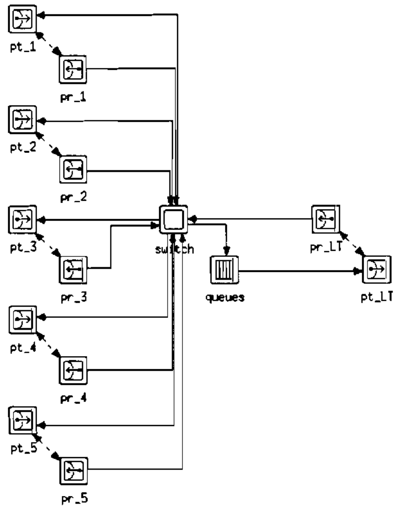

Figure 16: Node model of the B-NT

4.4.1 The B-NT switch

While the "queues" node only specifies the behaviour of the queuing point, the "switch" node has to take care of the initialization and signaling information. It also has to filter all received information from the LT, since the LT will send the downstream traffic broadcast. The most important filter action is based on the presence of active B-NTs. Since the sources will send their signaling information upstream, the switch knows for which B-NT numbers it is acting. The signaling information of the sources is also used to create "signaling information per B-NT". This information is send in "nt_init" cells to the LT in order to give the MAC controller information about the served traffic.

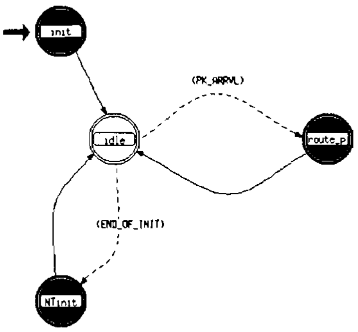

Figure 17: Process model of the B-NT switch

4.4.2 Queues

The model for the queuing points on the B-NT consists of several parallel First-In-First-Out (FIFO) queuing disciplines. Per B-NT four (sub-)queues are used to handle the different QoS. When an ATM-cell enters the queue module the ARRIVAL interrupt will be set. This causes an transition to the INS_TAIL state. In this state the QoS will be detected and the cell will be stored at the tail of the corresponding queue. By also checking the VPI of the ATM cell, the model can detect to which B-NT the cell belongs. For each B-NT four queues are available. In this way the model can simulate the behaviour of several B-NTs.

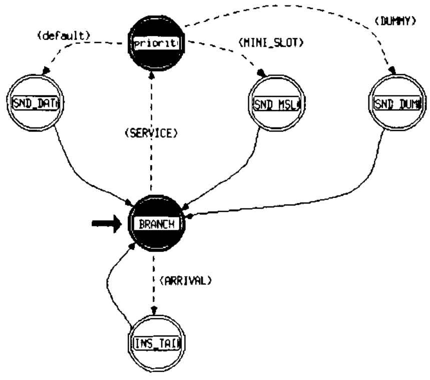

Figure 18: Process model of the B-NT queuing point

The queuing model is based on a passive queue which means that the queue only sends cells when it is ordered to. In this framework the queue gets an interrupt from an other process when the upstream channel can be used. With the interrupt an information vector is included in order to detect which B-NT is ordered to send and what should be send. This vector contains information about which B-NT is ordered to send and what should be sent. This can be a:

- Minislot cell, or
- Normal ATM Cell.

Sending an Minislot can be done with or without QoS feedback. When using QoS feedback the model will send information about all sub-queues belonging to the B-NT. Without QoS feedback it will only send information about the complete queue of the B-NT.

When sending a "normal" ATM cell the queuing model needs to know where the cell should be taken. This can be done by specifying the QoS (0..3) or by giving the B-NT the right to search a cell of highest available QoS. This option can be used to evaluate distributed intelligence. In Figure 19, the structure of this model is shown. In the case that the queue where the cell should be taken is empty, a dummy cell will be sent. This is done in order to detect empty upstream slots.

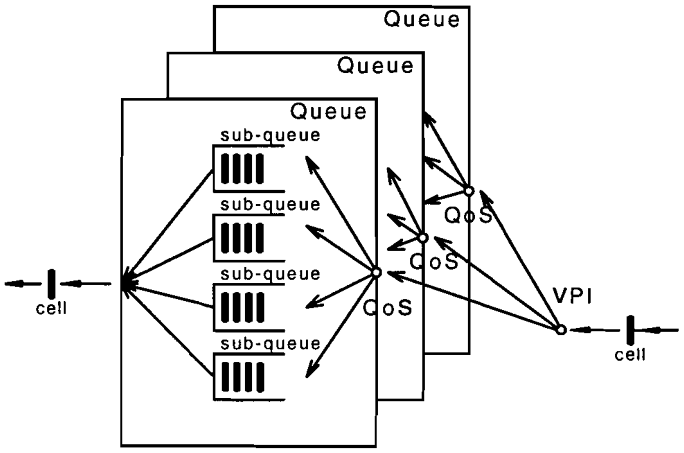

Figure 19: Structure of the B-NT queuing model

4.5 TRAFFIC SOURCES

Several traffic sources are modeled in order to create realistic traffic scenarios. This section only handles the general aspects of the traffic source model. Detailed descriptions of all these models are further discussed in chapter 5.

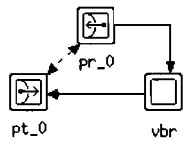

Figure 20: Node model of traffic source

The traffic source models can generate traffic specified by a certain pattern. Specifications like the sustainable bit rate can be specified at node- or network-level. This model can also act like several traffic sources. In this case all sources use the same specifications.

While using a source model in order to generate traffic for several traffic sources two cases are distinguished. The model can act like several sources aggregated on one B-NT or like a source for several B-NTs. In the first situation the number of sources can be specified by the parameter "#SRC/NT", in the second by the parameter "#NTs". Combinations of both parameters are also possible. The generated ATM cell carries the fields "VPI" and "VCI". In order to trace the data of one traffic source, the combination of VPI and VCI has to be unique. VPI labels are used to indicate for which B-NT the traffic is generated. The VCI label makes it possible to give all sources aggregated on one B-NT a unique identifier. The adjudication of VCI and VPI labels for aggregate sources is done automatically and successive. By specifying the "VPI offset" and the "VCI offset" one can control which numbers should be used by the model.

Another field in the ATM cell is the "QoS" field. This gives an indication about the QoS of the generated traffic. This is needed in order to choose the correct subqueue. The desired QoS label can be specified in the source model. For now the following source models are available:

- CBR model, specified by PCR (=SCR),
- VBR model, bursty source specified by PCR, SCR and mean Burst size (BS),
- UBR model, like the VBR model with additional MCR specification,
- IEEE source, bursty model specified by burst size PDF, PCR and SCR,
- Two level VBR model.

The structure of the two level model is further discussed in the next section. Since a detailed description of the source models will be discussed in chapter 5 no further details of the models will be given in this section.

4.5.1 Two level traffic sources

Particularly for the bursty sources it can be very difficult to model the behaviour of a traffic source. For instance the VBR model is just a general model of a bursty source. Analyzing VBR traffic it can be concluded that the generated traffic is influenced by the traffic contract created for the VBR service and the traffic characteristics of the higher layer application which generates the traffic. The best way for modelling this kind of traffic sources is creating a two level source model. The highest level symbolises the application which generates the traffic. The lower level characterises a traffic shaper. This model has to convert the bursty traffic conforming the traffic contract.

The two level traffic source is created by using the VBR-bursty source model as the application layer and the GCRA based mechanism for shaping [18]. The GCRA mechanism will be further discussed in appendix D and section 4.6 since it is also used in the policer model. In Figure 21 the node model of the two layer VBR source is shown.

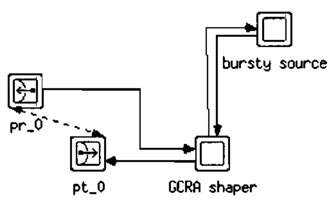

Figure 21: Node model of the two-layer VBR source

Assuming a ATM cell from a higher layer application is arriving in the shaper device (ARRIVAL interrupt), the process will check whether the cell is conforming the traffic contract or not. When the cell can not be sent conforming this traffic contract, it will be delayed until it is conforming. It must be stressed that the sequence of the cells does not cange during the shaping. This means that the shaper acts like a per connection FIFO queue.

4.6 POLICER

As already discussed, the access network can cause some CDV. This influences the PCR as well as the moving average of SCR. Therefor a policing device is needed to protect the network and the user in order to achieve network performance objectives. The policer device has to detect whether the data stream behaves conforming the traffic contract or not. In the develloped model the input traffic stream can be sent transparantly to a BackBone for further analyses. In Figure 22, the node model of the policer is shown. It should be noted that the policer only analyses upstream traffic (from receiver "pr_LT" to transmitter "pt_BB").

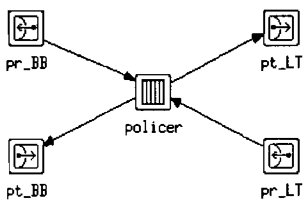

Figure 22: Node model of the policer

In the traffic contract [18] the interarrival time between two cells based on PCR or SCR is specified (T_{PCR} and T_{SCR}) as well as the tolerance on the interarrival time (τ_{PCR} and τ_{SCR}). The behaviour of the policing device for traffic control is specified in the Generic Cell Rate Algorithm (GCRA) and standarized in ITU-T Recommendation I.371 [18]. This algorithm measures the interarrival times of cells and compares them with the traffic contract.

While the traffic contract can differ per QoS, the policer bahaviour is also depending from the QoS. The implemented policer model as shown in Figure 23 controls CBR and UBR traffic for PCR behaviour and VBR for both PCR and SCR behaviour. Therefor a one-level as well as a two-level GCRA version are implemented in this process model. In appendix D both GCRA versions are described.

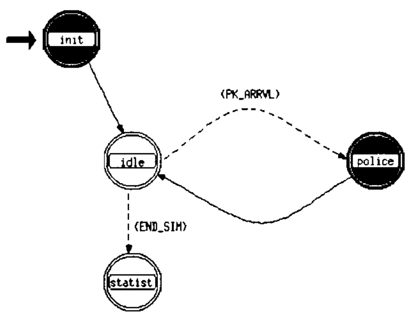

Figure 23: Process model of the policer

5. SOURCE MODELS

ATM is now widely accepted as the chosen transport technology for the forthcoming high speed telecommunications age. The superiority of ATM rests upon its flexibility to support a wide diversity of services and applications within a single networking infrastructure. Its maturity is illustrated by the specification of various ATM service categories (ASC), cfr. ATMF [27] and ITU-T [18]. An overview of the ATM Forum and ITU-T service categories is specified in appendix B.

The recognition that different applications have diverse expectations from the ATM layer behaviour, lead to several ASCs with diverging ATM layer QoS. The extent of this variability in QoS requirements is witnessed, on the one hand, by the stringency of the Cell Loss Ratio (CLR), Cell Transfer Delay (CTD) and Cell Delay Variation (CDV) guarantees that pertain to the Constant Bit Rate (CBR) category, whereas no QoS specification applies to the Unspecified Bit Rate (UBR) ASC. In between, the Variable Bit Rate (VBR) and the Available Bit Rate (ABR) ASCs are characterised by possible QoS commitments with regard to specific QoS parameters.

In this report only the following ATCs are considered:

- Constant Bit Rate (CBR)
- real time and non-real time Variable Bit Rate (rt-VBR and nrt-VBR)
- Unspecified Bit Rate (UBR and UBR+)

In order to create realistic traffic in the access network, models had to be developed for these ASCs. In the next paragraphs these models are discussed.

5.1 CONSTANT BIT RATE SOURCE MODEL

A CBR source generates ATM cells with a constant inter-arrival time (T), determined by the inverse of the associated Cell Rate (CR). So:

$$T = \frac{1}{CR\,[cells/s]}\,[s] \tag{9}$$

An example of a service carried over the CBR ASC is the Plain Old Telephony Service (POTS). Although the CBR sources generate their ATM cells with a constant inter-arrival time, it can not be assumed in the simulations that all sources will generate their first cell on the same time instance. Therefore the model of the CBR source uses a random start phase for all used CBR connections. The start phase is determined by using a uniform PDF. This function determines a start delay between 0 and T seconds with probability 1/T.

5.2 VARIABLE BIT RATE SOURCE MODEL

5.2.1 VBR source characterisation

VBR traffic sources are characterised by their bursty nature. Therefore they are modelled with an "ON-OFF" model. In the ON-state the source is sending a burst of cells at PCR. In the OFF-state the source is idle. The burst-size as well as the time in OFF-state are determined by Poisson processes.

For implementation in OPNET, the traffic source uses time-slots with length 1/PCR. When the source is in the ON-state it generates one cell every timeslot, when it is in OFF-state the timeslots are left empty. The burst size (BS) is equal to the number of timeslots in ON-state. In the same way, the idle size (IS) can be derived from the number of timeslots in OFF-state. The time during which the traffic source is in the ON-state is called t_{on}, the time in the OFF-state t_{off}.

When computing the characteristics of the traffic source, e.g. the mean Cell Rate ($\overline{CR}$), one can use the t_{on} and t_{off} as well as the BS and IS definitions. Because the BS/IS specifications don't contain dimensions they can easily be scaled to any realistic cell rate.

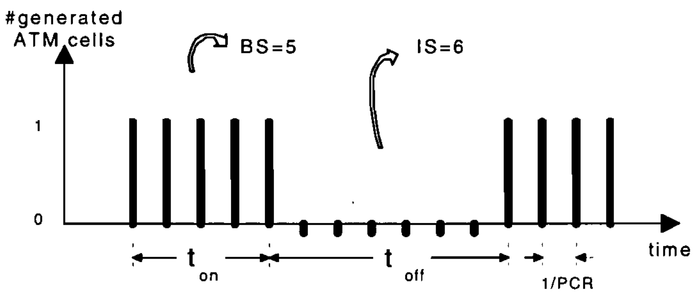

Figure 24: VBR source characterisation

A VBR source is specified by its PCR, mean cell rate ($\overline{CR}$) and its maximum burst size. However, in our VBR source model, we use the mean burst size ($\overline{BS}$) to characterise the VBR traffic. The mean cell rate is calculated like:

$$\overline{CR} = \frac{PCR \cdot \overline{BS}}{\overline{BS} + \overline{IS}} \tag{10}$$

Using these parameters it is possible to calculate the mean number of idle timeslots ($\overline{IS}$) as follows:

$$\overline{IS} = \left(\frac{PCR}{\overline{CR}} - 1 \right) \cdot \overline{BS} \tag{11}$$

The traffic source can be modeled by generating two distribution functions with average $\overline{IS}$ and $\overline{BS}$.

5.2.2 VBR source modeling

The bursty behaviour can be modeled with a Markov-chain. The states (ON and OFF) are represented by 1 and 0. We can use two (binary) Bernoulli distributions depending on the actual state of the process. Figure 25 depicts the model.

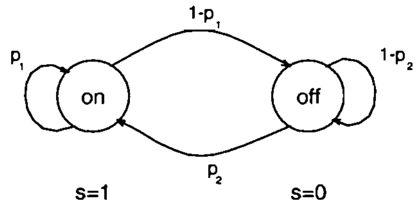

Figure 25: Markov model of ON-OFF source

The probability to stay in the active mode is called p_1. Consequently, the probability to leave the active mode is 1-p_1. Define $\underline{n}$ as the number of time slots needed to leave the active mode. The probability function can be written like:

$$P(\underline{n} = k) = p_1^{k-1} \cdot (1 - p_1) \qquad (k = 1,2,3\ldots 0 < p_1 < 1) \tag{12}$$

This distribution is known in the literature [9] as the Geometric Distribution. The mean value of this distribution can be calculated using the expected value. In general, the expected value (E) can be calculated like:

$$E_{\underline{x}} = \sum_{i=1}^{\infty} x_i \cdot p_i \tag{13}$$

In order to classify the distribution, the standard deviation will be used. It is defined by:

$$\sigma_{\underline{x}} = \sqrt{\mathrm{var}(\underline{x})} \tag{14}$$

with

$$\mathrm{var}(\underline{x}) = E_{\underline{x}^2} - \left(E_{\underline{x}}\right)^2 \tag{15}$$

Using these definitions for deriving the expected value and standard deviation of the Geometric Distribution results in:

$$E_{\underline{n}} = \frac{1}{1 - p_1} \qquad \sigma_{\underline{n}} = \frac{\sqrt{p_1}}{1 - p_1} \tag{16}$$

When leaving the active mode after k timeslots, this results in a burst size of k. This means we can derive p_1 by substituting the mean burst size with the expected value of $\underline{n}$. Consequently:

$$\overline{BS} = E_{\underline{n}} = \frac{1}{1-p_1} \tag{17}$$

In the same way the probability to stay in idle mode is called 1-p_2 and the probability to go to the active mode is called p_2. Define m as the number of time slots, needed to leave the idle mode. This results in:

$$P(\underline{m} = k) = p_2 \cdot (1-p_2)^{k-1} \qquad (k = 1,2,3\ldots 0 < p_2 < 1) \tag{18}$$

and

$$E_{\underline{m}} = \frac{1}{p_2} \qquad \sigma_{\underline{m}} = \frac{\sqrt{1-p_2}}{p_2} \tag{19}$$

As such,

$$\overline{IS} = E_{\underline{m}} = \frac{1}{p_2} \tag{20}$$

Because the OFF-period is also generated with the Bernoulli PDF, the behaviour will be the same as for the burst size.

Based on these formulas. the values for p_1 and p_2 can be calculated in order to get the source behaviour specified by the PCR, the mean CR and the mean burst size. The expected value and the standard deviation of the complete ON-OFF source can also be calculated. The probability function for the state ($\underline{s}$) of the ON-OFF source is given by:

$$\begin{aligned} P(s=1) &= \overline{CR}/PCR \qquad (ON-state) \\ P(s=0) &= 1-\overline{CR}/PCR \quad (OFF-state) \end{aligned} \tag{21}$$

This results in:

$$E_{\underline{s}} = \frac{\overline{CR}}{PCR} \qquad \sigma_{\underline{s}} = \sqrt{\frac{\overline{CR}}{PCR} \cdot \left(1-\frac{\overline{CR}}{PCR}\right)} \tag{22}$$

5.2.3 VBR source model evaluation

The simulation results used to evaluate the developed VBR source model are generated with OPNET. In this section the burst size and (average) cell rate generated by the VBR model are verified.

Burst Size measurements

In Figure 26 the PDF of the burst size is given for respectively 10^3,10^4 and 10^5 generated bursts with a mean burst size of 10. Figure 27 plots the relative error between the PDF generated with the OPNET model and the theoretical PDF.

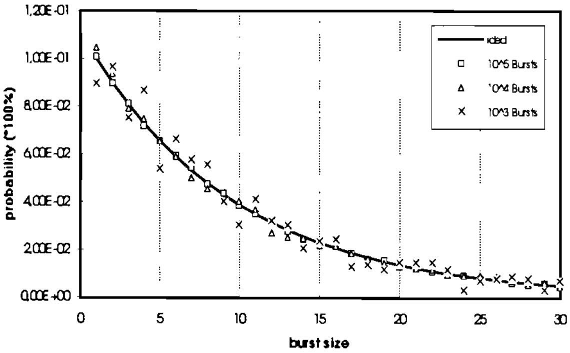

Figure 26: PDF of BS for the VBR source model

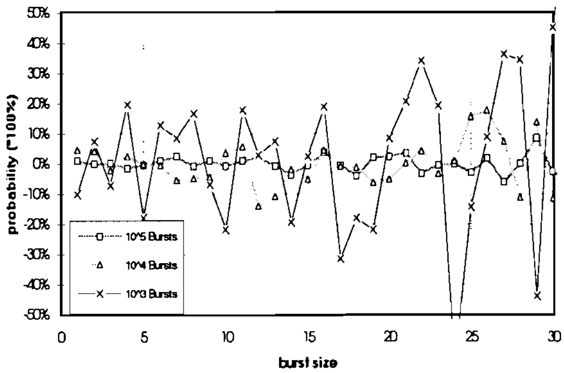

Figure 27: Relative error on PDF of BS for VBR source model

Figure 27 illustrates that the number of generated bursts has to be at least 10^4 in order to get a fair approximation of the theoretical PDF. The match will be better for smaller burst sizes. This can be explained by the fact that these smaller burst sizes have higher probability and consequently they will be generated more often.

Cell Rate measurements

The CR is measured with a moving average technique. This means that the number of generated cells within a window is counted. The windows size (WS) is expressed in timeslots. The duration of a timeslot is based on the PCR of the traffic source. Every time slot, the CR is calculated from the number of cells generated during the WS most recent timeslots. Figure 28 shows the PDF of the CR.

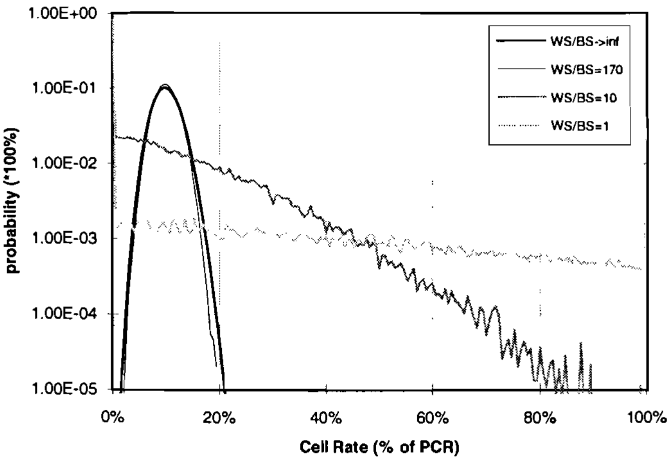

Figure 28: PDF of the (mean) cell rate

The used ON-OFF model, is characterised by a PCR of 10 Mbps and a mean CR of 1 Mbps. The size of the window WS equals 170 and the mean burst size is varied. The relation between the mean burst size and the window size is very important. Using a very large window results in a long-term average of the CR. The PDF of the number of cells (n) generated within a window of size WS can be expressed as:

$$P(\underline{n}=k)=\binom{ws}{k}\cdot p_{on}^{\ k}\cdot\left(1-p_{on}\right)^{ws-k}\qquad (k=0,1,2,\ldots ws\ \&\ 0\le p_{on}\le 1)\tag{23}$$

Using very short windows will result in a different PDF. When the window size is chosen equal to 1 cellslot, there are only two possible cell rates: 0 and PCR resp. corresponding to OFF and ON. So it is obvious the window introduces a low-pass filter effect on the data. Longer windows have lower cut-off frequencies.

When measuring data with a moving average window it is very important to analyse the effect of the window on the measured data. Figure 29 depicts typical PDF curves for very small (-a-) and very large (-b-) measuring windows.

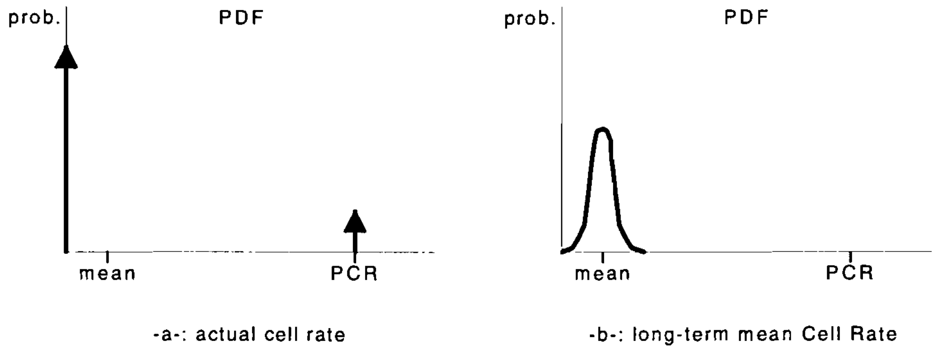

Figure 29: PDF of actual and mean Cell Rate using an ON-OFF Source

5.2.4 Multiplexing N VBR sources

In this section, the behaviour of N multiplexed ON-OFF traffic sources is analysed. The probability function for the multiplexed stream of N independent traffic sources is Binomial distributed like:

$$P(\underline{t}=k)=\binom{N}{k}\cdot p_{on}^{\ k}\cdot\left(1-p_{on}\right)^{N-k}\qquad (k=0,1,2,\ldots N\ \&\ 0\le p_{on}\le 1)\tag{24}$$

with

$$\underline{t}=\sum_{i=1}^{N}\underline{s}_i\ ,\tag{25}$$

The probability to be in active mode is expressed as $p_{on}=\overline{CR}/_{PCR}$. Based on this function, the following expected value and the standard deviation can be found for the number of cells generated at each time instance for the aggregate ON-OFF source:

$$E_{\underline{t}} = N \cdot p_{on} \qquad \sigma_{\underline{t}} = \sqrt{N \cdot p_{on} \cdot (1 - p_{on})} \tag{26}$$

When comparing these results with the values of just one ON-OFF source it can be concluded that the multiplexing of N sources can be related to the original source like:

$$\begin{aligned} E_{\underline{t}} &= N \cdot E_{\underline{s}} \\ \sigma_{\underline{t}} &= \sqrt{N} \cdot \sigma_{\underline{s}} \end{aligned} \tag{27}$$

Poisson model for the aggregate ON-OFF sources

the usage of the binomial distribution in a simulation with a large number of sources requires enormous amount of processing power. In order to decrease the simulation time, the binomial distribution should be approximated by another distribution. From literature [9] it is known that, the binomial distribution equals the Poisson distribution, when N goes to infinity. The Poisson distribution is given by:

$$P(\underline{x} = k) = e^{-\mu} \cdot \frac{\mu^k}{k!} \qquad (k = 0,1,2,3,\ldots \;\&\; \mu > 0) \tag{28}$$

with:

$$\mu = N \cdot p_{on} = \overline{x} = E_{\underline{x}} \qquad (N \to \infty) \tag{29}$$

Calculating the standard deviation for the Poisson process results in

$$\sigma_{\underline{x}} = \sqrt{\mu}\,. \tag{30}$$

In Figure 30, the relative error between the PDF of the Poisson process and the PDF of N multiplexed ON-OFF sources is plotted.

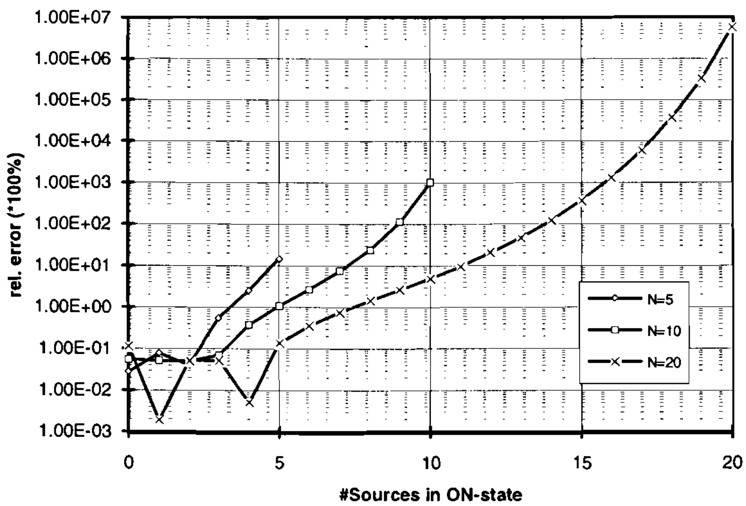

Figure 30: Relative error in PDF using Poisson approach of N ON-OFF sources

In order to get an objective comparison, these relative errors have to be weighted with the probability of their occurance. This weighted relative error is the absolute error between the PDF of the Poisson process and the PDF of the multiplexed ON-OFF sources.

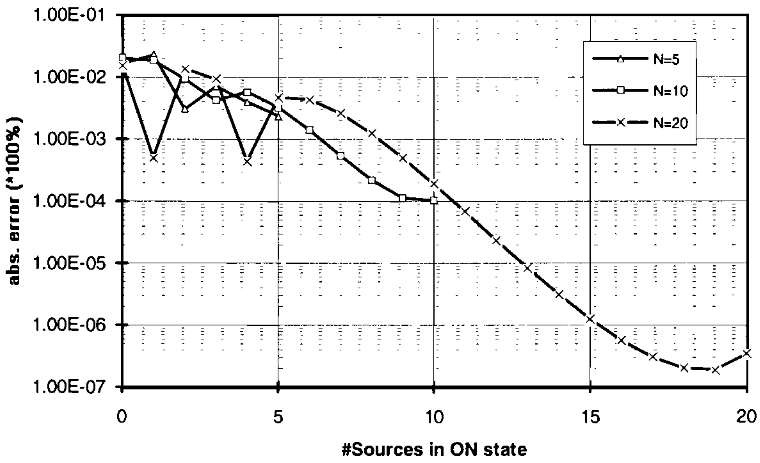

Figure 31: Absolute Error in PDF using Poisson approach of N ON-OFF sources

It can be concluded that the relative error in probability can be quite large when the absolute probability is small. The main disadvantage of the Poisson model is given by the fact that this model has no upper bound. So the Poisson model for 20 ON-OFF sources can also generate traffic as if 21 or more sources were in the ON state. This causes an bad short term estimation. When analysing the long term estimation this effect disappears. In the simulations discussed in this thesis report, the Poisson approach was never used.

5.3 UNSPECIFIED BIT RATE SOURCE MODEL

The UBR sources are modelled in the same way as the VBR sources. The same ON-OFF model is used. Because a UBR+ source may also be characterised by a non-zero MCR, the complete model of a UBR source is modelled by the superposition of a CBR source with CR=MCR and an ON-OFF source with maximum cell rate PCR-MCR. Calling the CBR source "c" and the ON-OFF source "v" the UBR source "u" is given by:

$$\underline{u} = \underline{v} + c \tag{31}$$

In literature [9] the relation between the expected value and the standard deviation of these sources is given by:

$$E_{\underline{u}} = E_{\underline{v}+c} = E_{\underline{v}} + c \tag{32}$$

$$\sigma_{\underline{u}} = \sigma_{\underline{v}+c} = \sigma_{\underline{v}} \tag{33}$$

5.4 AVAILABLE BIT RATE SOURCES

The ATM Forum and ITU-T have specified a dynamic ATM layer service category, known as the Available Bit Rate (ABR) capability, that can be considered as a higher performing transfer capability than the Unspecified Bit Rate (UBR) service. ABR is targeted at the efficient support of bursty, non real-time applications. An additional goal of this service category is to emulate the behaviour of a shared medium network within an ATM network, which allows a single connection to grab all the available link bandwidth if it is the only active one, whereas the latter available bandwidth capacity is to be fairly distributed among multiple connections which are simultaneously active.

The ABR service relies on the regular insertion of standard Resource Management (RM) cells within the Virtual Path Connection (VPC)/Virtual Channel Connection (VCC) to allow the traversed network elements to convey feedback information towards the connection end points about the availability of bandwidth across the end-to-end communication path. Specific data within the RM cell information field can subsequently be used by an originating connection end point or source end point to deduce the upper bound on the cell rate. As such, the network can dynamically modulate, in an advisory fashion, the cell rate of the ABR connections' source end points, based upon the assessed availability of network bandwidth and possibly buffer resources.

The implementation of an ABR source model in OPNET is for further study.

5.5 MODELLING TRAFFIC SOURCES BY SPECIFYING THE PDF

In IEEE802.14 [16] four kinds of traffic are defined for the evaluation of MAC protocols on HFC access networks. These models will evolve in time as more data becomes available on the type of traffic to be handled by cable-modems.

“Source Type 1” of the IEEE802.14 proposal is a model for bursty data traffic. The model specifies six different kind of “messages” and associated with each message type the probability of its occurance. The (average) data rate can be controlled by specifying the inter arrival time ($1/\lambda$) of the messages. The arrivals of messages are Poisson distributed with λ. In Table 1 all messages, their sizes and their probabilities are given.

Table 1: IEEE802.14 - Source Type 1

Message type	Size		probability
	(bytes)	*(ATM cells)*	
X_1	64	2	0.60
X_2	128	3	0.06
X_3	256	6	0.04
X_4	512	11	0.02
X_5	1024	22	0.25
X_6	1518	32	0.03
mean	***368.1***	***8.3***	

The OPNET tool is able to generate a random function with statistics specified in a PDF using the “Parameter Editor”. In this section the described IEEE802.14 source type is modelled with this technique.

Noticing the mean number of ATM cells per message is 8.3 (Table 1) the relation between the (long-term average) cell rate and the inter-arrival time of these messages can be given by:

$$CR\,[cells/s] = 8.3\,[cells\,/\,message]\cdot\frac{1}{\lambda}\,[messages\,/\,s] \tag{34}$$

Using this probability function for the burst size the PDF of the (mean) cell rate was measured. The PDF of the burst size was also measured in order to verify the model. The results are given in Figure 33 and Figure 32. From measurements it can be concluded that the error on the PDF of the BS can be limited to 1% when the number of bursts is above 5^*10^5.

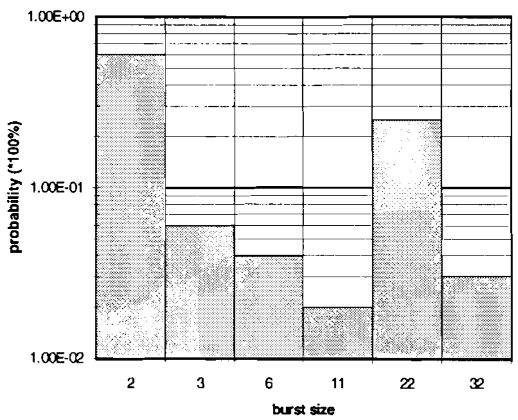

Figure 32: PDF of Burst size IEEE source

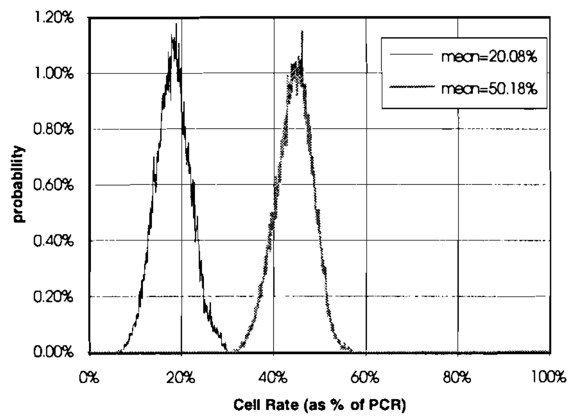

Figure 33: PDF of mean Cell Rate IEEE source

6. TRAFFIC SCENARIOS

The optimal MAC protocol and network element traffic control functions to be applied on the access network will of course depend on the traffic expectations. For a performance evaluation of multi-access protocols for shared-medium access networks, it makes no sense to investigate only one or a few complex traffic mixes (as can be found in many papers).

When designing and evaluating a QoS policy, one will have to use source models and traffic mixes partly based on forecasts of possible services which are likely to become important in the future. Based on these service forecasts, source models can be designed and traffic scenario's can be developed which can be used for a basic evaluation of the implemented QoS policy. Marketing studies should also determine the expected load conditions of the access network. The load conditions, i.e. the characteristics of the background traffic, will influence the perceived performance on some reference application.

One should however bear in mind that a good QoS policy must offer a high degree of "service transparency", so it should be flexible with respect to new services. Besides familiar services like telephony, fax messages, Internet applications and compressed video, an access network must also be able to support future services such as high resolution video, video conferences, etc.

Performance studies must be as "service transparent" as possible in order to capture the impact on the performance characteristics of all features of the adopted QoS policy. This motivates the evaluation of the proposed MAC protocols based on several traffic source models combined in several traffic scenarios.

6.1 TRAFFIC SOURCES

Because the characteristics of the traffic which should be handled by the MAC protocol are not known exactly, the performance of a MAC protocol should be tested with all kinds of (realistic) traffic scenario's.

Table 2: Source characteristics

Reference	ASC	PCR [kbps]	MCR [kbps]	mean CR [kbps]	mean BS [cells]	service
C64k	CBR	64	64	64	-	POTS
C2M	CBR	2048	2048	2048	-	MPEG
V10M/1M/10	VBR	10240	-	1024	10	
V25M/5M/10	VBR	25600	-	5120	10	
U25M/10k/100k/5	UBR	25600	10	100	5	
U25M/10k/5M/5	UBR	25600	10	5120	5	

In Table 2, the used traffic sources are specified. The VBR and UBR sources are based on the bursty source model as described in chapter 5.

6.2 LOAD OF THE ACCESS NETWORK

The load of a PON access network (ρ) is defined as the ratio of the total bandwidth needed to service all assigned connections and the link capacity. Since this total needed bandwidth depends on the hierarchical level, It is important to specify on which level the load will be calculated. For the PON access network the most logical levels are:

- physical layer,
- ATM layer, and
- Application layer.

It must be noted that every layer causes overhead information for signaling purpose. For instance on the physical layer a physical preamble of 3 bytes per upstream ATM cell is generated for synchronization. The ATM layer introduces the 5 byte header per 53 byte cell and the overhead for higher applications will be sent with the ATM adaptation layer (AAL) bytes. All this overhead decreases the available bit rate for higher applications. Since the overhead and link capacity can also differ per interface, different values of the load exist at T-, U- and V-interface. The V-interface is chosen as a reference, because this is the interface to the backbone network. So it gives the best indication of the load of the entire access network on the backbone network. The load of the access network on application level at T- resp. V- interface can be computed as follows:

$$\rho_T = \sum_{\substack{active\ Tb \\ connections}} \frac{Mean\ bitrate \cdot \frac{53}{48-AAL\ bytes}}{Net\ T_b - capacity} \tag{35}$$

and

$$\begin{aligned} \rho_V &= \sum_{\substack{active\ T_b \\ connections}} \rho_T \cdot \frac{Net\ T_b - capacity}{Net\ V_b - capacity} \\ &= \frac{1}{Net\ V_b - capacity} \cdot \sum_{\substack{active \\ B-NTs}} \sum_{\substack{active\ Tb \\ connections}} Mean\ bitrate \cdot \frac{53}{48-AAL\ bytes} \end{aligned} \tag{36}$$

The overhead used by the ATM Adaptation Layer (ranging between 1 and 4 bytes) should be incorporated into the load of the access network. This can be done with AAL-bytes [24]. The traffic sources in the OPNET model don't generate these AAL-bytes. Actually they don't generate any overhead traffic at all because the specified bit rate of the traffic source in the OPNET model is defined on physical link level.

6.3 MULTIPLEXING GAIN

In order to evaluate traffic scenario's with bursty sources, there must be an objective parameter to quantify the burstiness of the network traffic. This burstiness may cause temporarily overload situations. The multiplexing gain of the access network is defined as the sum of the peak bit rates (PBR) of all active connections and the available transmission capacity (BW_{all}). Obviously when using only peak bit rate allocation (for instance CBR) the multiplexing gain equals one. The multiplexing gain is computed on the V_b-interface [24]:

$$MGain_V = \frac{\sum\limits_{\substack{active \\ B-NTs}} \sum\limits_{\substack{active\ Tb \\ connections}} PBR}{BW_{all}} \tag{37}$$

6.4 APON TRAFFIC SCENARIOS

The traffic sources will be used to create traffic scenarios. In the following tables some homogeneous and heterogeneous scenario's are specified.

Table 3: Homogeneous traffic scenarios

Reference	Source reference	#sources/B-NT	#active B-NT's	Load [%]	Multiplexing . Gain
S1	C64k	64	32	89.05	1.00
S2	C2M	12	5	83.48	1.00
S3	V10M/1M/10	12	10	83.48	8.35
S4	V25M/5M/10	3	8	83.48	4.17
S5	U25M/10k/100k/5	40	32	86.96	222.63
S6	U25M/10k/5M/5	3	8	83.48	4.17

Table 4: Heterogeneous traffic scenarios

Reference	**Source reference**	**#sources/B-NT**	**#active B-NT's**	**Load [%]**	**Multiplexing . Gain**
S7	C64k	14	16	9.74	1.00
	V10M/1M/10	2	16	22.26	2.23
	U25M/10k/100k/5	46	16	50.00	128.01
total:		**62**	**16**	**82.01**	**130.33**
S8	C64k	49	22	46.87	1.00
	V10M/1M/10	1	22	15.31	1.53
	U25M/10k/100k/5	14	22	20.93	53.57
total:		**64**	**22**	**83.10**	**55.57**

NOTE: The Bit rates of the traffic sources are specified on physical link level. This means that all overhead traffic is included. Consequently the corresponding bit rates available on application layer level are smaller.

7. PERFORMANCE ANALYSES

The performance analyses as described in this chapter are based on the APON access network configuration unless specified different. To analyze the performance of the MAC protocols the scenarios as specified in chapter 6 are simulated for all APON MAC protocols. In this chapter the simulation results are evaluated.

7.1 CBR TRAFFIC

7.1.1 Introduction

The performance of the MAC protocols, when serving CBR traffic is good for all evaluated protocols. Obviously, the performance of the Alcatel APON MAC (AAM) exceeds the performance of all the request based protocols. Because of fact that the AAM protocol is not request based, the ETE-delay can be much smaller compared to the other protocols. The smaller ETE-delays also result in smaller queue sizes on the B-NTs.

Assuming that the aggregate ‘real’ cell rate of the CBR sources connected to one B-NT can exactly be matched by a corresponding grant rate for that B-NT, the CBR cells can be transferred to the LT with zero CDV. In this case there is frequency synchronisation between the cell arrival process at the B-NT and the grant generation process at the LT. While there is no phase synchronisation, the queuing delay will not be zero. However when considering a number of CBR sources with the same PCRs, the phase mismatch will be constant for each source. This explains the constant ETE delay and the zero CDV. The value of the queuing delay is determined by the relative phase of the arriving cells compared with the arrival of grants.

7.1.2 Frequency mismatch

When there is a mismatch in the frequency synchronisation between the arrival of cells at the B-NT and the generation of permits for this B-NT, CDV will be introduced. The frequency mismatch can be caused by required rounding of the interarrival time or due to numerical inaccuracy of the specified cell rate (Figure 34). If grants can not be generated at exactly the aggregated PCR of the established connections, a higher rate will be used. Other CDV sources are a variable phase mismatch caused by jitter on the source traffic. In the next figure the effect of a possible frequency mismatch on the CDV is illustrated.

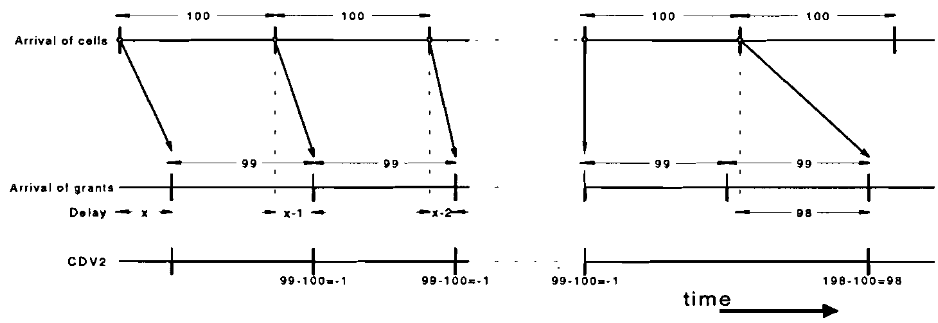

Figure 34: CDV caused by mismatch in frequency synchronisation

As we can see in this example, the 2-point CDV will always be -1 or 98. The mean CDV will of course be zero. In general the maximum 2-point CDV caused by this mismatch effect is the interarrival time of the grants minus the error between this interarrival time of grants and interarrival time of cells (ignoring the effect of aggregation).

Suppose there's only one 64 kb/s connection active on a B-NT. The interarrival time of grants, derived from the cell rate, is 2299 upstream slots, while the error between this interarrival time and the real interarrival time (2299 or 2300) is zero or one slot. The maximum CDV is this configuration can approach 2298 or 2299 slots. However it is mentioned that most of the time the CDV will be very small.

7.1.3 Aggregation of the CBR sources with different cell rates

The aggregation of several CBR sources with different PCR may also result in additional CDV. The phase mismatch will no longer be a constant for each of the sources (Figure 35).

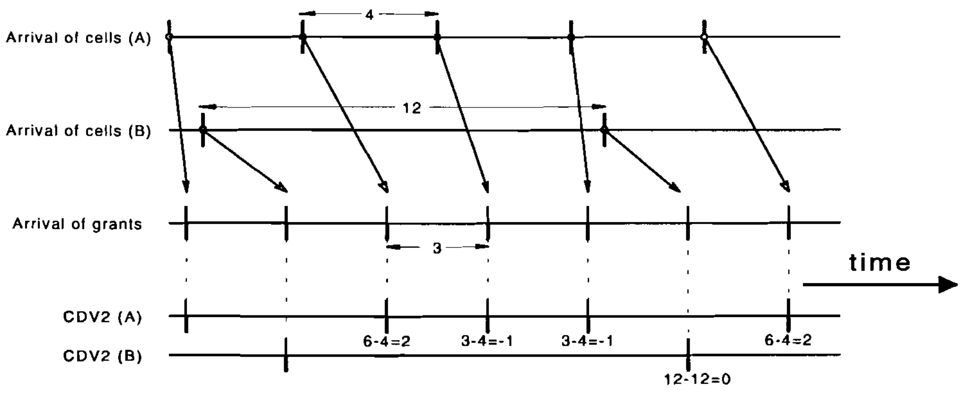

Figure 35: CDV caused by the aggregation of traffic with different cell rate

In the case there are several traffic sources with different cell rates, the interarrival time of grants is possibly not a multiple of the interarrival time of cells. Suppose there are two CBR sources connected to a B-NT with resp. interarrival times of 4 and 12 slots (Figure 35). This results in a mean interarrival time of 3 slots so every three slots a grant is given. Because the interarrival time of the first connection is not equal to an integer times the interarrival time of the grants, the queuing delay is not constant resulting in additional CDV. The interarrival time of the second connection (12 slots) is a multiple of the interarrival of the grants. This results in a constant phase delay which does not cause any additional CDV. This effect is illustrated in Figure 35.

Summarized: the effect of aggregation of connections with a constant but different interarrival time between cells (CBR) will cause a cyclic pattern of CDV with an average CDV of zero.

7.1.4 Frequency mismatch and traffic source aggregation

As already described in section 7.1.2, frequency mismatch can be caused for instance by the required rounding of the interarrival time or due to numerical inaccuracy of the specified cell rate. Assuming the aggregation of several sources on one B-NT , the impact of these CDV sources is analyzed. The configuration of scenario S1 will be used to illustrate this effect.

Suppose 64 CBR traffic sources of each 64kb/s are connected to one B-NT. The mean interarrival time between the cells on the B-NT will be:

$$\delta\, t_{all\ sources} = \frac{147.189 Mbit/s}{\sum_{64 sources} 64 kbit/s} = 35.93 \tag{38}$$

In order to achieve this mean interarrival time the simulation model uses floating point values. This results in interarrival times of 35 and 36 slots where the ratio between the number of 35- and 36-slot interarrivals is derived from the average interarrival time.

However, the classical AAM protocol like it is implemented in the current APON configuration would give grants to this B-NT every 35 slots in order to guarantee enough bandwidth. The mean interarrival time of one 64 kb/s connection is:

$$\delta\, t_{one\ source} = \frac{147.189 Mbit/s}{64 kbit/s} = 2299.83 \tag{39}$$

When dividing this interarrival time by the interarrival time of the grants (35) the mean number of grants between two cell arrivals of the same source is derived. Since the result is somewhere between 65 or 66 grants, this means that the time between two transmitted cells of the same traffic source is 2275 or 2310 (resp. 65*35 or 66*35) upstream time slots. Since the interarrival time of these cells will be 2299 or 2300 slots, the effect of the mismatch on the cell delay variation can be computed. In this simplified scenario the possible values for the 2-point CDV are:

2310-2299 =+11
2310-2300= +10
2275-2299= -24
2275-2300= -25

NOTE: CDV's are expressed in upstream timeslots

7.1.5 Simulation Results using scenarios with CBR traffic

In the simulated scenarios CDV caused by the aggregation of traffic sources with different cell rates or frequency mismatch are not considered. Consequently the CDV performance of the AAM protocol will be (almost) perfect for CBR traffic. Obviously this is not a realistic scenario. In order to control CDV when using AAM, additional features like synchronisation between given grants and the arrival of cells should be implemented.

Using the request based protocols will also introduce a certain CDV. However this CDV can be bounded by the used algorithm and the update frequency of requests. Concerning the CDV control for CBR scenarios, the best performing request based MAC protocol seems to be CPP. Reviewing also the ETE delay, CPP seems less performing than for instance EGF. Obviously, the CPP ring which controls the CDV causes an additional delay compared to the Global FIFO mechanism. In appendix G the simulation results assumed to ETE-delay, CDV and queue measurements are shown.

7.2 VBR TRAFFIC

7.2.1 Modeling the VBR source behaviour with a G/D/1 Queue

Since the VBR source is modeled with a bursty source, many parameters can influence the queue sizes and queuing delay. The behaviour of the VBR source will be verified with an analytical model of the B-NT queue. It is assumed that the cells can leave the queue in regular intervals. A static MAC protocol will generate grants conforming this requirement. Therefor the analytical model will be compared with the AAM protocol.

The interarrival time probability of cells when using an bursty source as specified in section 5.2.2 is dependent of the fact whether the source is in the ON- or OFF-state. In queuing theory this means the source has “memory”.

In general when the arrival process is Poisson, the queue system can be considered in steady state on the moment of the arrival. This is called “Poisson Arrivals See Time Averages” (PASTA) [9]. While the arrival process is not Poisson, the PASTA rule can not be used. This means the system can not be evaluated on the moment of a new arrival.

The analytical model for the queue can be specified by a general arrival probability distribution (called G), a deterministic service time (D) and one server. This type of model is called G/D/1 queuing model [30]. The chance *k* cells will be served during the interarrival time of two cells is defined like β_k. Assuming an ON-ON transition (with chance p_1) the interarrival time expressed in upstream slots will be:

$$\delta_{on} = \frac{busspeed}{PCR} \tag{40}$$

Other possible transitions are ON-OFF-ON. In this case the interarrival time will be:

$$\delta_{off} = n \cdot \frac{busspeed}{PCR} \qquad n \geq 2 \; \& \; n \in N \tag{41}$$

It is assumed that ‘n-2’ OFF-OFF transitions are made. The corresponding probability function is given by the chance of one ON-OFF transition, followed by n-2 OFF-OFF transitions and ended by one OFF-ON transition. This chance is given by:

$$p_n = (1-p_1)\cdot(1-p_2)^{n-2}\cdot p_2 \qquad n \geq 2\ \&\ n \in N \tag{42}$$

with p_1 the chance of an ON-OFF transition and p_2 the chance of an OFF-ON transition (section 5.2.2). The complete probability function for the interarrival time can be specified like:

$$p_n = \begin{cases} p_1 & n = 1 \qquad n \in N \\ (1-p_1)\cdot(1-p_2)^{n-2}\cdot p_2 & n = 2,3,\ldots \end{cases} \tag{43}$$

When k cells will be served during the interarrival time it is known that

$$k = \left\lfloor \frac{n \cdot \frac{busspeed}{PCR}}{\delta_g} \right\rfloor \qquad n \geq 1\ \&\ n \in N \tag{44}$$

with δ_g the interarrival time between two grants. Deriving the boundaries for 'n' results in:

$$\delta_g \cdot \tfrac{PCR}{busspeed} \cdot k \leq n < \delta_g \cdot \tfrac{PCR}{busspeed} \cdot (k+1) \qquad n \geq 1\ \&\ n \in N \tag{45}$$

Defining:

$$\begin{aligned} n_{dwn} &= \left\lceil \delta_g \cdot \tfrac{PCR}{busspeed} \cdot k \right\rceil \\ n_{up} &= \left\lfloor \delta_g \cdot \tfrac{PCR}{busspeed} \cdot (k+1) \right\rfloor \qquad k \geq 1\ \&\ k \in N \end{aligned} \tag{46}$$

an expression for β_k can be given like:

$$\beta_k = \sum_{n=n_{dwn}}^{n_{up}} p_n \tag{47}$$

Figure 36 shows the queue size transition chances expressed in terms of β_k.

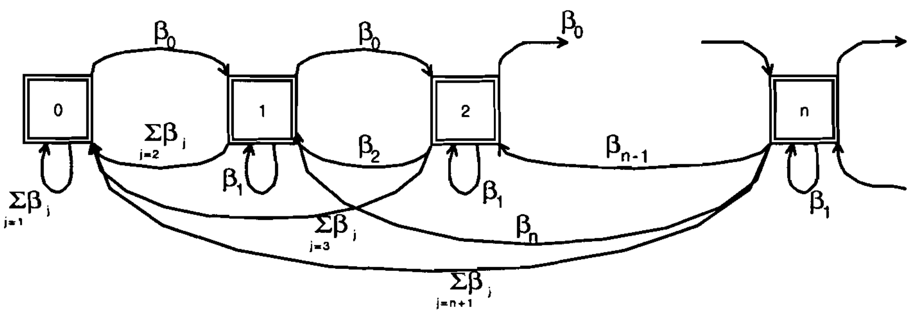

Figure 36: Queue size transitions for the G/D/1 model

Define q_n as the chance, the queue size is "n". Since the values of q_n and β_k are related to each other, q_n can be expressed in terms of β_k when the system is in balance. The distribution of q_n will be calculated with an iterative process. The "new" values of q_n can be derived from the "old" values and the known β_k's like:

$$q_k = \beta_0 \cdot q_{k-1} + \beta_1 \cdot q_k + \beta_2 \cdot q_{k+1} + \ldots \qquad k = 1,2,\ldots$$
$$q_0 = \sum_{j=1}^{\infty} \beta_j \cdot q_0 + \sum_{j=2}^{\infty} \beta_j \cdot q_1 + \sum_{j=3}^{\infty} \beta_j \cdot q_2 + \ldots \tag{48}$$

When the difference between old and new q_n's is very small, the equilibrium of the q_n distribution is (almost) reached. In Figure 37 this technique is used to compare the queue size distribution based on the following scenario:

- APON, upstream BW = 155.52Mbps
- 64 B-NTs
- 1 VBR source/B-NT, PCR 10Mbps, SCR 2Mbps, mean BS 5

Since the aggregation of several sources on one B-NT makes the definition of the interarrival time unnecessary complicated this analytical model will be compared with simulation results, using AAM and one VBR source per B-NT.

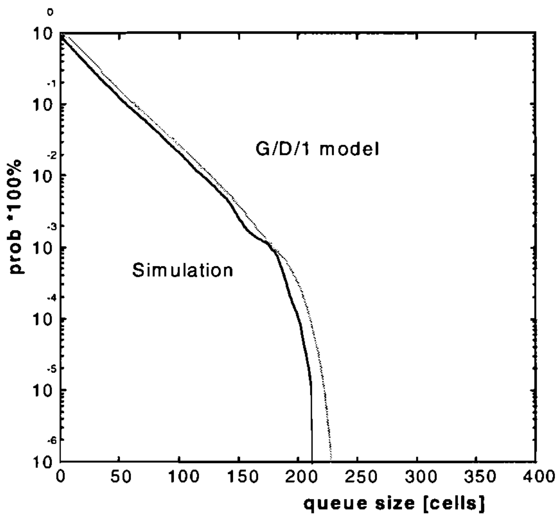

Figure 37: P(Q_size>n) Simulation vs M/G/1 model

The analytical distribution is calculated with 80 terms of β_k. The simulation results are based on averages of 64 queues. However there are some differences, it should be concluded that the results of the analytical model and the OPNET simulations are quite similar. This verifies the usage of the simulation model for further performance analyses. Since the analytical model is quite complicated it will not be used anymore.

7.2.2 Performance of the AAM protocol

While the performance of AAM for CBR traffic was quite good, the performance for VBR traffic is rather poor. It is clear that the static bandwidth allocation of the AAM protocol is not able to handle the bursty traffic generated by the VBR traffic sources.

The performance of the MAC protocols will increase when the VBR traffic is less bursty (compare scenario 3 with 4). The performance of the AAM protocol serving VBR traffic will increase when the relatively allocated bandwidth compared to the sustainable cell rate increases (compare scenario 3/4 with 7/8). In the heterogeneous scenarios, the presence of traffic with a lower priority than VBR makes it possible handle the VBR bursts faster because AAM generates colorless grants. The implemented static priority scheduling discipline in the B-NTs uses these colorless grants to serve waiting cells with the highest priority QoS. So the UBR traffic arriving during a VBR burst has to wait until all VBR traffic on the same B-NT is served. This statistical multiplexing can give good results when the number of traffic sources is quite large and the burstiness of the total traffic is small. Assuming configurations with a small number of traffic sources per B-NT (for instance Fiber To The Home) the advantage of statistical multiplexing is not large enough. Therefore the AAM protocol can not be used effectively in these situations.

7.2.3 Performance of request based MAC Protocols

In general, the request based MAC protocols are better performing than AAM when serving VBR traffic. However it is not possible to qualify one of these protocols as the best performing for VBR traffic, since the performance is dependent of the analyzed VBR scenario. Watching the ETE delay and the CDV, CPP en EGF seem to give good performance but there are some problems with specific scenarios. SP seems to be the worst request based protocol for VBR traffic. In general the lower multiplexing gain of scenario 4 compared to scenario 3 results in a better performance. The only exception is the CPP protocol which is even less performing than the SP protocol in scenario 4. Further analyses to the influence of the multiplexing gain on the performance are made in section 7.5.

Comparing GF and EGF the most important difference is the spacing mechanism on EGF. Analyzing the results it seems that this mechanism can improve the performance but this is not guaranteed. The influence of the load and the burstiness on the effectiveness of the spacing mechanism is quite large. This relation is further analyzed in section 7.4.

In general, the performance when serving VBR traffic is much better in the heterogeneous scenarios (7 and 8) than in the homogeneous scenarios (3 and 4). The largest improvement is made by the EGF protocol which is the best performing protocol for VBR traffic in mixed scenarios. This can be explained by the usage of priority classes. The VBR traffic can only 'see' the load generated by CBR and VBR traffic. So the UBR traffic (which has a lower priority than VBR traffic) has almost no influence on the performance of the VBR traffic. It must be noted again that the simulation results assumed to ETE-delay, CDV and queue measurements are shown in appendix G.

7.3 UBR TRAFFIC

UBR traffic is meant to serve bursty non real-time data services. As a result the UBR traffic can not be handled efficiently when using a static protocol like AAM. Considering all simulated scenarios with UBR traffic, the performance of AAM and GF can not approach the performance of request-based protocols. It should be noted that GF behaves static for UBR traffic.

The performance of static MAC protocols when serving UBR traffic depends on the burstiness of the traffic. Comparing the performance in scenario 5 and 6 it is striking that the performance of AAM and GF is much better for a lower multiplexing gain. The effect of the multiplexing gain on the performance of the MAC protocol is further investigated in section 7.5.

While UBR services are not meant to handle real time applications, ETE delay and CDV are no absolute performance parameters for UBR, but it is clear that larger ETE-delays also cause larger queue sizes. Because of this relation it is useful to minimize ETE-delay for UBR traffic. Analyzing the performance of the request based protocols it seems that SP and EGF give best performance for homogeneous scenarios. In the heterogeneous scenarios the CPP protocol performs better than in the homogeneous scenarios. This can be explained by the CPP spacing algorithm for CBR and VBR traffic. While this mechanism controls CDV for real-time traffic by not using some slots, the UBR traffic can be served faster due to the usage of these slots. Again, the simulation results assumed to ETE-delay, CDV and queue measurements are shown in appendix G.

7.4 INFLUENCE OF THE LOAD

In order to analyze the effect of the load on the performance of the MAC protocol the number of sources per B-NT is varied for the homogenous scenarios 1, 3 and 5. The results are summarized in appendix G. It should be noted that changing the number of traffic sources does not only influence the load but also the multiplexing gain. The influence of the multiplexing gain is further analyzed in section 7.5.

7.4.1 CBR traffic load

It can be concluded that request-based MAC protocols are robust for changing loads. The mean ETE delay and the maximum absolute CDV does not change a lot. The maximum queue sizes increase steadily when the load is increasing. However there is no explosion of queue sizes (Figure 38).

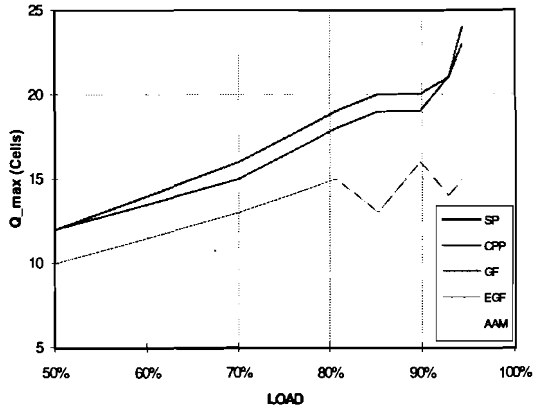

Figure 38: Maximum Queue Size CBR traffic

Because the AAM protocol only allocates PCR for each CBR connection and ignores the rest of the unused bandwidth, it behaves unpredictable when the load changes. The smallest mean ETE delay is reached when the load is somewhere between 70% and 90%. The CDV performance for the AAM protocol is optimal when the load is around 85% or 92%. The queue sizes when using the AAM protocol show the same trend as for the other protocols, but the maximum queue sizes are smaller. This can be explained by the relation with the smaller ETE-delay for the AAM protocol. When the load becomes very high (around 95%) the max ICDVI seems to increase heavily when using the AAM protocol while the mean CDV stays quite close to zero. This can be caused by all kinds of mismatches as described in section 7.1.

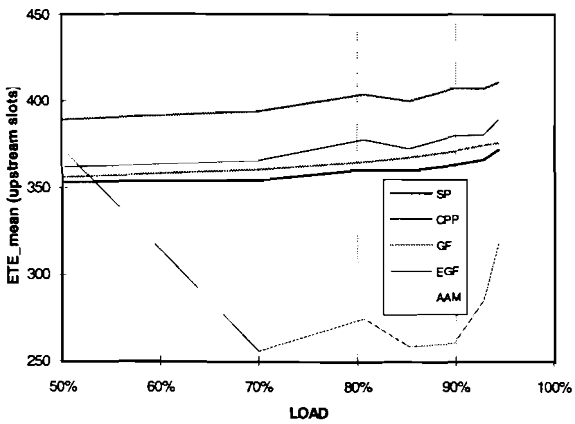

Figure 39: mean ETE-delay CBR traffic

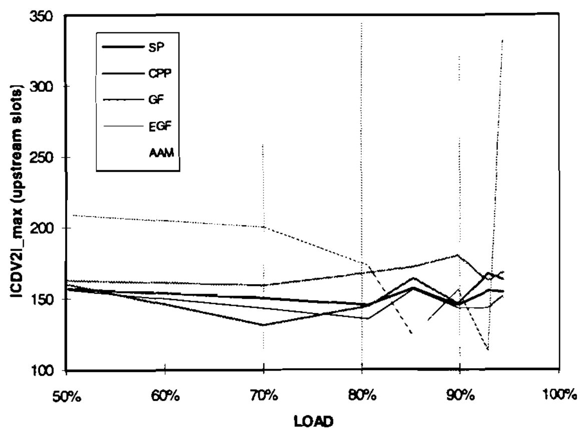

Figure 40: max ICDV2I CBR traffic

7.4.2 VBR traffic load

When considering the mean ETE-delay, it is clear that the AAM protocol is the least robust (Figure 41). While the mean ETE-delay when using AAM is much smaller for a load below 80%, it is much larger for loads above 85%. The characteristics of the mean ETE-delay using a request based protocol show the same behaviour, except for the CPP protocol which produces mean ETE-delays around 40 slots larger than the other request-based protocols do.

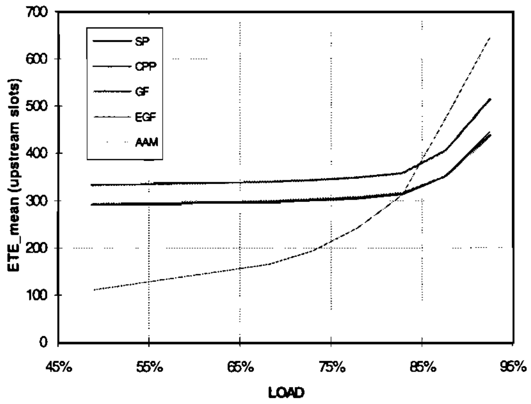

Figure 41: mean ETE-delay VBR traffic

Watching the max ICDVI it is obvious that AAM gives less performance in general (Figure 42). However, in case the load is above 80% the CPP and EGF protocol seem to produce very large maximum ICDVI 's. Comparing the performance in CDV for GF and EGF it is most remarkable that the maximum ICDVI are almost equal for loads below 80% while the results for loads above 80% are much worse for the EGF. The most reasonable explanation for the bad performance in CDV for the CPP and EGF protocol seems to be the spacing algorithm. This algorithm is able to control CDV by spacing the permits of an B-NT over a period. Of course this causes additional delay and reduces the effective throughput. When the load is very high, the spacing algorithm is limiting the possibilities to serve a burst of cells fast enough. This means that a queue may not be empty when the next burst is arriving on the B-NT. This causes very large queue sizes as can be seen in Figure 43.

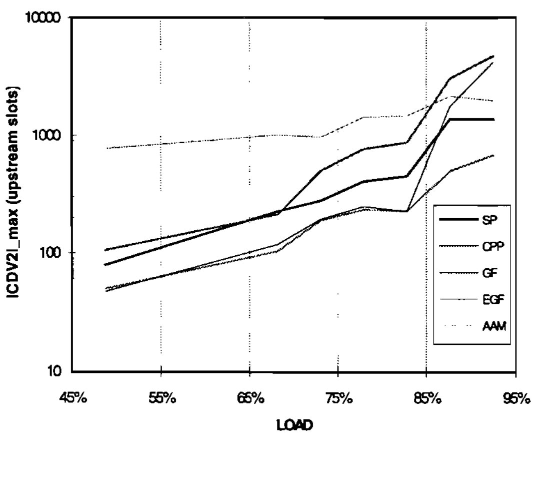

Figure 42: max ICDV2I VBR traffic

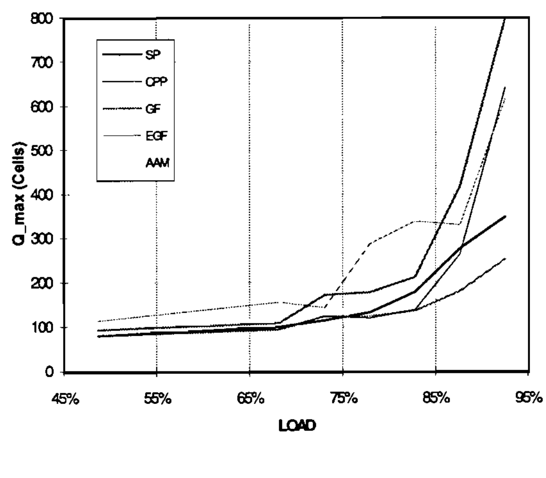

Figure 43: Maximum Queue Size VBR traffic

7.4.3 UBR traffic load

Using UBR traffic in order to analyze the performance of the MAC protocols seems to give similar results as for the VBR traffic scenario. The static protocols (in this case GF and AAM) have tremendous problems with high traffic loads (Figure 44 and Figure 45). Especially above 80% load the performance of the GF and AAM is rather bad. It is also quite obvious that the CPP protocol has performance problems above 85%. Most likely this is caused by the spacing algorithm. The most performant protocols seem to be SP and EGF.

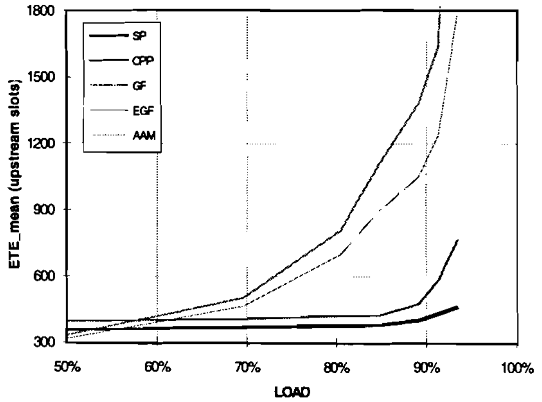

Figure 44: mean ETE-delay UBR traffic

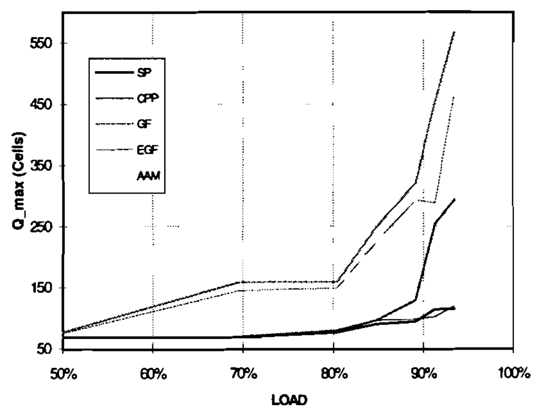

Figure 45: Maximum Queue Size UBR traffic

It must be noted that the maximum ICDV2l of the static protocols is much larger than for request based protocols (Figure 46). However the maximum ICDV2l for request based protocols is increasing very fast for higher loads. Espescially the CPP protocol can not handle heavy loads. The spacing algorithm in the CPP ring will only function when the number of empty slots is large enough. Otherwise the error between the ideal CPP ring position and the available positions will be too large.

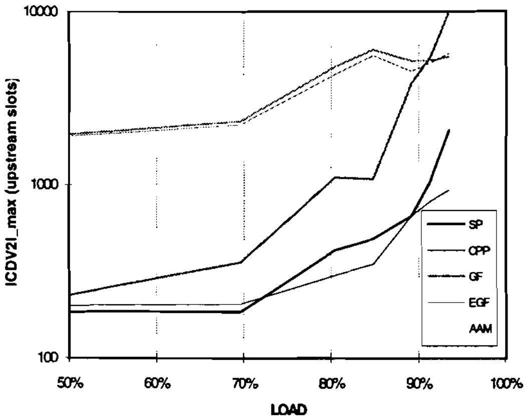

Figure 46: max ICDV2l UBR traffic

7.5 INFLUENCE OF THE MULTIPLEXING GAIN

7.5.1 Introduction

As described in section 6.3 the multiplexing gain can be used to qualify the burstiness of the traffic. In order to evaluate the performance of the MAC protocols for bursty traffic, the influence of the burstiness on this performance must be known. Therefore the basic scenario S3 is used. In this scenario 12 B-NTs with 10 VBR sources generate an average load of 83.48%. The multiplexing gain of this scenario can be varied by changing the PCR of the VBR connections. Using this scenario with PCR-values between 2Mbps and 147.189Mbps results in multiplexing gains between 1.67 and 120. The complete simulations results are given in appendix G.

7.5.2 Multiplexing gain analyses

Analyzing the simulation results, it is clear that the performance of the AAM protocol decreases dramatically for high multiplexing gains. The request based protocols give also worse performance for high multiplexing gain but the influence of the multiplexing gain is much smaller.

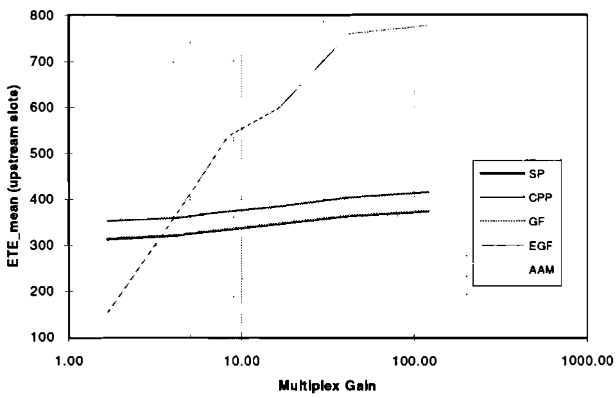

Figure 47: mean ETE-delay VBR traffic

When considering the mean ETE-delay the AAM protocol performs better than request based protocols when the multiplexing gain is below 4 (Figure 47). This can be explained by the required request phase for the request-based MAC protocols. However, when the multiplexing gain is larger than 4, the performance of the AAM protocol is getting worse while the performance of the request based protocols is almost the same. The maximum queue sizes, when using AAM are always larger than the queue sizes with a request-based protocol. Also when the multiplexing gain increases the maximum queue sizes increase much faster when using the AAM protocol. So for increasing multiplexing gain, the queue-size performance of AAM decreases compared to other protocols (Figure 48).

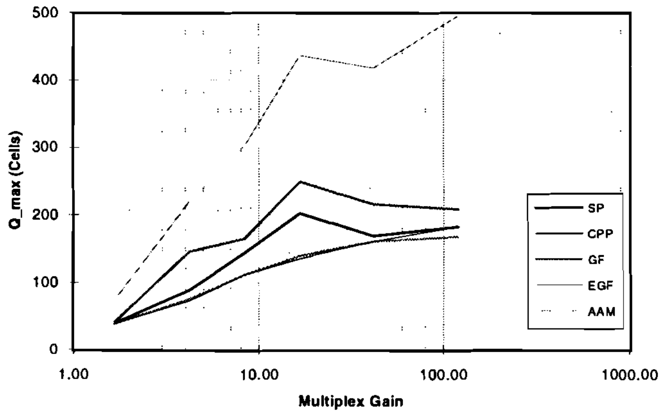

Figure 48: Maximum Queue Size VBR traffic

Comparing the request-based protocols GF and EGF seem to perform best. For small multiplexing gains, the behaviour of GF and EGF seem to be exactly the same. For large multiplexing gains, GF is performing a little better than EGF. This can be caused by the spacing mechanism in EGF which restricts a fast burst processing.

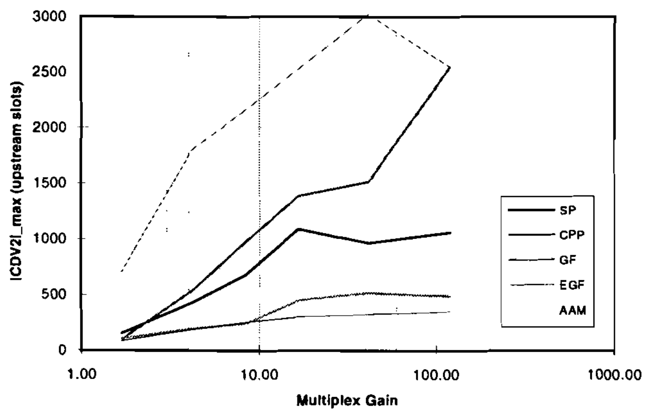

Figure 49: max ICDV2I VBR traffic

The CPP protocol has a poor performance compared to the other request-based protocols. Clearly, this protocol has problems with serving very bursty traffic. This results in large ICDVI values for high multiplexing gains (Figure 49). The mean ETE-delay shows the same trend as for other request-based protocols. However the mean ETE-delay using CPP is about 40 slots larger.

8. CONCLUSIONS AND RECOMMENDATIONS

In this thesis, the multiplexing policy for ATM based Passive Optical Networks is studied. Time Division Multiple Access is used to multiplex the traffic of all distributed terminals on the common upstream link of the point-to-multipoint based access network. The mechanism which handles the shared medium access control is called the MAC protocol. In this thesis a simulation model has been designed to evaluate the performance of several MAC protocols.

An essential choice for the performance of the shared medium access control mechanism is the question whether the MAC protocol is based on a static or dynamic mechanism. In contrast with the static protocols the dynamic protocols can react on traffic fluctuations. Using a static MAC protocol to serve bursty traffic will decrease the burstiness of the traffic. Assuming the static bandwidth allocation is below the peak cell rate of the source, the arrival frequency of cells in a busy period will be higher than the arrival frequency of grants. This causes queue growth. After the burst the queue will shrink again, however it takes some time before it is completely empty again. This results in bursts which grow to each other. So the traffic will be less bursty and it looks more like constant bit rate traffic.

Since the constant interarrival time between the upstream grants does not fit on the probability density function of the arriving cells, a serious over allocation of bandwidth is needed to avoid very large queue sizes and corresponding cell transfer delays. Since the total upstream bandwidth is fixed, this over allocation reduces the upstream efficiency and causes a higher blocking probability for new connections. It must be concluded that the introduction of service categories with a variable bit rate in ATM makes the design and construction of a dynamic or pseudo-dynamic MAC protocol inevitable.

The essence of the Shared Medium Access Control mechanism are the distributed queues. The actual queue status is only known by the terminal. The MAC controller can never react perfectly on traffic fluctuations, because the queue status known in the central point where the protocol is implemented is not up to date, This limitation of performance is determined by the delay between the terminals and the central point and the burstiness of the served traffic.

The maximum number of terminals specified by topology, is also important for the performance. The usage of a small number of terminals with a lot of aggregated traffic, introduces the advantages of statistical multiplexing. The aggregated traffic will behave less bursty and the usage of distributed intelligence in the terminals makes a faster reaction on traffic fluctuations possible. Serving a large number of terminals, the upstream efficiency is much more important.

Considering the fact that characteristics like the maximum number of terminals and the delay between terminals and the central point can differ per physical implementation of the access network, it must be concluded that one general strategy for shared medium access control may not be very performing. The behaviour of the MAC protocol must be optimized for characteristics of the access network and the served traffic.

Except for the traffic and topology characteristics, the performance of a dynamic MAC protocol can also be influenced by the update frequency of queue status, controlled by the polling sequence. The time between two polling grants for one specific terminal should not be larger than the tightest cell delay variation tolerance. The usage of other additional MAC communication channels like Piggybacking can improve the performance.

Analyzing the simulation results with the PON configuration, it is concluded that all dynamic MAC protocols perform quite similar. Although more complex grant generation mechanisms might be able to outperform the others for certain scenarios, it is on this moment not possible to identify a MAC protocol which is the best performing over a wide range of traffic scenario's. Especially mechanisms used to reduce CDV like spacing should be dimensioned very conservative since they can disturb the throughput under heavy loads. Therefore it must be concluded that the performance of a MAC protocol should be analyzed with several, well chosen traffic scenarios. To qualify the performance of a MAC protocol, it is more important to perform good in a wide range of traffic scenario's than to perform excellent in certain specific scenarios.

The designed OPNET model for MAC performance evaluations is a powerful tool to investigate the influence of traffic and topology characteristics. It can also be used to optimize several parameters of the MAC protocol. Although the MAC protocol behaviour can be specified with external C-code and the topology of the access network and the traffic characteristics are configurable, some irnprovements have to be made to make it more user-friendly.

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ABBREVIATIONS

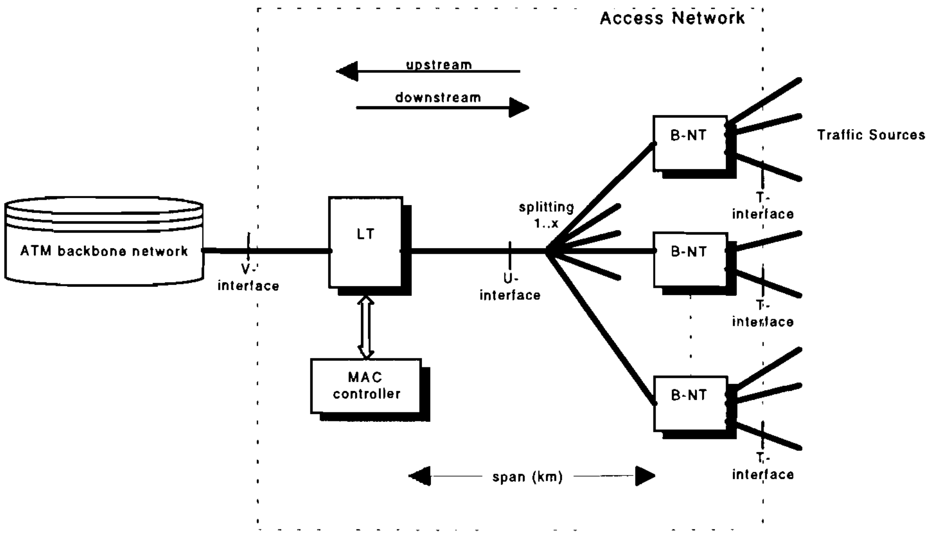
AAM	Alcatel APON MAC
ABR	Available Bit Rate
ADSL	Asynchronous Digital Subscriber Line
AN	Access Network
APON	ATM based PON
ATM	Asynchronous Transfer Mode
ATHOC	ATM Applications over Hybrid Optical Fibre Coax
B-NT	Broadband Network Termination
BRM	Backward Resource Management
B-TE	Broadband Terminal Equipment
CBR	Constant Bit Rate
CCT	Controlled Cell Transfer
CDC	Count Down Counter
CDT	Controlled Dynamic Transfer
CDV	Cell Delay Variation
CDVT	Cell Delay Variation Tolerance
CLR	Cell Loss Ratio
CPP	Circular Permit Programming
CPR	Centralized Priority Reservation
CR	Cell Rate
CRF	Call Related Functions
DBR	Deterministic Bit Rate
EGF	Enhanced Global FIFO
FIFO	First In First Out
GF	Global FIFO
GFR	Guaranteed Frame Rate
HFC	Hybrid Fiber Coax
MAC	Medium Access Control
MACC	MAC Controller
MCR	Minimum Cell Rate
NPC	Network Parameter Control
nrt	non real-time
OAM	Operations and Maintenance
PCR	Peak Cell Rate
PDF	Probability Density Function
PLP	Physical Layer Preamble
PLOAM	Physical Layer Operation And Maintenance
PON	Passive Optical Network
RAM	Random Access Memory
RC	Request Counter
RM	Resource Management
rt	real-time
RTD	Round Trip Delay
SBR	Statistical Bit Rate
SCR	Sustainable Cell Rate
SES	Source End Point
SN	Service Node/Sequence Number
SNI	Service Node Interface
SPON	SuperPON
STM	Synchronous Transfer Mode
TC	Transmission Convergence
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
UBR	Unspecified Bit Rate
UNI	User Network Interface
UPC	Usage Parameter Control
VBR	Variable Bit Rate
VP	Virtual Path

APPENDICES

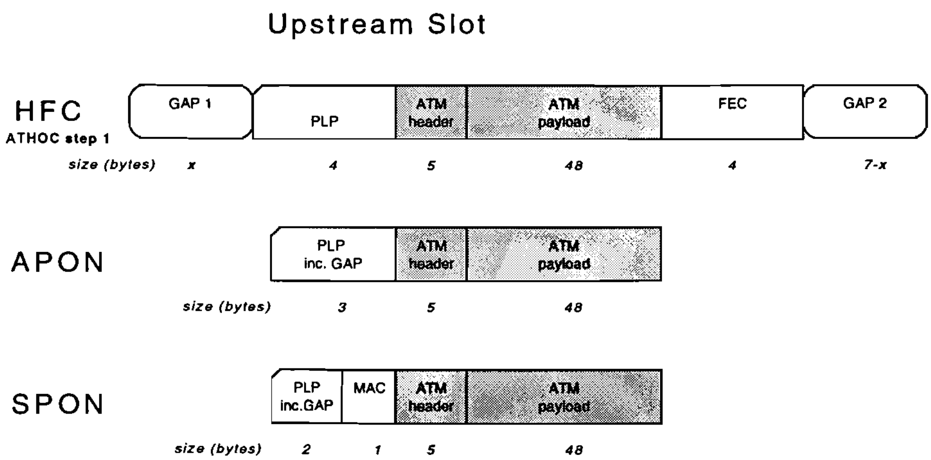
Appendix A: Access Network Characteristics

The most important characteristics of the point-to-multipoint access netorrks are given below.

	Splitting	Span	upstream BW	downstream BW
	(max #NTs)	*(km)*	*(Mbps)*	*(Mbps)*
HFC	20..50	20..80	2.048 (typ.)	40 (in 8 Mhz)
(A)PON	16..64	10	155.52	155.52/622.08
SuperPON	2048	100	311.04	2488



The upstream slot structure is quite different for several physical implementations. In the next figure this structure is shown for HFC, (A)PON and SuperPON. Obviously the introduced overhead with HFC is much larger compared to PON. This results in a relatively low ATM bit rate.



Appendix B: ATM Forum and ITU-T service categories

ATM Forum ATM Service Category	ITU-T ATM Transfer Capability	Typical characteristics	Source Traffic Descriptor	Guarantees			Feedback Control
				CLR	Delay and CDV	Bandwidth	
CBR Constant Bit Rate	DBR Deterministic Bit Rate	open loop real-time	PCR	YES	YES	YES	NO
rt-VBR real-time Variable Bit Rate	rt-SBR real-time Statistical Bit Rate	open loop real-time	PCR, SCR, MBS	YES on a longer time scale	YES	YES	NO
nrt-VBR non real-time Variable Bit Rate	nrt-SBR non real-time Statistical Bit Rate	open loop non real-time	PCR, SCR, MBS	YES on a longer time scale	NO	YES	NO
ABR Available Bit Rate	ABR Available Bit Rate	closed loop rate based non real-time	PCR, MCR + source behaviour parameters	YES	NO	YES	YES
rt-ABR (1) real-time Available Bit Rate	no equivalent	closed loop rate based real-time	PCR, MCR + source behaviour parameters	YES	YES	YES	YES
UBR Unspecified Bit Rate	UBR Unspecified Bit Rate	open loop non real-time	PCR	NO	NO	NO	NO
UBR+ (1) enhanced Unspecified Bit Rate	UBR+ (1) enhanced Unspecified Bit Rate	open loop non real-time	PCR, MCR, MBS	NO	NO	YES	NO
no equivalent	ABT-DT ATM Block Transfer with Delayed Transmission	closed loop rate based real-time	PCR, optional: SCR and MBS	YES on an ATM block basis if the Block Cell Rate (BCR) is allocated	YES on an ATM block basis if the Block Cell Rate (BCR) is allocated	YES on an ATM block basis if the Block Cell Rate (BCR) is allocated	YES
no equivalent	ABT-IT ATM Block Transfer with Immediate Transmission	open loop real-time	PCR, optional: SCR and MBS	NO	YES on an ATM block basis if the Block Cell Rate (BCR) is allocated	YES on an ATM block basis if the Block Cell Rate (BCR) is allocated	NO
no equivalent	CDT (1) Controlled Dynamic Transfer	closed loop credit based non real-time	PCR	YES	NO	NO	YES
no equivalent	CCT (1) Controlled Cell Transfer	closed loop credit based non real-time	PCR	YES	NO	NO	YES
GFR (1) Guaranteed Frame Rate	no equivalent	open loop non real-time	PCR, MCR, MTU-size (2)	NO	NO	YES on a frame basis	NO

(1) not specified yet; (2) the MTU size can be translated into an equivalent MBS.

Appendix C: Overview of evaluated APON MAC protocols

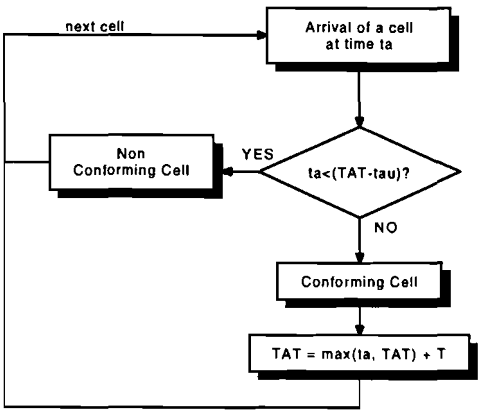
Name	Configuration	Requests	Approval	Access control
AAM Alcatel APON MAC Alcatel	PON	no requests	grants are directed to a B-NT. No QoS indication is incorporated in the permits. The B-NT implements a static priority scheduling discipline, CBR > VBR > ABR > UBR	Permits are produced according to connection profile parameters of connections established at each termination Not transparent: needs a dedicated fast signalling protocol
CPP Circular Permit Programming	PON	Minislot frames are used to poll 8 B-NTs simultaneously. The requests contain the number of cells that have arrived since the last request. A distinction is made between CBR, VBR, ABR and UBR requests	Grants are generated to a B-NT with a QoS indication	Based on four CPP RAMs. Transparent MAC protocol
GF Global FIFO sometimes referred to as the BAF (Broadband Access Facilities) MAC protocol Philips et al.	PON	Minislot frames are used to poll 8 B-NTs simultaneously. The requests contain the number of cells that have arrived since the last request. A distinction is made between CBR, VBR and ABR requests. UBR services are supported using pre-arbitrated permits.	Grants are generated to a B-NT with a QoS indication	CBR and VBR requests are immediately transferred into permits (no spacing) A spacer function provides MCR guarantees for ABR traffic. Excess ABR requests are distributed in a round-robin fashion. UBR permits are generated in a round-robin fashion, only using empty slots (not based on requests). Not transparent: needs a dedicated fast signalling protocol
EGF Adapted Multi-Service Global FIFO Extension ot the original GF protocol	PON	Minislot frames are used to poll 8 B-NTs simultaneously. The requests contain the number of cells that have arrived since the last request. A distinction is made between CBR, VBR, ABR and UBR requests	Grants are generated to a B-NT with a QoS indication	Based on the GF architecture. MCR is enforced for ABR and UBR traffic, PCR spacing is employed for CBR and VBR services. The Bounded Period Rule in employed. Not transparent: needs a dedicated fast signalling protocol
SP Static Priority	PON	Minislot frames are used to poll 8 B-NTs simultaneously. The requests contain the number of cells that have arrived since the last request. A distinction is made between CBR, VBR, ABR and UBR requests	Grants are generated to a B-NT with a QoS indication	Requests are generated using a Static Priority Scheduling Discipline. Round Robin scheduling makes sure that B-NTs are treated on an equal footing. Transparent MAC protocol

Appendix D: GCRA model

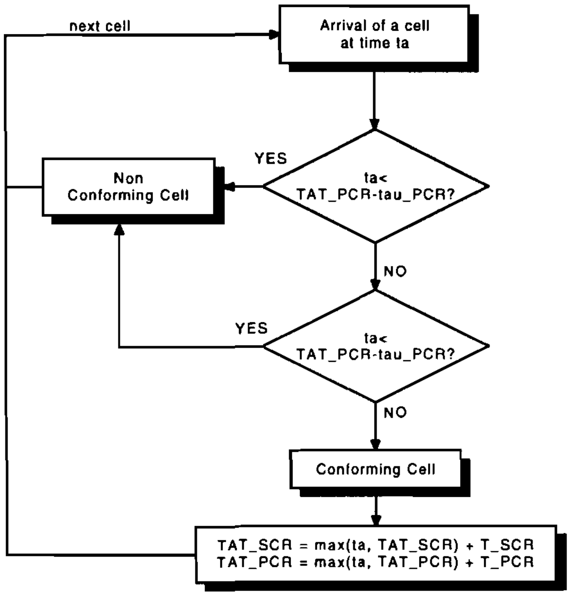
The Generic Cell Rate Algorithm is designed for traffic control. It is standarized in ITU-T Recommendation I.371 “Traffic Control and Congestion Control in B-ISDN”

GCRA(T,τ)

all values are expressed in sec.



GCRA(T_{PCR}, T_{SCR} τ_{PCR}, τ_{SCR})



TAT	Theoretical Arrival Time
t_a	Time of arrival of a cell
T_{PCR}	Reciprocal of PCR
T_{SCR}	Reciprocal of SCR
t_{PCR}:	Tolerance associated with T_{PCR}
t_{SCR}:	Tolerance associated with T_{SCR} (= t_{IBT} + t'_{SCR})

The values of τ depend on the network interface. In the backbone network (V-inferface and further) the requirements for τ (in sec.) are specified by:

$$\tau_{PCR} = \max\left\{T_{PCR}, 80*\delta*\frac{1-\delta}{T_{PCR}}\right\}$$

with:

$$\delta = {}^{1}\!/_{transmission \quad speed}$$

and

$$\tau_{SCR} = 80*\delta*\frac{1-\delta}{T_{SCR}} + \tau_{burstsize}$$

with:

$$\tau_{burstsize} = (BS_{MAX} - 1)*(T_{SCR} - T_{PCR})$$

Since the multiplexing introduces CDVs, the requirements for the ATM traffic source have to be much stricter. The GCRA algorithm used for “source policing”is defined by:

$$\tau_{PCR} = 0$$

and

$$\tau_{SCR} =_{burstsize}$$

Appendix E: Features & Limitations of the OPNET model MAC 4/5

The OPNET model for MAC simulations (MAC4/5) is designed as a ATM transparent system. It supports the use of various *(extern specified)* MAC protocols. The following (optional) features are NOW available:

MAC algorithm
- Behaviour of new algorithms can be specified in external C-code
- Multiple MAC protocols (algorithms) supported
  - *Static:* *Alcatel APON MAC, ATHOC step 1*
  - *Request based:* *Static Priority, , CPP, Enhanced Global FIFO*
  - *Hibride:* *Global FIFO, SPON1*

MAC communication channels
- PiggyBacking
- Polling
  by Minislots or normal Grants
- Minislots
  in order to poll 8 ONU's in one timeslot
  manual or automatic specification of Minislots
- PLOAM cells available
  in order to send the grands to the ONU's in groups of for instance 27 grants.

Traffic Sources
- (mean) bit rate of traffic source in kbit/s
- specification of QoS class
- random phase for every traffic source
- ON-OFF model for bursty sources specified by:
  - *Peak Cell Rate (VBR/UBR)*
  - *Minimum Cell Rate (UBR)*
  - *mean Burst size (VBR/UBR)*
- *Burst size PDF specification*
- *Two Level sources using GCRA shaping*

ONU characteristics
- QoS Feedback
- Sub-Queue's
  different queue's for all QoS classes in every ONU

LT characteristics
- QoS Feedback
- Using empty slots for polling

Policer
- GCRA policing per connection
- QoS support

OPNET
- Multiple Sources or ONU's in just **one** PROCESS or NODE
- Broadcast downstream traffic possible
- Automatic initialisation routine
  - *automatic generation of Routing tables*
  - *PCR, mean CR and MCR specifications* ***per ONU per QoS*** *available for the protocol*
- *Output files for statistic analyses with Excel*

Main Limitations

- ABR model with feedback not implemented
- No Contention Based Model Features
  implementation of Aloha/Ethernet based protocols not yet possible
- Routing tables are generated in upstream direction
  no downstream traffic possible before the upstream traffic started

Appendix F: Interface between MAC grant generation algorithm and OPNET model

In this appendix, the procedures, as described in chapter 4 where specified. It must be noted that several libraries were developed for all different access networks.

mac4.h

```
/********** MAC protocol library ************************
programmed by F.M. Ploumen  28-9-97

This library is automatically included in the OPNET model when using the mac_LT4 controller
Changing the protocol is done by the void MAC_init_process
The necessary libraries should be included in this library

********************************************************
protocol  naam
 1        CPP     Circular Permit Programming (3 levels)
 2        GF      Global FIFO
 3        EGF     Enhanced Global FIFO
 4        AAM     Alcatel APON MAC (not request based)
 5        ATH     ATHOC (HFC)
*******************************************************/
#include <math.h>

#define NTmax    64
#define BUSSPEED 147189 /* ATM bitrate = 53/56*155.520 Mbps */

int        Tot_req[NTmax], Request[NTmax][4], pri, permit, protocol, NoE, NoTmax, NTcc;

float bounded_period(double CR, double TotalCR, float etha, int Tmax)
        {
        int        Tspacer;

        Tspacer= (int) floor(etha*TotalCR/CR);
        if (Tmax< Tspacer) Tspacer=Tmax;
        return  Tspacer;
        }

/********** include MAC protocols ***************************************************/

#include "maccpp2.h"
#include "mac4gf.h"
#include "mac4egf.h"
#include "mac42aam.h"
#include "macathoc.h"

/***********default MAC protocol "Static Priority" ***********************************/

/* dit protocol handelt cyclisch de requests af en met een FIXED priority */
void init_permit()
 {
 int i;

 for (i=0; i<NTmax; i++)
  {
  Tot_req[i] = 0;
  Request[i][0] = 0;
  Request[i][1] = 0;
  Request[i][2] = 0;
  Request[i][3] = 0;
  Tot_req[i] = 0;
  }
 pri = 0;
```

```
 permit = -1;
 }

void place_permit(NoR,NoT,Pri)
 {

 Request[NoT][Pri] = Request[NoT][Pri] + NoR;
 printf("\n%d requests placed for NT %d QoS: %d", NoR, NoT, Pri);
 printf("\n total requests for this NT: %d", Request[NoT][Pri]);
 }

void get_permit()
 {
 int GrantGiven, retry;

 GrantGiven=0;
 printf("\nTot_req= %d Request = %d ", Tot_req[NTcc], Request[NTcc][0]);
 printf("\nNTcc= %d", NTcc);
 retry =0;
 while (GrantGiven ==0)
  {
  if (Tot_req[NTcc]>0)
   {
   if (Request[NTcc][0]>0)
    {
    permit = NTcc;
    pri = 0;
    Request[NTcc][0] = Request[NTcc][0] -1;
    }
   else if (Request[NTcc][1]>0)
    {
    permit = NTcc;
    pri = 1;
    Request[NTcc][1] = Request[NTcc][1] -1;
    }
   else if (Request[NTcc][2]>0)
    {
    permit = NTcc;
    pri = 2;
    Request[NTcc][2] = Request[NTcc][2] -1;
    }
   else if (Request[NTcc][3]>0)
    {
    permit = NTcc;
    pri = 3;
    Request[NTcc][3] = Request[NTcc][3] -1;
    }
   Tot_req[NTcc] = Tot_req[NTcc] -1;
   GrantGiven = 1;
   }
  NTcc = NTcc +1;
  if (NTcc==NoTmax) NTcc=0;

  retry = retry +1;
  if (retry == NoTmax + 1)
   {
   permit = -1;
   pri = 0;
   GrantGiven = 1;
   }
  }
 }

/*****************************************************************************/

void MAC_init_process(int prot, int noc, int noe)
 {
 protocol = prot;
 NoE = noe;
```

```
NoTmax = noc;
if (protocol==1)
  {
  CPP_init_permit();
  printf("\nCircular Permit Programming (CPP) geinitialiseerd");
  }
else if (protocol==2)
  {
  GF_init_process();
  printf("\nGlobal FIFO (GF) geinitialiseerd");
  }
else if (protocol==3)
  {
  EGF_init_process();
  printf("\nEnhanced Global FIFO geinitiabliseerd");
  }
else if (protocol==4)
  {
  AAM_init_permit();
  printf("\nAlcatel APON MAC geinitialiseerd");
  }
else if (protocol==5)
  {
  ATHOC1_init_process();
  printf("\nAlcatel ATHOC (HFC) MAC geinitialiseerd");
  }
else
  {
  init_permit();
  printf("\nNo protocol, permits are given cyclic with fixed priority");
  }
 }
/*************************************************************************/
void MAC_init_nt(int NoT, double  MAC_CBR_CR,
                 double MAC_VBR_PCR, double MAC_VBR_meanCR, double MAC_VBR_MCR,
                 double MAC_ABR_PCR, double MAC_ABR_meanCR, double MAC_ABR_MCR,
                 double MAC_UBR_PCR, double MAC_UBR_meanCR, double MAC_UBR_MCR)

 {
 if (protocol==2) GF_init_nt(NoT, MAC_ABR_MCR);
 else if (protocol==3) EGF_init_nt(NoT, MAC_CBR_CR, MAC_VBR_PCR, MAC_ABR_MCR, MAC_UBR_MCR);
 else if (protocol==4) AAM_init_nt(NoT, MAC_CBR_CR , MAC_VBR_meanCR,  MAC_ABR_MCR , MAC_ABR_PCR,
MAC_UBR_MCR, MAC_UBR_PCR);
 }

/*************************************************************************/
void MAC_place_permit(int NoR, int NoT, int Pri)
 {
 int i;

 Tot_req[NoT] = Tot_req[NoT] + NoR;
 if (protocol==1)
  {
  Pri = Pri - 1;
  if (Pri==-1)  Pri = 0;
  CPP_place_permit(NoR, NoT, NoE, Pri);
  }
 else if (protocol==2)
  {
  if (Pri==0)
    Pri = 1;
  GF_place_permit(NoR, NoT, Pri);
  }

 else if (protocol==3)
  {
  EGF_place_permit(NoR, NoT, Pri);
  }
 else if (protocol ==4)
```

```
  {
  /* geen permits plaatsen want protocol is niet request based*/
  }
 else if (protocol==5)
  {
  ATHOC1_place_permit(NoR, NoT+17, Pri);
  }
 else
  {
  place_permit(NoR, NoT, Pri);
  }
 }
/*************************************************************************/
void MAC_get_permit()
 {
 if (protocol==1)
  {
  CPP_get_permit();
  if (pri==1) pri=4;  /* fixed priority for CBR>>VBR */
  }
 else if (protocol==2)
  {
  GF_get_permit();
  if (pri==1) pri=4;  /* fixed priority for CBR>>VBR */
  }
 else if (protocol==3) EGF_get_permit();
 else if (protocol==4) AAM_get_permit();
 else if (protocol==5)
         {
         ATHOC1_get_permit();
         if (permit >10) permit=permit-17;
         }
 else get_permit();
 }
```

mac5.h

```
/********** MAC protocol library *************************
programmed by F.M. Ploumen  27-11-'97
updated by R. Hoebeke 19/12/97

This library is automaticly included in the OPNET model
when using the mac_LT5 controller

mac5S:  SuperPON

*********************************************************
protocol naam
 1      SPON1   SPON MAC 1
 2      AAM     Alcatel APON MAC
 3      SPON2   SPON MAC 2
 4      SPON3
 5      SPON4
 6      SPON5

********************************************************/
#include <math.h>

int     Tot_req[NTmax], Request[NTmax][4], pri, permit, protocol, NoE, NoTmax, NTcc;

float bounded_period(double CR, double TotalCR, float etha, int Tmax)
        {
        int       Tspacer;

        Tspacer= (int) floor(etha*TotalCR/CR);
        if (Tmax< Tspacer) Tspacer=Tmax;
        return  Tspacer;
        }

/****************************************************************************/
#define TRUE 1
#define FALSE 0

#include "mac5SPON1.h"
#include "mac5aam.h"

/********************************************************************************/
void init_permit()
 {
 int i;

 for (i=0; i<NTmax; i++)
   {
   Tot_req[i] = 0;
   Request[i][0] = 0;
   Request[i][1] = 0;
   Request[i][2] = 0;
   Request[i][3] = 0;
   Tot_req[i] = 0;
   }
 pri = 0;
 permit = -1;
 }

void place_permit(NoR,NoT,Pri)
 {
 /* dit protocol handelt cyclisch de requests af en met een FIXED priority */
 Request[NoT][Pri] = Request[NoT][Pri] + NoR;
 printf("\n%d requests placed for NT %d QoS: %d", NoR, NoT, Pri);
 printf("\n total requests for this NT: %d", Request[NoT][Pri]);
 }
```

```
void get_permit()
 {
 int GrantGiven, retry;

 GrantGiven=0;
 printf("\nTot_req= %d Request = %d ", Tot_req[NTcc], Request[NTcc][0]);
 printf("\nNTcc= %d", NTcc);
 retry =0;
 while (GrantGiven ==0)
  {
  if (Tot_req[NTcc]>0)
   {
   if (Request[NTcc][0]>0)
    {
    permit = NTcc;
    pri = 0;
    Request[NTcc][0] = Request[NTcc][0] -1;
    }
   else if (Request[NTcc][1]>0)
    {
    permit = NTcc;
    pri = 1;
    Request[NTcc][1] = Request[NTcc][1] -1;
    }
   else if (Request[NTcc][2]>0)
    {
    permit = NTcc;
    pri = 2;
    Request[NTcc][2] = Request[NTcc][2] -1;
    }
   else if (Request[NTcc][3]>0)
    {
    permit = NTcc;
    pri = 3;
    Request[NTcc][3] = Request[NTcc][3] -1;
    }
   Tot_req[NTcc] = Tot_req[NTcc] -1;
   GrantGiven = 1;
   }
  NTcc = NTcc +1;
  if (NTcc==NoTmax) NTcc=0;

  retry = retry +1;
  if  (retry == NoTmax + 1)
   {
   permit = -1;
   pri = 0;
   GrantGiven = 1;
   }
  }
 }

/****************************************************************************/

void MAC_init_process(int prot, int noc, int noe)
 {
 protocol = prot;
 NoE = noe;
 NoTmax = noc;
 if (protocol==1)
  {
  SPON1_init_process(3,1);
  printf("\nSPON1 MAC geinitialiseerd");
  }
 else if (protocol==2)
  {
  AAM_init_permit();
  printf("\nAAM geinitialiseerd");
  }
```

```
 else if (protocol==3)
  {
  SPON2_init_process(3,1);
  printf("\nSPON2 MAC geinitialiseerd");
  }
 else if (protocol==4)
  {
  SPON3_init_process(3,1);
  printf("\nSPON3 MAC geinitialiseerd");
  }
 else if (protocol==5)
  {
  SPON4_init_process(3,1);
  printf("\nSPON4 MAC geinitialiseerd");
  }
 else if (protocol==6)
  {
  SPON5_init_process(3,1);
  printf("\nSPON5 MAC geinitialiseerd");
  }
 else
  {
  init_permit();
  printf("\nNo protocol, permits are given cyclic with fixed priority");
  }
 }
/*************************************************************************/
void MAC_init_nt(int NoT, double  MAC_CBR_CR,
                  double MAC_VBR_PCR, double MAC_VBR_meanCR, double MAC_VBR_MCR,
                  double MAC_ABR_PCR, double MAC_ABR_meanCR, double MAC_ABR_MCR,
                  double MAC_UBR_PCR, double MAC_UBR_meanCR, double MAC_UBR_MCR)

 {
 if (protocol==1) SPON1_init_nt(NoT, MAC_CBR_CR, MAC_VBR_PCR, MAC_VBR_meanCR, MAC_ABR_MCR,
MAC_UBR_MCR);
 else if (protocol==2) AAM_init_nt(NoT, MAC_CBR_CR , MAC_VBR_meanCR,  MAC_ABR_MCR , MAC_ABR_PCR,
MAC_UBR_MCR, MAC_UBR_PCR);
 else if (protocol==3) SPON2_init_nt(NoT, MAC_CBR_CR, MAC_VBR_PCR, MAC_VBR_meanCR, MAC_ABR_MCR,
MAC_UBR_MCR);
 else if (protocol==4) SPON3_init_nt(NoT, MAC_CBR_CR, MAC_VBR_PCR, MAC_VBR_meanCR, MAC_ABR_MCR,
MAC_UBR_MCR);
 else if (protocol==5) SPON4_init_nt(NoT, MAC_CBR_CR, MAC_VBR_PCR, MAC_VBR_meanCR, MAC_ABR_MCR,
MAC_UBR_MCR);
 else if (protocol==6) SPON5_init_nt(NoT, MAC_CBR_CR, MAC_VBR_PCR, MAC_VBR_meanCR, MAC_ABR_MCR,
MAC_UBR_MCR);

 }

/*************************************************************************/
void MAC_place_permit(int NoR, int NoT, int Pri)
 {
 int i;

 Tot_req[NoT] = Tot_req[NoT] + NoR;
 if (protocol==1) SPON1_place_permit(NoR, NoT, Pri);
 else if (protocol ==2)
  {
  /* geen permits plaatsen want protocol is niet request based*/
  }
 else if (protocol==3) SPON2_place_permit(NoR, NoT, Pri);
 else if (protocol==4) SPON3_place_permit(NoR, NoT, Pri);
 else if (protocol==5) SPON4_place_permit(NoR, NoT, Pri);
 else if (protocol==6) SPON5_place_permit(NoR, NoT, Pri);
 else place_permit(NoR, NoT, Pri);
 }
/*************************************************************************/
void MAC_get_permit()
 {
 if (protocol==1) SPON1_get_permit();
```

```
else if (protocol==2) AAM_get_permit();
else if (protocol==3) SPON2_get_permit();
else if (protocol==4) SPON3_get_permit();
else if (protocol==5) SPON4_get_permit();
else if (protocol==6) SPON5_get_permit();
else get_permit();
}
```

Appendix G: APON simulation results

G1 Homogeneous Scenarios

Simulation Results Scenario 1

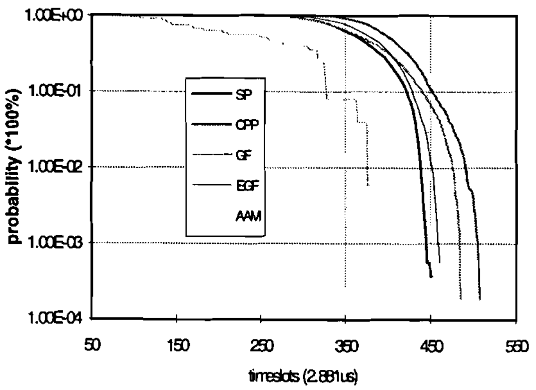


Figure 1: P(ETE>n) Scenario 1

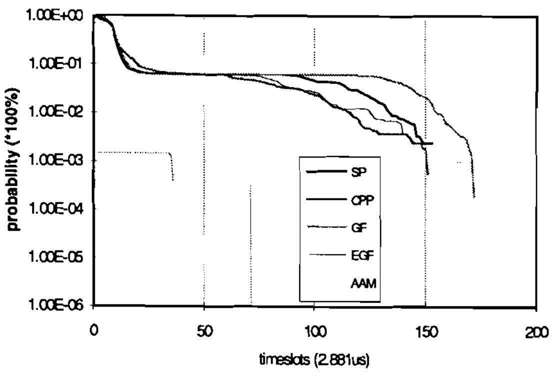


Figure 2: P(|CDV2|>n) Scenario 1

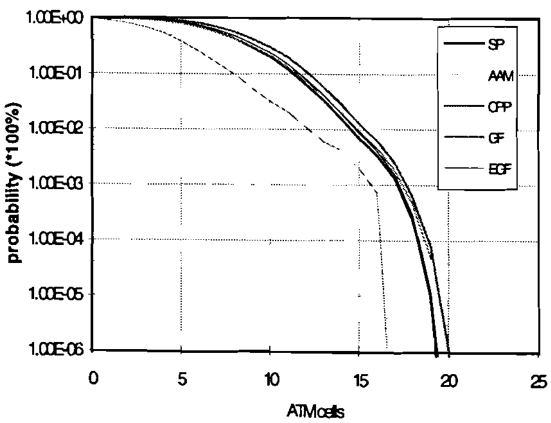


Figure 3: P(Q_size>n) Scenario 1

Simulation Results Scenario 2

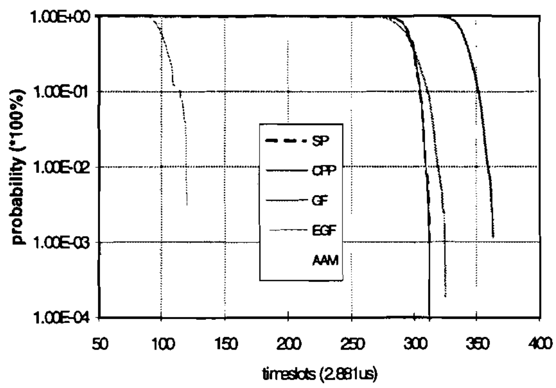


Figure 4: P(ETE>n) Scenario 2

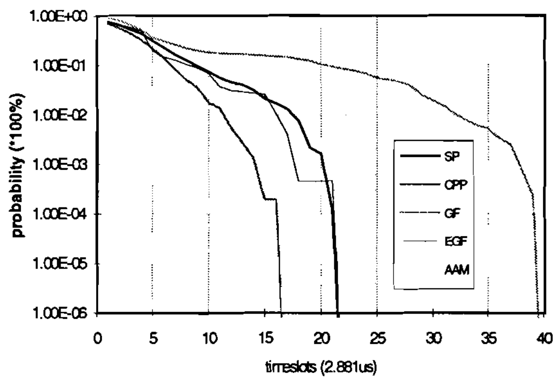


Figure 5: P(|CDV2|>n) Scenario 2

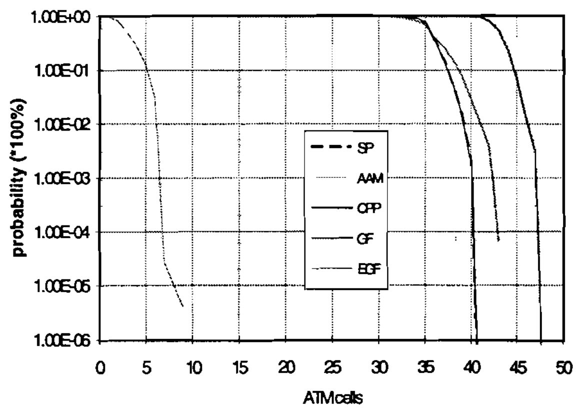


Figure 6: P(Q_size>n) Scenario 2

Simulation Results Scenario 3

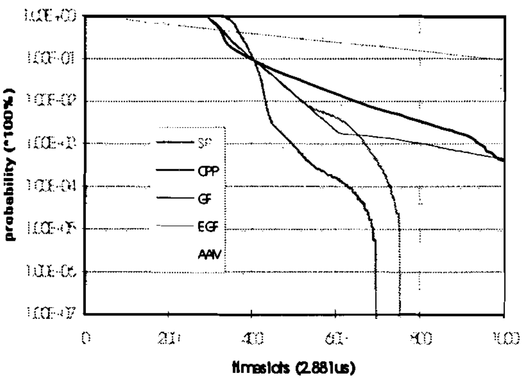


Figure 7: P(ETE>n) Scenario 3

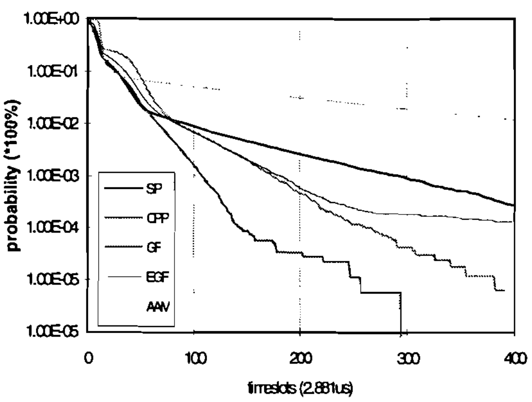


Figure 8: P(|CDV2|>n) Scenario 3

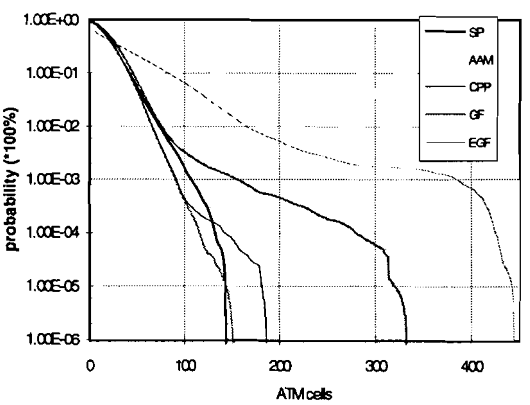


Figure 9: P(Q_size>n) Scenario 3

Simulation Results Scenario 4

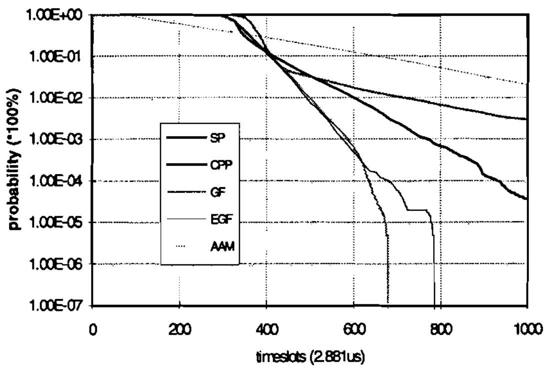


Figure 10: P(ETE>n) Scenario 4

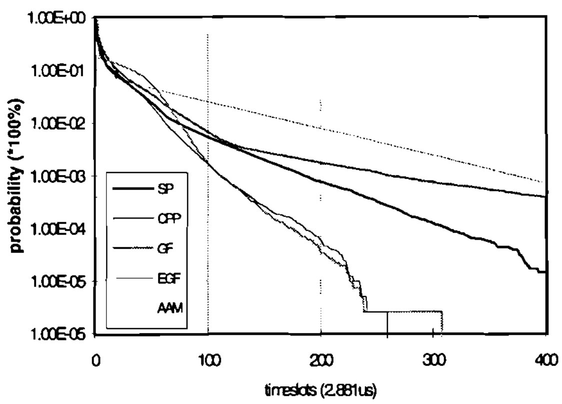


Figure 11: P(|CDV2|>n) Scenario 4

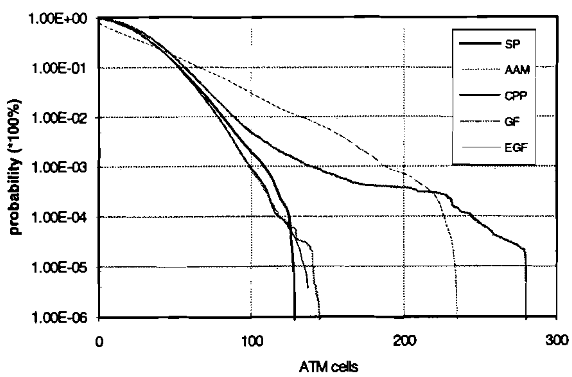


Figure 12: P(Q_size>n) Scenario 4

Simulation Results Scenario 5

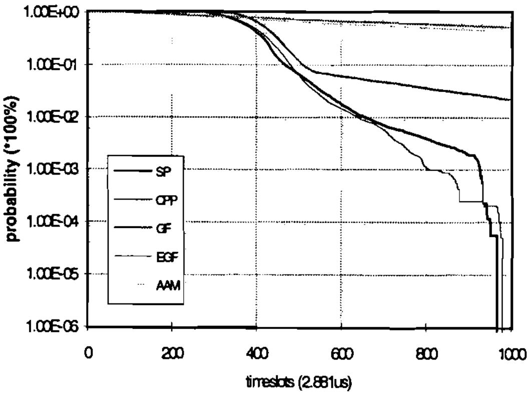


Figure 13: P(ETE>n) Scenario 5

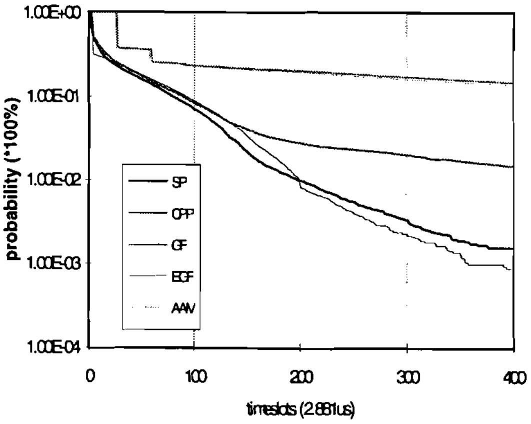


Figure 14: P(|CDV2|>n) Scenario 5

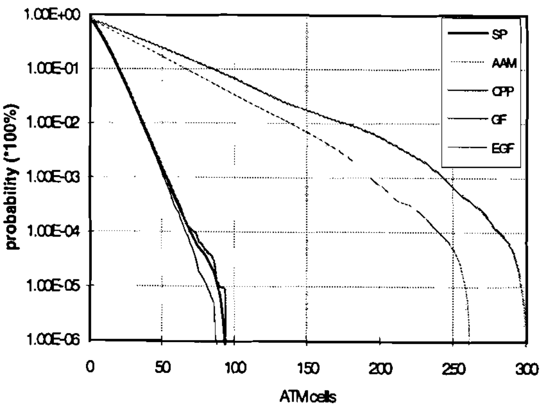


Figure 15: P(Q_size>n) Scenario 5

Simulation Results Scenario 6

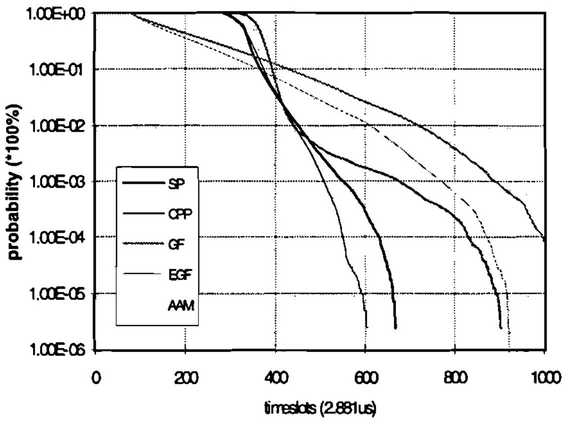


Figure 16: P(ETE>n) Scenario 6

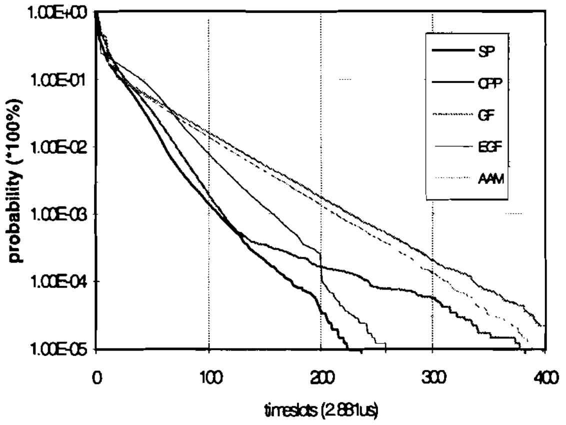


Figure 17: P(|CDV2|>n) Scenario 6

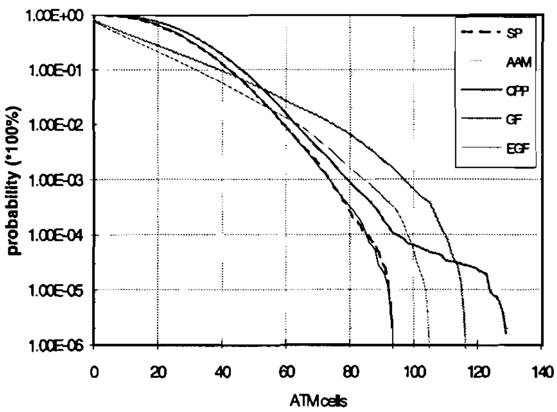


Figure 18: P(Q_size>n) Scenario 6

G2: Heterogeneous Scenarios

Simulation Results Scenario 7, CBR

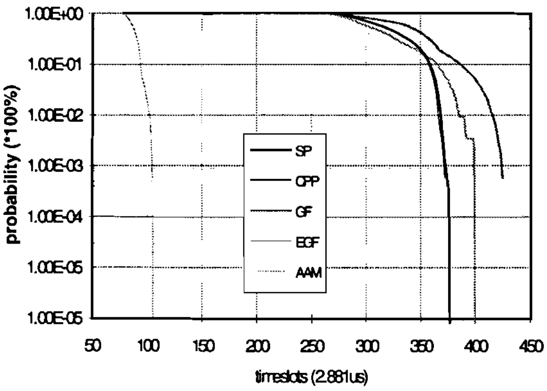


Figure 19: P(ETE>n) Scenario 7, CBR

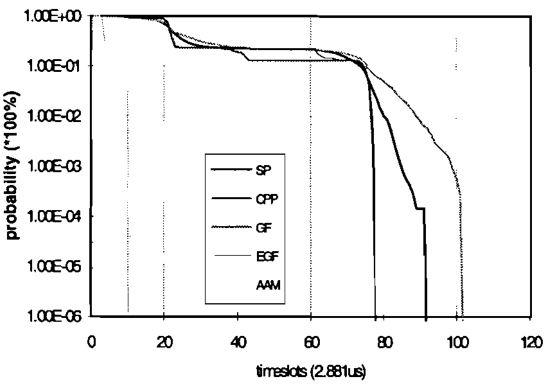


Figure 20: P(|CDV2|>n) Scenario 7, CBR

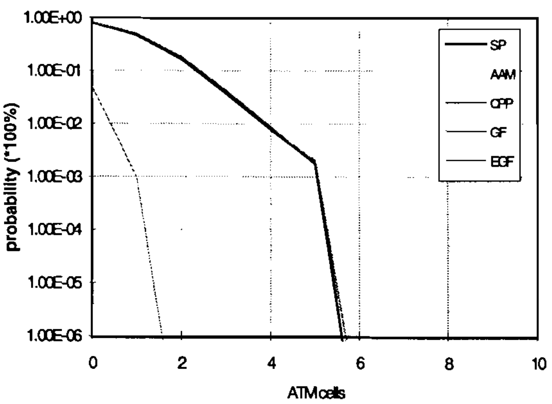


Figure 21: P(Q_size>n) Scenario 7, CBR

Simulation Results Scenario 7, VBR

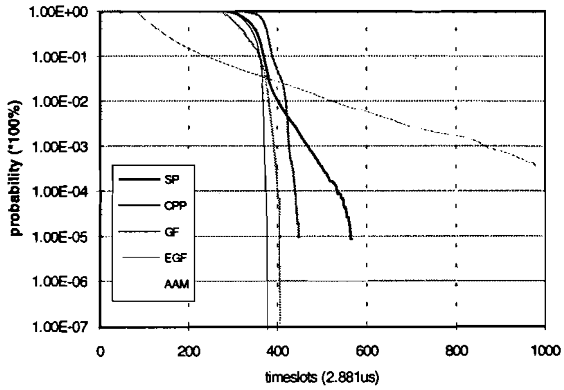


Figure 22: P(ETE>n) Scenario 7, VBR

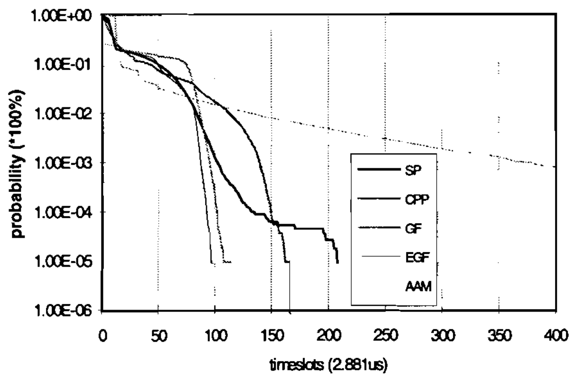


Figure 23: P(|CDV2|>n) Scenario 7, VBR

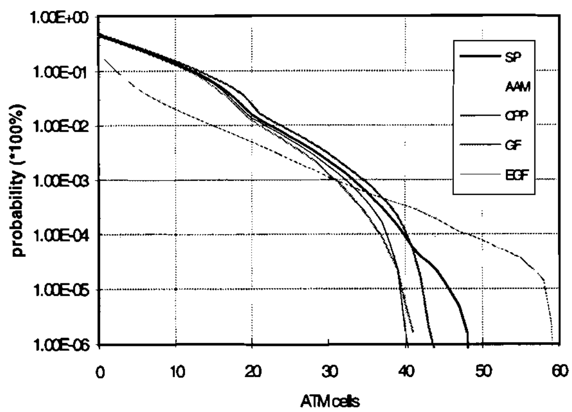


Figure 24: P(Q_size>n) Scenario 7, VBR

Simulation Results Scenario 7, UBR

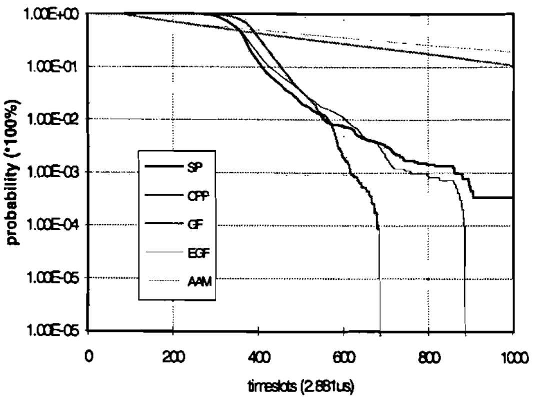


Figure 25: P(ETE>n) Scenario 7, UBR

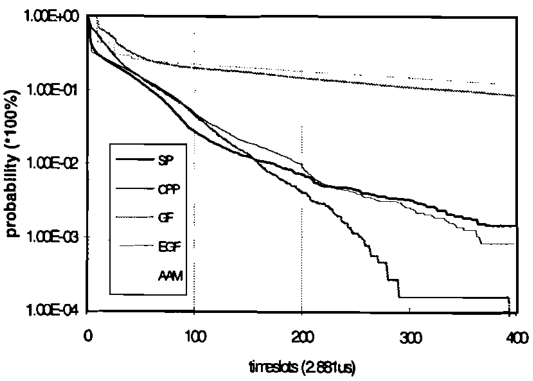


Figure 26: P(|CDV2|>n) Scenario 7, UBR

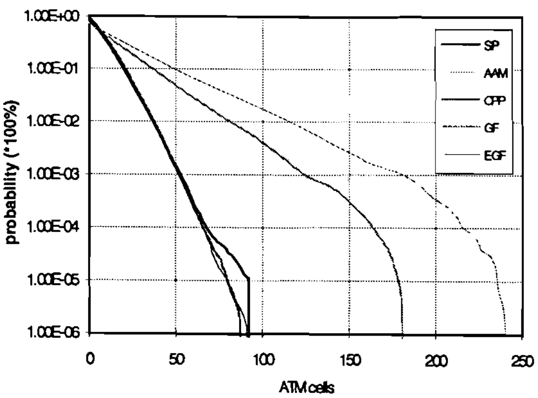


Figure 27: P(Q_size>n) Scenario 7, UBR

Simulation Results Scenario 8, CBR

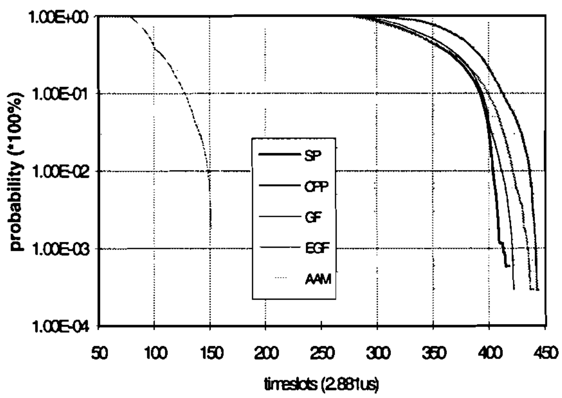


Figure 28: P(ETE>n) Scenario 8, CBR

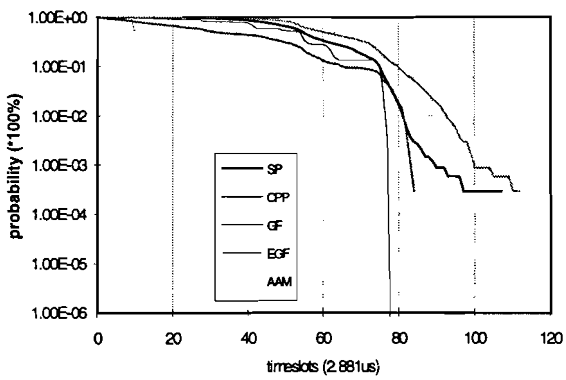


Figure 29: P(|CDV2|>n) Scenario 8, CBR

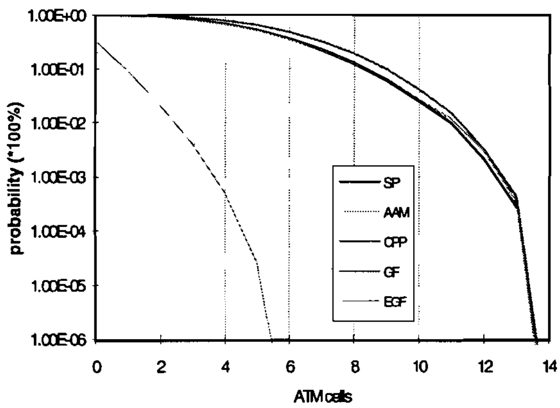


Figure 30: P(Q_size>n) Scenario 8, CBR

Simulation Results Scenario 8, VBR

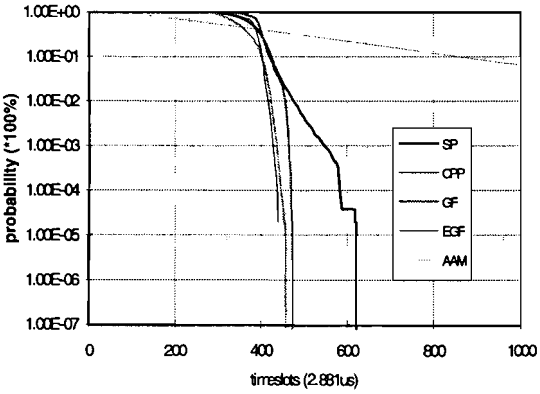


Figure 31: P(ETE>n) Scenario 8, VBR

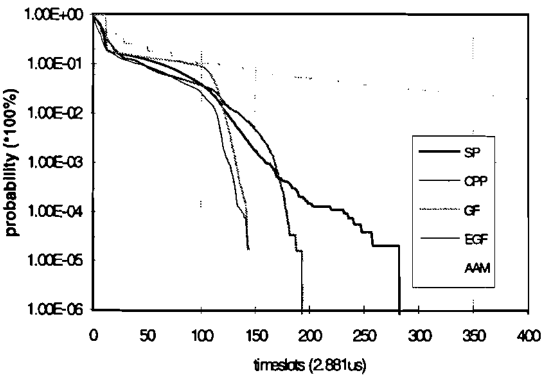


Figure 32: P(|CDV2|>n) Scenario 8, VBR

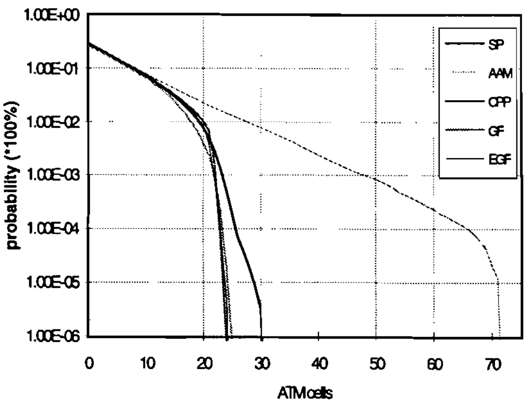


Figure 33: P(Q_size>n) Scenario 8, VBR

Simulation Results Scenario 8, UBR

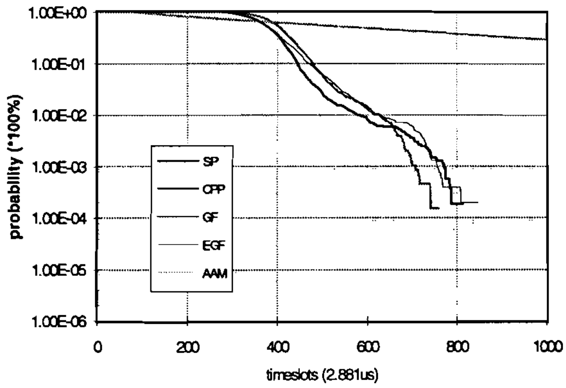


Figure 34: P(ETE>n) Scenario 8, UBR

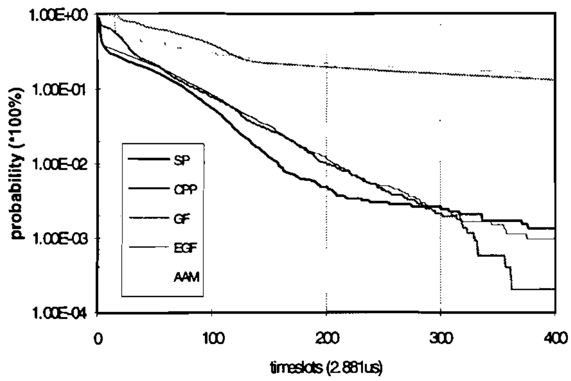


Figure 35: P(|CDV2|>n) Scenario 8, UBR

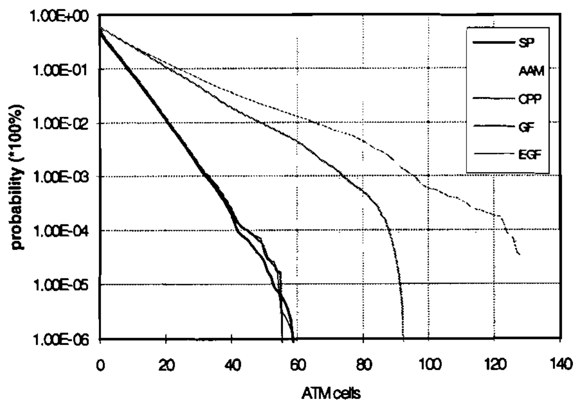


Figure 36: P(Q_size>n) Scenario 8, UBR

G3: Influence of the load

Influence of the load for a homogeneous CBR scenario

- only 64kbps CBR traffic
- 35 B-NTs
- variable number of sources/B-NT

#SRCs/B-NT		33	46	53	56	59	61	62
Load	load	50%	70%	81%	85%	90%	93%	94%
Q_max	CPP	12	16	19	20	20	21	24
	GF	12	15	18	19	19	21	23
	EGF	12	15	18	19	19	21	23
	AAM	10	13	15	13	16	14	15
	SP	12	15	18	19	19	21	23
Q_mean	CPP	4.48	6.39	7.43	7.88	8.35	8.67	8.87
	GF	3.96	5.60	6.51	6.93	7.38	7.70	7.88
	EGF	4.08	5.83	6.82	7.26	7.74	8.08	8.28
	AAM	3.55	4.19	4.41	4.59	4.86	4.73	5.19
	SP	3.96	5.60	6.51	6.93	7.38	7.70	7.88
ETE_max	CPP	492	481	507	489	497	496	496
	GF	453	457	465	471	477	484	481
	EGF	440	447	481	470	457	455	475
	AAM	595	493	417	428	439	444	486
	SP	437	442	447	448	441	454	460
ETE_min	CPP	271	276	273	275	274	277	287
	GF	267	267	267	267	267	267	267
	EGF	266	267	267	267	267	267	270
	AAM	89	81	80	91	100	95	88
	SP	267	267	267	267	267	267	267
ETE_mean	CPP	389	394	404	400	407	407	411
	GF	356	360	365	368	371	374	376
	EGF	362	366	378	373	380	380	389
	AAM	371	256	274	258	260	285	318
	SP	353	354	360	360	363	366	372
CDV2_max	CPP	44	97	62	52	52	51	51
	GF	20	30	17	21	24	23	39
	EGF	12	38	17	16	22	21	53
	AAM	209	200	173	123	156	113	333
	SP	17	23	24	20	26	38	49
CDV2_min	CPP	-160	-131	-144	-164	-146	-167	-163
	GF	-163	-159	-168	-172	-180	-162	-168
	EGF	-156	-143	-135	-156	-143	-143	-151
	AAM	0	0	0	0	0	0	0
	SP	-157	-150	-145	-157	-145	-155	-154
CDV_mean	CPP	0.08	0.07	0.07	0.06	0.09	0.05	0.10
	GF	-0.08	-0.07	-0.08	-0.08	-0.03	-0.11	-0.07
	EGF	0.04	0.05	0.08	0.05	0.11	0.04	0.09
	AAM	0.10	0.29	0.18	0.06	0.11	0.09	0.21
	SP	-0.07	-0.06	-0.05	-0.05	0.01	-0.05	0.04

Influence of the load for a homogeneous VBR scenario

- only V10M/1M/10 VBR traffic
- 7 B-NTs
- variable number of sources/B-NT

#SRCs/B-NT		10	14	15	16	17	18	19
Load		49%	68%	73%	78%	83%	88%	93%
Q_max	CPP	93	108	171	177	211	418	799
	GF	80	93	123	123	136	180	252
	EGF	79	94	123	119	138	263	642
	AAM	113	155	143	286	338	330	616
	SP	80	99	114	132	178	276	348
Q_mean	CPP	17.67	25.49	27.48	29.99	32.45	39.18	52.09
	GF	14.80	21.39	23.12	25.34	27.59	34.03	46.63
	EGF	14.80	21.39	23.12	25.34	27.59	34.03	46.63
	AAM	2.20	8.54	11.47	17.99	26.94	45.40	77.59
	SP	14.80	21.39	23.12	25.34	27.59	34.03	46.63
ETE_max	CPP	387	576	852	1113	1190	3474	5756
	GF	346	412	503	551	530	892	1288
	EGF	335	392	490	541	511	2218	4832
	AAM	864	1091	1046	2081	2396	2349	3385
	SP	369	527	568	707	772	1819	2329
ETE_min	CPP	269	270	270	270	269	272	272
	GF	266	267	267	267	267	267	267
	EGF	266	266	266	266	266	267	266
	AAM	80	80	80	80	80	80	80
	SP	266	266	266	266	266	266	266
ETE_mean	CPP	333	339	343	348	357	405	514
	GF	293	299	303	308	316	351	435
	EGF	292	297	301	306	314	351	445
	AAM	110	165	194	242	312	475	644
	SP	110	165	194	242	312	475	644
CDV2_max	CPP	68	178	498	767	769	3047	4717
	GF	46	85	189	223	211	495	577
	EGF	40	90	186	233	211	1770	4178
	AAM	598	906	748	1248	1321	2149	1430
	SP	60	180	261	292	414	1381	1223
CDV2_min	CPP	-105	-213	-419	-633	-868	-2786	-2258
	GF	-50	-103	-189	-233	-227	-388	-677
	EGF	-47	-118	-194	-249	-225	-1461	-2413
	AAM	-768	-1007	-966	-1429	-1465	-1651	-1971
	SP	-79	-226	-279	-406	-447	-1022	-1363
CDV_mean	CPP	-0.13	-0.13	-0.13	-0.13	-0.11	-0.05	0.18
	GF	-0.05	-0.05	-0.05	-0.05	-0.04	-0.01	0.13
	EGF	-0.05	-0.06	-0.06	-0.07	-0.07	-0.05	0.15
	AAM	0.11	-0.02	-0.06	-0.08	-0.10	-0.02	0.06
	SP	-0.05	-0.07	-0.08	-0.09	-0.11	-0.11	0.01

Influence of the load for a homogeneous UBR scenario

- only U25M/10k/100k/5 UBR traffic
- 32 B-NTs
- variable number of sources/B-NT

#SRCs/B-NT		23	32	37	39	41	42	43
Load	load	50%	70%	80%	85%	89%	91%	93%
Q_max	CPP	68	69	80	96	129	253	294
	GF	77	159	159	249	320	451	567
	EGF	68	69	76	96	98	102	120
	AAM	75	145	149	225	292	288	465
	SP	68	68	76	90	94	114	115
Q_mean	CPP	5.03	7.12	8.41	8.99	9.94	11.25	12.36
	GF	3.92	9.62	17.99	25.08	42.96	65.14	87.66
	EGF	4.41	6.33	7.56	8.12	9.03	10.35	11.37
	AAM	3.67	8.65	15.22	20.37	31.66	43.70	53.39
	SP	4.41	6.33	7.56	8.12	9.03	10.30	11.37
ETE_max	CPP	587	789	1708	1428	4321	7205	11058
	GF	2213	2780	4979	6433	6676	8155	15135
	EGF	542	541	677	662	1077	1176	1486
	AAM	2100	2616	4524	5947	5751	6922	9588
	SP	534	547	762	831	1219	1473	2728
ETE_min	CPP	268	269	270	272	272	273	272
	GF	80	80	80	80	80	80	80
	EGF	267	266	267	267	267	267	267
	AAM	80	80	80	80	80	80	80
	SP	267	266	266	267	267	267	268
ETE_mean	CPP	397	406	422	424	476	583	765
	GF	333	502	807	1110	1386	1642	3093
	EGF	359	371	382	386	406	437	468
	AAM	317	464	699	897	1052	1239	1791
	SP	356	365	375	379	397	426	459
CDV2_max	CPP	209	265	912	1077	3845	5434	9964
	GF	1942	2309	4828	6045	4454	4858	4900
	EGF	200	201	300	345	657	727	878
	AAM	1899	2209	4363	5575	3873	4339	4550
	SP	169	176	241	318	600	1025	2047
CDV2_min	CPP	-230	-354	-1101	-1051	-3739	-5448	-7823
	GF	-1950	-2211	-3498	-4521	-5204	-5239	-5478
	EGF	-184	-204	-238	-246	-585	-799	-924
	AAM	-1853	-2055	-3712	-4190	-4519	-5040	-5758
	SP	-184	-183	-418	-483	-655	-1043	-1553
CDV_mean	CPP	0.03	0.10	0.19	0.15	0.34	0.28	1.27
	GF	0.12	0.18	0.29	0.67	5.88	2.49	2.75
	EGF	0.51	0.54	0.56	0.50	0.56	0.83	0.77
	AAM	0.11	0.07	-0.01	0.42	4.05	0.94	0.76
	SP	0.47	0.38	0.28	0.17	0.14	0.01	0.17

G4: Influence of the multiplexing gain

- Scenario 3 is used with 12 B-NTs each carrying 10 sources. This represents a load of 83.48 %

PCR (kbps)		2048	5120	10240	20480	51200	147189
Multiplexing Gain		1.67	4.17	8.35	16.70	41.74	120.00
Q_max	CPP	41	145	164	249	215	208
	GF	38	75	111	139	160	167
	EGF	38	72	111	135	160	182
	AAM	74	219	302	436	418	495
	SP	39	88	143	202	168	182
Q_mean	CPP	19.11	19.62	20.49	21.29	22.68	23.47
	GF	16.29	16.83	17.71	18.51	19.87	20.57
	EGF	16.38	16.83	17.71	18.51	19.87	20.57
	AAM	5.05	20.11	34.03	39.13	45.74	49.89
	SP	16.29	16.83	17.71	18.51	19.87	20.57
ETE_max	CPP	438	893	1393	1697	1966	2917
	GF	405	519	576	799	814	800
	EGF	390	501	560	777	668	771
	AAM	921	2483	3246	3571	4464	6009
	SP	462	750	1035	1532	1286	1383
ETE_min	CPP	272	270	271	270	269	269
	GF	267	267	267	267	267	267
	EGF	266	267	266	266	266	266
	AAM	80	80	80	80	80	80
	SP	267	267	266	266	266	266
ETE_mean	CPP	353	360	373	384	404	415
	GF	315	323	335	347	364	375
	EGF	313	321	332	344	361	372
	AAM	153	368	537	600	759	778
	SP	313	321	333	347	364	373
CDV2_max	CPP	95	535	970	1268	1514	2543
	GF	76	191	232	451	392	482
	EGF	63	182	208	271	311	348
	AAM	364	1343	1812	2073	3023	2338
	SP	93	338	643	1090	781	982
CDV2_min	CPP	-83	-487	-952	-1386	-1135	-1614
	GF	-103	-194	-238	-451	-514	-458
	EGF	-80	-186	-250	-302	-324	-334
	AAM	-701	-1801	-2155	-2527	-2702	-2539
	SP	-151	-426	-672	-848	-960	-1054
CDV_mean	CPP	0.38	0.23	-0.08	-0.24	0.30	0.00
	GF	0.67	0.29	0.14	0.07	0.72	-0.01
	EGF	0.46	0.26	0.09	-0.03	0.25	-0.01
	AAM	0.05	0.14	0.02	-0.64	0.02	0.05
	SP	0.45	0.24	0.00	-0.21	0.06	0.01