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Performance Analysis of a Multiple Access Mechanism for ATM Access Networks

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Abstract

This paper presents an analytical model for Request Polling, which is part of many tree topology shared media ATM access network proposals. The upstream transmission of ATM cells is controlled by a centralised MAC controller in the headend. Physical layer functions demand a per-cell overhead, which can also be used to carry MAC (Media Access Control) information. In order to give previously inactive stations a chance to transmit their MAC information, additional overhead must be spent, which reduces the upstream ATM cell transport capacity. An access network using only this additional overhead to carry MAC information, is modelled in this paper by analysing a $D^{[GI]}/D/1$ model with cyclic vacations. To compute the end-to-end delay distribution, the delay distribution obtained from the $D^{[GI]}/D/1$ analysis is convolved with the distribution seen in a clocked batch gate. Results indicate the optimum amount of transport capacity to spend for Request Polling to minimise the delay quantiles.

Keywords: ATM, Access Network, Media Access Control, Batch $D^{[GI]}/D/1$, Vacation, Delay Distribution

1 Introduction

In a modern high-speed communication infrastructure, providing cost-effective access to a global broadband network is a crucial point. Shared media ATM access networks have been under study for some time [4, 5, 1]. As most studies assume a passive tree physical infrastructure, the transmission of information from the access stations to the wide area network ("upstream") needs to be coordinated by a centralised Media Access Control (MAC) protocol. The MAC protocol needs a part of the upstream bandwidth to collect information from the stations attached, which is then used for scheduling upstream cell transmissions from each station dynamically. Some of this "request information" can be transmitted in the per-cell overhead which is always necessary for physical layer functions but in order to obtain request information also from stations which have been previously inactive or which have a low cell rate, some upstream slots must be used to transport request information instead of ATM cells.

In an ATM based B-ISDN (Broadband Integrated Services Digital Network) not only the achievable throughput but also the Quality of Service (QoS) in terms of Cell Loss Ratio (CLR) and Cell Delay Variation (CDV) is an important factor. In order to limit the CDV introduced by the access network, the maximum admissible load to each part of the network must be limited. It is the aim of this paper to show how the amount of overhead spent for upstream MAC transmission can be optimised to achieve the highest possible admissible load at a given limit for the end-to-end delay quantile in an access network relying solely on Request Polling, i.e. with no MAC request information carried in the per-cell overhead.

In section 2, the system model to be analysed is defined and an example for the information flow in the system is shown. Section 3 derives the analytical models for the initial clocked batch gate, the batch arrival process at the headend MAC controller for different input traffic types and the distribution of the headend MAC queue length. The delay distribution in the headend queue is derived and the end-to-end ensemble delay distribution is approximated by a convolution. Finally, in section 4, analytical results are shown and the optimisation of the percentage of upstream slots used for MAC overhead is discussed.

2 System Model

2.1 Network Architecture

Fig. 1 shows the interconnection of stations (e.g. residential homes) to a Wide Area Network (WAN) via an access network based either on a Passive Optical Network (PON) or a Hybrid Fibre Coax (HFC) network. Data are transmitted as fixed size packets (ATM cells) in both directions. Data coming from the WAN and destined for a station are transmitted "downstream" and broadcast to every station due to the physical topology of the access network. The access station addressed by a cell filters it out of the downstream cell flow and passes it on to the equipment connected to it.

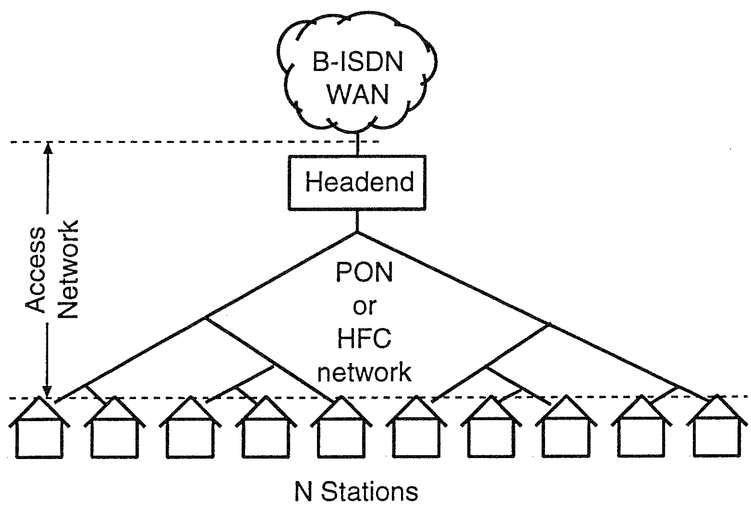

Figure 1: Network Architecture

In the upstream direction (from stations to the WAN), the cell streams coming from different stations have to be multiplexed so that collisions between data cells are avoided. This is being done by a Media Access Control (MAC) mechanism (described further in section 2.2 together with a physical layer Ranging procedure [2] which ensures that all stations are at the same virtual distance (measured in terms of the round trip time between the headend and a station) from the headend.

2.2 Information Flow

Most ATM access networks known from the literature with a topology as described above use a centralised scheduler in the headend to schedule the cell emission instants from different stations so that the resulting cell streams interleave without collisions at the optical or electrical coupling devices inside the passive access network [4, 5, 1, 3]. The scheduler issues a *permit* (also called *transmission grant* or *transmission opportunity*) addressed to the station from which a cell can be transmitted one propagation delay τ (equalised by ranging, see above) later, so that the upstream cell arrives at the headend 2τ later. In this way, each slot in the downstream permit departure process from the headend corresponds to an upstream ATM cell one round trip delay (RTD) of 2τ later.

MAC protocols which dynamically schedule permits taking into account the cell arrivals at the stations need a mechanism in addition to the permit procedure described above to propagate arrival information from the stations to the headend MAC controller [6, 7, 8]. The MAC messages containing arrival information are called *requests* and are also scheduled by the headend MAC controller, using a *request grant* to make the requests interleave with upstream ATM cells by using an ATM cell slot. A request can either code explicitly the number of cells arrived since the last request was transmitted or the current queue length of the corresponding station. In the latter case, the headend MAC controller has to compute the number of new arrivals from the request information, which can be used to increase robustness against transmission errors in request fields, as discussed in [1, section 3.6.7].

In this paper we assume that m minislots for request transmission fit into one cell slot of duration t_C. In a request polling mechanism, each of the N stations is assigned its own minislot for request transmission, i.e. it is polled once every $\frac{N}{m}$ minislots. For simplicity, we assume the ratio $\frac{N}{m}$ to be integer. Request slots are scheduled every d_P slots by the headend MAC controller.

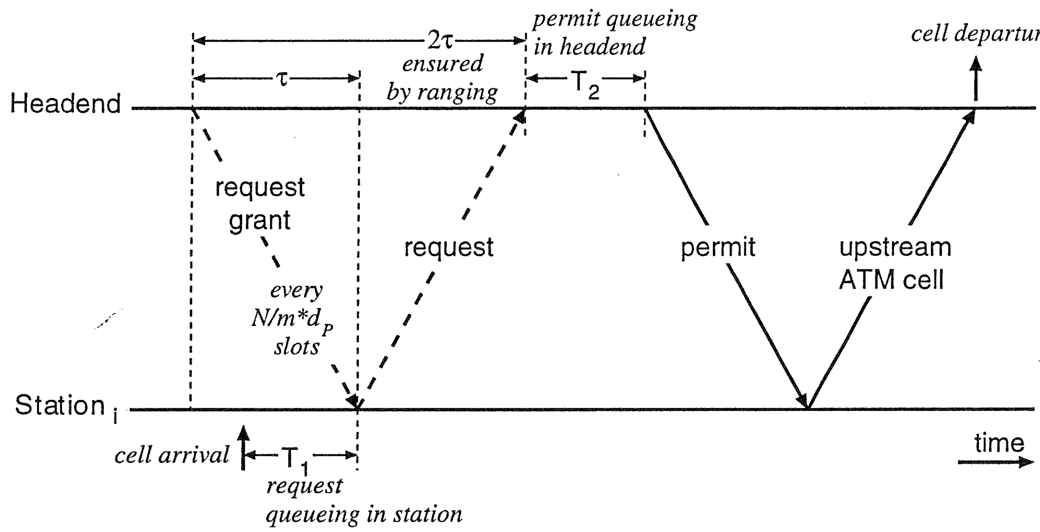

Figure 2: Information Flow – Request Polling

Fig. 2 illustrates the information flow between the headend and a station: The headend issues a request grant allowing the station to send its arrival status in a request. When the arrival information is received, the corresponding number of permits is generated and queued together with permits for other stations in the headend for transmission to the stations. One permit is transmitted per time slot (except for the slots when a request grant is scheduled). As can be seen in Fig. 2, the end-to-end delay for an ATM cell consists of a constant part of 3τ for the propagation delays of request, permit and the upstream cell itself and two variable parts, namely the time T_1 it takes until the headend can be notified of the new arrival and the time T_2 during which the permit for this cell is queued in the headend scheduler queue.

2.3 Frame Formats

Fig. 3 illustrates the slot contents. Downstream ATM cells have a permit attached, which can be addressed to a different station than the cell. Upstream ATM cells and request slots need special preambles for the physical layer to provide bit and slot synchronisation, amplitude adjustment and to support ranging. Some of these functions also require physical layer overhead to be transmitted downstream. Therefore, upstream and downstream ATM cells and request fields (RF) have a "PHY" preamble attached to them. An upstream slot used for request polling is shared between m stations in TDM mode, providing one minislot for each of a group of m stations to transmit their MAC request information.

3 Analytical Model for Request Polling

The variable delay contributions occurring in the mechanism illustrated in Fig. 2 can be modelled by the queueing model in Fig. 4, neglecting the constant contribution of 3τ, which can easily be included in the results later.

The time taken to poll stations for requests (1 out of every d_P slots) is modelled as a deterministic vacation of a deterministic server which otherwise serves the headend permit queue. During this vacation, all requests collected by the cumulative station queue are transfered as a batch arrival to the headend permit queue.

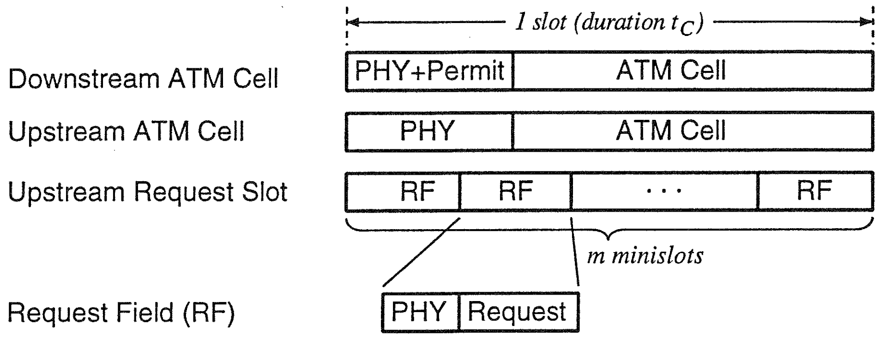

Figure 3: Frame Formats

A discrete-time analytical method is used to solve the batch queueing system modelling the headend for periodic renewal batch input processes and periodic vacations. The method is similar to the one presented in [9] but with vacations. The assumption of independence between the delays in different stages of the queueing model presented above allows an approximation of the end-to-end delay distribution through convolution of the single stage distributions. The following sections analyse the delay distributions for the waiting time in the station queue, the batch arrival process of requests at the headend station and the headend station queueing behaviour. The delay distributions derived are ensemble distributions of all sources under all possible phase relations.

3.1 Arrival Process at the Headend Queue

Requests arrive at the headend queue in periodic batches. The distribution of batch sizes depends on the cumulative number of cell arrivals at m stations during a request polling period of d_{PS} slots.

d_{PS} is obtained from the system polling period d_P and the ratio of number of stations N and number of minislots m per request slot according to Eq. (1):

$$d_{PS} = \frac{N}{m} d_P \tag{1}$$

In the case of homogeneous negative-exponential inter-arrival time distributions at all sources, the cumulative batch size R arriving in a request slot has a Poisson distribution. Eq. (2) uses the total arrival rate λ which is $\lambda = N \cdot b \cdot \lambda_0$ if λ_0 is the arrival rate of one source. The mean number of arrivals during the effective polling period d_{PS} of a group of m stations is $mb\lambda_0 \frac{N}{m} d_P t_C = Nb\lambda_0 d_P t_C = \lambda d_P t_C$

$$\mathrm{P}\{R = r\} = \frac{(\lambda d_P t_C)^r}{r!} \mathrm{e}^{-\lambda d_P t_C} \tag{2}$$

In the case of b periodic sources (D) with a period of d_S time slots at each of the N stations, the cumulative batch size distribution depends on the ratio of d_P and d_S. If we define by κ the number of source periods *completely covered* by the effective polling period d_{PS}

$$\kappa = \left\lfloor \frac{N}{m} \cdot \frac{d_P}{d_S} \right\rfloor = \left\lfloor \frac{d_{PS}}{d_S} \right\rfloor \quad , \tag{3}$$

we see that $\kappa d_S \le d_{PS} < (\kappa + 1) d_S$ This means that, obviously, there are at least κmb and at most $(\kappa+1)mb$ arrivals during one polling period. In Eqs. (3), (11) and (12), the floor function $\lfloor \alpha \rfloor$ denotes the largest integer which is less or equal to α. The distribution of the batch size is obtained as

$$\mathrm{P}\{R = r\} = \begin{cases} \binom{mb}{r - \kappa mb} \left(\frac{d_{PS} - \kappa d_S}{d_S} \right)^{r - \kappa mb} \left(\frac{(\kappa + 1) d_S - d_{PS}}{d_S} \right)^{(\kappa+1)mb - r} & \text{for } \kappa mb \le r \le (\kappa + 1) mb \\ 0 & \text{otherwise} \end{cases} \tag{4}$$

Using (4) for the batch size distribution with D traffic in the following analysis, which needs renewal input, is an approximation. The correlation between successive batches with D traffic reduces the probability of successive batches being very large, so that the resulting queue length of the headend permit queue will be over-estimated by the analysis.

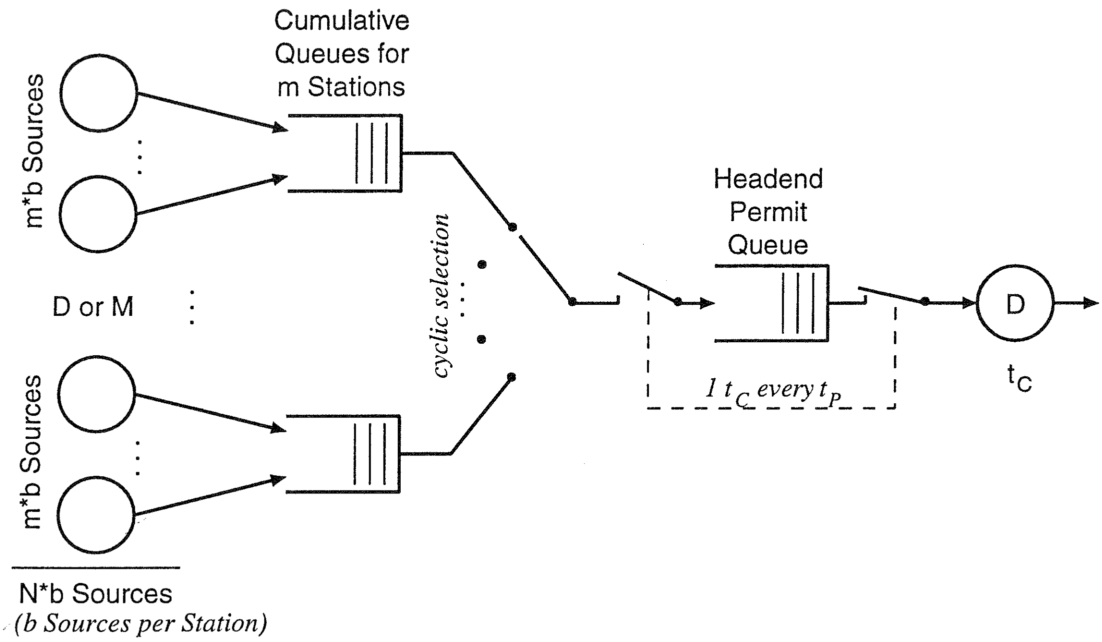

Figure 4: Model for Request Polling

3.2 Waiting Time in the Station Queue

Let T_1 be a discrete random variable for the waiting time of a request in the station queue until the first access possibility. T_1 is distributed equally between one slot and the request polling period of d_{PS} slots perceived by a single station. Therefore, the distribution for T_1 is given by:

$$\mathrm{P}\{T_1 = t\} = \begin{cases} \frac{1}{d_{PS}} & \text{for } t = t_C, 2t_C \ldots, d_{PS}t_C \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

It can be shown that this ensemble distribution of T_1 holds both for Poisson arrivals and for D sources, regardless of the source period: In the case of Poisson arrivals, the result can be obtained from renewal theory, e.g. from the analysis of an M/D/1 queue with deterministic vacations [10]. The case of D sources is in the time continuous case characterized by the source period $t_S = d_S \cdot t_C$, the polling period $t_{PS} = d_{PS}t_C$ and the minimum number of cells κ emitted by the source during a polling period. The first cell sees an access time T_1 equally distributed in $T_1 \in (t_{PS} - t_S, t_{PS}]$, the second cell sees $T_1 \in (t_{PS} - 2t_S, t_{PS} - t_S]$, and so on until the κth cell, which sees $T_1 \in (t_{PS} - \kappa t_S, t_{PS} - (\kappa - 1)t_S]$. The last cell sees $T_1 \in (0, t_{PS} - \kappa t_S]$ if it falls into the polling interval under consideration, which happens with probability $\frac{t_{PS} - \kappa t_S}{t_S}$. The ensemble distribution obviously is the equal distribution over $T_1 \in (0, t_{PS}]$.

3.3 Analysis of the Headend Queue Behaviour

Fig. 5 shows an example for the queueing process in the headend permit queue. The server can serve the queue during $d_P - 1$ time slots until it takes a vacation of one time slot to collect new requests. These requests are assumed to arrive in a batch of random size R during the vacation slot (see section 3.1).

The discrete-time analysis of this system follows the Embedded Markov Chain approach given in [9], extended to periodic vacations and batches of zero size. Let X and Y be random variables for the number of requests in the headend queue *before* and *after* a batch arrival during a vacation slot. We introduce the system capacity s here in order to get a finite number of equations from the following system of equations, but are not interested in loss figures as it is not very useful to have losses in the permit queue of an ATM access network.

If there were Y requests in the queue after a vacation, the server can serve the maximum of Y and $d_P - 1$ requests until the next vacation. In steady state, therefore, the distribution of X can be

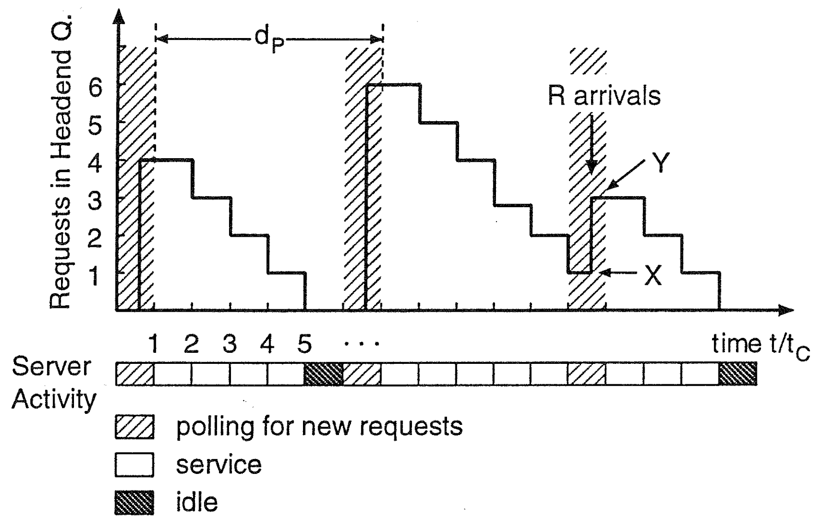

Figure 5: Example for Headend System Occupation Process

given as a function of the distribution of Y (6) and vice versa, linked by the number of arrivals in the batch in between (7):

$$\mathrm{P}\{X=x\} \quad = \quad \begin{cases} \sum_{k=0}^{d_P-1} \mathrm{P}\{Y=k\} & \text{for } x=0 \\ \mathrm{P}\{Y=x+d_P-1\} & \text{for } x=1,2,\ldots,s+1-d_P \\ 0 & \text{for } x>s+1-d_P \end{cases} \tag{6}$$

$$\mathrm{P}\{Y=y\} \quad = \quad \begin{cases} \sum_{k=0}^{y} \mathrm{P}\{X=k\}\mathrm{P}\{R=y-k\} & \text{for } y=0,1,\ldots,s-1 \\ \sum_{k=0}^{s+1-d_p} \mathrm{P}\{X=k\} \cdot \sum_{r=s-k}^{\infty} \mathrm{P}\{R=r\} & \text{for } y=s \\ 0 & \text{for } y>s \end{cases} \tag{7}$$

Substituting (7) in (6), a system of $s-d_p+2$ linear equations is obtained:

$$\mathrm{P}\{X=x\} = \begin{cases} \sum_{k=0}^{d_P-1} \sum_{j=0}^{k} \mathrm{P}\{X=j\}\mathrm{P}\{R=k-j\} & \text{for } x=0 \\ \sum_{k=0}^{x+d_P-1} \mathrm{P}\{X=k\}\mathrm{P}\{R=x+d_P-1-k\} & \text{for } x=1,2,\ldots,s-d_P \\ \sum_{j=0}^{s-d_P+1} \mathrm{P}\{X=k\} \sum_{j=s-k}^{\infty} \mathrm{P}\{R=j\} & \text{for } x=s-d_P+1 \\ 0 & \text{for } x>s-d_P+1 \end{cases} \tag{8}$$

A solution for the distribution of the pre-vacation state X can be obtained by iterating the equations (8) until convergence is reached.

3.4 Delay Analysis

To find the distribution of the delay T_2 experienced by arbitrary requests in the headend queue, we introduce the random variable E denoting the entry position of an arbitrary new request entering the headend queue. Assuming a fair service discipline, this entry position is distributed equally between $X+1$ (the first free place in the system) and $X+R$ (the last place reached by the corresponding batch) or s (the last place in the system). The probability for an arriving request to enter the system and be in a batch of size $R=r$ is $\frac{r}{\mathrm{E}[R]} \cdot \mathrm{P}\{R=r\}$, so that the distribution of E is given by (9) using (10) for the expectation of the number of requests entering the queue when there are X requests in the queue before the batch arrives, $\{R'|X = x\}$:

$$\begin{aligned} \mathrm{P}\{E=e\} &= \sum_{x=0}^{e-1} \frac{\mathrm{P}\{X=x\}}{\mathrm{E}\left[R'|X=x\right]} \cdot \sum_{r=e-x}^{\infty} \mathrm{P}\{R=r\} \\ &= \sum_{x=0}^{e-1} \frac{\mathrm{P}\{X=x\}}{\mathrm{E}\left[R'|X=x\right]} \cdot \mathrm{P}\{R > e-x-1\} \qquad (9) \\ \mathrm{E}\left[R'|X=x\right] &= \sum_{r=1}^{s-x} r \cdot \mathrm{P}\{R=r\} + (s-x)\mathrm{P}\{R > s-x\} \qquad (10) \end{aligned}$$

Note that (9) gives the distribution of entry position only for requests which enter the permit queue and are not blocked. Other requests obviously never experience a valid end-to-end delay and are therefore not considered any further.

In Eq. (9) the distribution of the queue state at a batch arrival instant is taken to be independent of the size of the arriving batch, which is the same as assuming independence between successive batch sizes. For the case of D sources, this can only be regarded as an approximation.

Considering the vacations that the server takes every d_P slots, the delay T_2 can be computed explicitly as a function of the entry position of a request as given in Eq. (11). Note that delays which are integer multiples of d_P can never occur.

$$\mathrm{P}\{T_2 = kt_C\} = \begin{cases} 0 & \text{for } k \in \{0, d_P, 2d_P, 3d_P, \ldots\} \\ \mathrm{P}\{E = k - \left\lfloor \frac{k}{d_P} \right\rfloor\} & \text{for } k \neq d_P \cdot \left\lfloor \frac{k}{d_P} \right\rfloor \end{cases} \qquad (11)$$

The complementary distribution of T_2 is correspondingly given by Eq. (12):

$$\mathrm{P}\{T_2 > kt_C\} = 1 - \sum_{e=1}^{k - \left\lfloor \frac{k}{d_P} \right\rfloor} \mathrm{P}\{E = e\} \qquad (12)$$

Neglecting the dependence of T_1 and T_2 (see above), the total variable part of the end-to-end delay of cells in the access network can be approximated by a convolution of the distributions of T_1 and T_2. Eq. (13) gives the complementary distribution of $T = T_1 + T_2$:

$$\mathrm{P}\{T > kt_C\} = \begin{cases} 1 & \text{for } k \leq 0 \\ \sum_{j=0}^{k-1} \frac{1}{d_{PS}} \mathrm{P}\{T_2 > jt_C\} + \frac{d_{PS} - k}{d_{PS}} & \text{for } k = 1, 2, \ldots, d_{PS} \\ \sum_{j=k-d_{PS}}^{k-1} \frac{1}{d_{PS}} \mathrm{P}\{T_2 > jt_C\} & \text{for } k > d_{PS} \end{cases} \qquad (13)$$

4 Results

All results in this section have been obtained by iterating the system of equations (8) until the values had sufficiently stabilised. The headend queue size was set to s=200 to get a loss probability of around 10^{-14} because loss results were not aimed for. The constant contribution of 3τ to the end-to-end delay is not included in the figures.

Figures 6 and 7 show the distribution of the entry position E of requests into the headend queue (dashed lines), the delay T_2 experienced by requests in the headend queue and the end-to-end delay $T = T_1 + T_2$ for M or D traffic from $N = 32$ stations with b=1 source each. A request slot is split into $m = 8$ minislots, so that a single station is polled for requests every $N/m = 4$ request slots. The cumulative offered traffic is 80% of the system capacity and every 7^{th} slot is a request slot, i.e. the system capacity spent for request polling is $\rho_P = 1/7 \approx 14.3\%$.

Fig. 6 shows the case of one D source at each station (source period $d_S = 40$ slots) and Fig. 7 shows the same for one M source (negative exponential inter-arrival time distribution with a mean of 40 slots) at each station. The effect of the periodic server vacations described by (11) causes

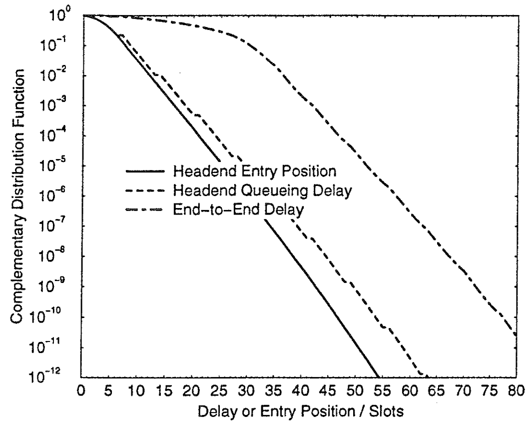

Figure 6: Headend Queueing – D Sources

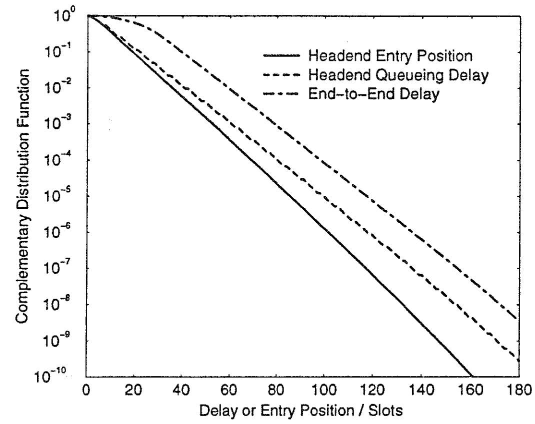

Figure 7: Headend Queueing – M Sources

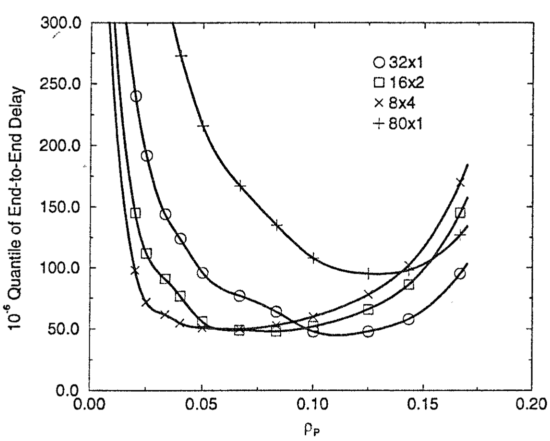

Figure 8: Delay Quantile – D Sources

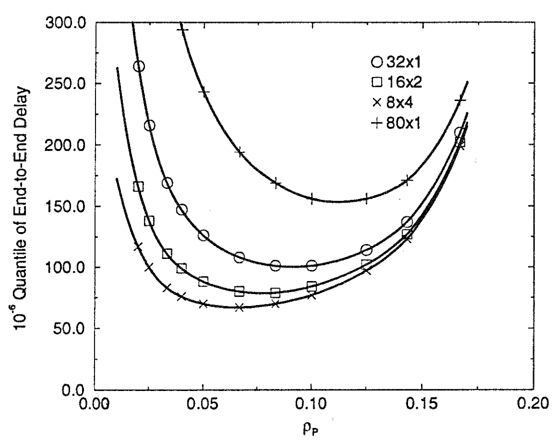

Figure 9: Delay Quantile – M Sources

the constant parts of the complementary distribution function (cdf) of T_2 and consequently a slower decrease than the cdf of E and $T_1 + T_2$.

In Fig. 8 and 9 the 10^{-6} quantile of the end-to-end delay cdf, $(t_q : \mathrm{P}\{T > t_q\} = 10^{-6})$ is plotted against the percentage of number of upstream slots spent for request polling, ρ_P. Note that only integer values of d_P and therefore only discrete values of $\rho_P = \frac{1}{d_P}$, which are marked with symbols, are possible. The cumulative offered traffic load is again 80% and the number of minislots per request slot is $m = 8$. There are four scenarios depicted of which three have the same total number of sources ($Nb = 32$) but distributed differently among the stations in the following combinations: $N = 32$ and $b = 1$; $N = 16$ and $b = 2$; $N = 8$ and $b = 4$. In addition, the case $N = 80$ and $b = 1$ with a total of 80 sources is plotted. Note that $\kappa > 0$ for $\rho_P < 0.1$ and $N = 32$, for $\rho_P < 0.05$ and $N = 16$ or $\rho_P < 0.025$ and $N = 8$. In these cases more than one cell arrives from each source during a request polling interval.

It can be clearly seen that the number of stations and thus the number of request polling cycles $\frac{N}{m}$ has a significant influence on the performance of the system. An interesting effect can be observed for a large number of stations with D traffic: The minimum of the delay quantile is found when more bandwidth is spent for request polling than for a smaller number of stations. This can again be explained by the number of cycles a station has to wait until it can transmit a request.

An optimum of ρ_P is found between 5 and 15% for an offered load of $\rho_{in} = 80\%$, depending on the number of stations to be polled.

5 Conclusions

A model for a batch $D^{[GI]}/D/1$ system with periodic vacations was presented. It allows to assess the performance of request polling, an important MAC mechanism in the upstream direction of ATM access networks. Results show that an optimum request polling period can be found, which depends on the number of stations to be polled and the utilisation to be achieved.

Further generalisations of the queueing model in section 3.3 could include the case of non-deterministic but limited distance between batches. The combined end-to-end delay analysis could be refined by taking into account the correlation between successive batches and between T_1 and T_2 and extended to additional request mechanisms like coupling requests to upstream ATM cells, which generates an additional arrival stream at the headend queue without server vacations.

References

[1] U. Killat (Ed.), *Access to B-ISDN via PONs - ATM Communication in Practice*, Wiley/Teubner 1996

[2] P. van Heijningen, T. Mosch, A. van Ooyen, L. d'Ascoli, K. de Blok, P. Solina, "Out-of-Band Ranging Method for ATM over PON Access Systems." *Proceedings of ECOC'94*, Florence, Italy, 1994

[3] The ATM Forum, "The UPSTREAMS Protocol for HFC Networks, Revision 1.", ATM Forum/IEEE Document 95-1435R1, January 1996

[4] J.W. Ballance, R.F. Lee, P.H. Rogers, M.F. Halls, "A B-ISDN Local Distribution System based on a Passive Optical Network." *Proceedings of GLOBECOM'90*, 1990, pp. 305.4.1–305.4.5

[5] M. Glade, H. Keller, "Novel Algorithm for Time Division Multiple Access in Broadband ISDN Passive Optical Networks." *International Journal of Digital and Analog Communication Systems* Vol. 6 (1993) pp. 55–62

[6] O. Casals, J. García, C. Blondia, "A Medium Access Control Protocol for an ATM Access Network." *Proceedings of the Fifth International Conference on Data Communication Systems and their Performance, High Speed Networks*, Eds. H. Perros, Y. Viniotis, North Carolina, USA, Oct. 1993

[7] J.D. Angelopoulos, I.S. Venieris, G.I. Stassinopoulos, "Dynamic Bandwidth Distribution for APONs with Emphasis on Low Cell Jitter." *Proceedings of the 11th Annual Conference EFOC&N*, The Hague, Netherlands, June/July 1993, pp. 86–90

[8] J.D. Angelopoulos, I.S. Venieris, "A Distributed FIFO Spacer/Multiplexer for Access to Tree APONs." *Proceedings of Supercomm/ICC*, New Orleans, Louisiana, May 1994

[9] D. Kouvatsos, R. Fretwell, "Closed Form Performance Distributions of a Discrete Time $GI^G/D/1/N$ Queue with Correlated Traffic." *Data Communications and their Performance: Proceedings of the Sixth IFIP WG6.3 Conference on Performance of Computer Networks*, Istanbul, Turkey, 1995, pp. 141–161

[10] H. Takagi, *Queueing Analysis: A Foundation of Performance Evaluation, Vol. 1: Vacation and Priority Systems, Part 1, Chapter 2.* Elsevier Science Publishers B.V., Amsterdam, The Netherlands, 1991.