The change of traffic characteristics in ATM networks 2[*]

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September 6, 1995

1 Introduction

In ATM networks connection acceptance control (CAC), i.e. the procedure that decides whether or not a new connection can be accepted, is an important issue. On one hand it has to achieve an efficient use of bandwidth, while on the other hand the required quality of service of each connection has to be guaranteed. CAC is based on a set of traffic parameters that (partly) characterizes a newly arriving cell stream. However, these traffic characteristics may change when the cell stream flows through the network, due to interference with other cell streams in the network nodes. This may lead to unacceptable cell loss rates, not foreseen by the CAC procedure. The change of traffic characteristics due to interference also plays a role in interconnected networks, where cell streams coming out of one network are offered to another network. For a proper choice of the policing/traffic parameters in the second network it is important to understand how cell streams change when they pass a number of switching nodes. The aim of the present study is to get more insight into this phenomenon by analysing a discrete-time tandem queueing model. In Section 2 we will describe the model. In Section 3 and 4 this model is analysed under heavy and light traffic conditions leading to two different approximations. Finally we discuss some numerical results in Section 5.

2 Model description

We consider a discrete-time queueing model consisting of K queues in series, each with unit (deterministic) service time. There are two types of arrivals to the system. First, there is

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[*]Extended abstract appeared in proceedings B-ISDN Teletraffic Modelling Symposium, p94-98, Alcatell Bell, Antwerp, February 17, 1995.

a main cell arrival stream that enters the system at the first queue and passes, successively, all the queues. Second, in each queue there are interfering arrival streams that, after passing the single queue, immediately leave the system. The superposition of the interfering streams at a particular queue will be considered as one single batch Bernoulli arrival process. This means that the numbers of arrivals in successive slots are independent, identically distributed random variables with an arbitrary distribution function. If cells of the main stream and cells of the interfering stream arrive at the same time at a certain queue, we assume that cells of the main stream have priority over cells of the interfering stream.

In the sequel, the sequence $X_1^k, X_2^k, \ldots$ denotes the interdeparture times of the k-th queue of cells of the main stream. Here, for example, $X_n^k = j$ means that there are $j - 1$ empty slots between the n-th and the $(n + 1)$-st departure of cells of the main stream at the k-th queue. For convenience, we also introduce the notation $X_1^0, X_2^0 \ldots$ to denote the interarrival times of cells of the main stream at the first queue. If we assume a CBR main stream, we have $P(X_n^0 = c) = 1$, where $1/c$ equals the cell rate of the stream.

3 Heavy traffic analysis

In general the output process from the k-th queue of cells of the main stream can be described as a function of the input process into the k-th queue of cells of the main stream and the superposition of the interfering streams at the k-th queue. However the exact description is not very tractable. The number of empty slots between two successive departures of cells of the main stream consists of two parts:

- number of empty slots caused by departures of cells of interfering streams.

- number of empty slots caused by emptiness of the queue.

In particular, the empty slots caused by emptiness of the queue are difficult to deal with. They cause dependencies between successive interdeparture times.

In the situation that all queues are highly loaded, empty slots between two successive departures of cells of the main stream are mainly caused by departures from interfering cells. In the most extreme case that the load of the queues equals one, (almost) all empty slots are caused by departures from interfering cells. In this case the analysis of the output process of the main stream becomes tractable. Therefore, in the rest of this section we make the following assumption.

Heavy traffic assumption
All empty slots between two successive departures of cells of the main stream are caused by departures from interfering cells.

Under this heavy traffic assumption the number of empty slots between the n-th and $(n + 1)$-st departure from the k-th queue is given by the number of interfering cells arriving between the n-th and $(n + 1)$-st arrival of the main stream at the k-th queue, i.e.

$$X_n^k = 1 + \sum_{i=1}^{X_n^{k-1}} Y_{i,k}, \tag{1}$$

2

where the $Y_{i,k}$'s are i.i.d. random variables representing the number of interfering cells arriving during the i-th slot between the n-th and $(n + 1)$-st arrival of the main stream at the k-th queue.

This result shows that (under the heavy traffic assumption and for fixed n) the sequence $X_n^0, \ldots, X_n^K$ is a discrete-time Markov chain. More specific, when the superpositions of interfering streams at all the different queues are identical, the process $\{X_n^k, \ k = 0, \ldots, K\}$ as defined in (1) is a branching process with immigration. The general theory for branching processes with immigration gives us an explicit result for the interdeparture time distribution of cells of the main stream from the k-th queue.

It can be shown that under the heavy traffic assumption, even when the interarrival times of cells of the main stream at the first queue are dependent, the interdeparture times of cells of the main stream become asymptotically independent when the number of queues tends to infinity.

4 Light traffic analysis

Constant bit rate audio and voice require typically bandwidths of 2 MBit/s and 64 Kbit/s. So, assuming 155 Mbit/s ATM links, the interarrival time of successive cells when entering the ATM network is about 78 and 2422 respectively. Because of this relatively large time between successive cells we define the following light traffic assumption.

Light traffic assumption
Cells of the main stream see the queues independent of all the previous cells of the main stream. Upon arrival at a queue they see a queue with only arrivals of the interfering streams.

It is clear that this assumption will only be reasonable if the load at every queue is not too large and the fraction of this load offered by the main stream is small. If the light traffic assumption is satisfied then the waiting time distribution of a cell of the main stream at a particular queue equals the steady state queue length distribution of a $BBP \mid D \mid 1$ queue.

In order to determine the interdeparture time distribution of an arbitrary queue of the tandem queue model we shall derive a relation between the interdeparture time distribution of two successive queues. Let W_n^k be the delay of the n-th cell at the k-th queue. Then it takes $W_n^k + 1$ slots for the n-th cell to leave the k-th queue after it arrived. Furthermore the $(n + 1)$-st cell leaves the k-th queue $X_n^{k-1} + W_{n+1}^k + 1$ slots after the time when the n-th cell arrived at the system. Therefore, under the light traffic assumption, the interdeparture time between the n-th and $(n + 1)$-st cell at the k-th queue is given by

$$X_n^k = X_n^{k-1} + W_{n+1}^k - W_n^k \ . \tag{2}$$

Let $\{x_n^k(i)\}$ denote the pdf of X_n^k. The light traffic assumption implies that W_n^k and W_{n+1}^k are i.i.d. and both independent of X_n^{k-1}. If the interarrival distribution of the cells of the main stream at the first queue is known, we can compute $\{x_n^1(i)\}$ by first determining the waiting time distribution at this queue and finally by convolution of X_n^0, W_{n+1}^1 and W_n^1 using equation (2). By recursively using (2) it is clear how to compute $\{x_n^K(i)\}$. Notice that the interfering streams at every switch do not have to be identically distributed.

The next two theorems follow from (2) and the light traffic assumption.

3

Theorem 1 *Under the light traffic assumption the variance of the interdeparture time distribution at the K-th queue satisfies*

$$var(X_n^K) = var(X_n^0) + 2 \sum_{k=1}^{K} var(W^k) \, ,$$

where W^k denotes the delay of an arbitrary cell of the main stream at the k-th queue.

Theorem 2 *Under the light traffic assumption the covariance of successive interdepartures times at the K-th queue satisfies*

$$cov(X_n^K, X_{n+1}^K) = cov(X_n^0, X_{n+1}^0) - \sum_{k=1}^{K} var(W^k) \, ,$$

where W^k denotes the delay of an arbitrary cell of the main stream at the k-th switch.

In particular when the main stream at the first queue equals a CBR stream it follows from Theorem 1 and 2 that, under the light traffic assumption, the correlation coefficient of two successive interdeparture times at an arbitrary queue equals $-\frac{1}{2}$.

5   Numerical Results

In this section we give a summary of the main numerical results. In all the numerical examples we assume that the interfering streams at each queue are a superposition of N independent streams, which all follow a geometric arrival process with the same probability p of having an arrival in a slot. Hence these interfering streams are a batch Bernoulli process with binomial distributed batches. We compare the output process under the heavy and light traffic assumption with the output process obtained by simulation. Successively, we focus on the interdeparture time distribution and the correlation of successive interdeparture times.

An important distinction between the two analyses is the behaviour of the variance of the interdeparture times when the number of queues tends to infinity. In the light traffic case, this variance is unbounded while in the heavy traffic case it remains bounded. Simulation reveals that the variance of the interdeparture time distribution also is bounded when the number of queues tends to infinity. It turns out that the heavy traffic approach approximates the interdeparture time distribution of the main stream well, when the load on every switch is large (≥ 0.9). However, the light traffic approach provides a good approximation for the interdeparture time distribution of the main stream when both the load on every switch (< 0.8) and the number of switches (≤ 25) are not too large.

Another difference between the two approaches is the behaviour of the correlation between successive interdeparture times. Under the light traffic assumption this correlation equals $-1/2$, while under the heavy traffic assumption the correlation tends to 0. Simulation shows that in all our experiments the correlation lies between $-1/2$ and 0. More specifically, when the load is small the correlation is near $-1/2$, and when the load is high the correlation is near 0. Furthermore, the correlation becomes less negative if the number of passed queues increases. We expect that when the number of passed queues tends to infinity the correlation converges to a non-positive limiting value.