Servicing Bursty Sources Efficiently via a Fast Circuit Switched System

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ABSTRACT

Asynchronous Transfer Mode (ATM) is considered a general solution for broadband networks providing a wide range of quality guarantees with optimal usage of network resources. However, the generality usually implies drawbacks in special circumstances. In the case of ATM this is obvious when strict delay and delay variance requirements should be maintained for real time applications. This difficulty origins from the packet switched nature of ATM. Circuit switching offers a simple and efficient solution for these applications but it usually does not support Variable Bit Rate (VBR) and Unspecified Bit Rate (UBR) applications. These traffic classes are suitable for the packet switched networks like ATM. In this paper we propose two solutions by introducing VBR and UBR classes in a fast circuit switched network. The approaches allow the usage of statistical multiplexing on a fast circuit switched system. A performance evaluation study with the comparison of proposed solutions is also presented.

1. Introduction

Both telecommunication industry and the internet community progress towards providing different kind of services and different service quality types for their users. The evolution of ATM (Asynchronous Transfer Mode) technology [13], TCP/IP protocol suite [17] and existing packet switched networks (Ethernet, FDDI) [1,6,8,9,13] prove that the demand of scalibility both in services and QoS (Quality of Service) is a real issue. Future networks have to support applications with connectionless and connection oriented operation, with real-time and delay-tolerant needs, and with different bandwidth requirements.

ATM is the most adequate answer to these demands so far. It is designed to fulfil all the above requirements. Delay and delay variation sensitive applications can use CBR (Constant Bit Rate) or rt-VBR (real-time Variable Bit Rate) service classes. ATM provides VBR service class for applications generating varying traffic. Applications with loose delay needs can use UBR (Unspecified Bit Rate) or ABR (Available Bit Rate) services [3]. ATM service classes provide advantages for both users and network operators. Users don't have to pay for features they don't need (e.g.: low delay or peak bandwidth reserved for the whole connection). Operators can optimize the usage of network resources (e.g.: bandwidth, buffers) due to statistical multiplexing.

A general solution, however, always has drawbacks in special circumtances. ATM is a fast packet switched technology thus it is difficult to keep the tight delay and delay variance parameters of real-time applications. This effect is more relevant if there are more switches and adaptation between the parties of the communication.

This paper presents different approaches to the same problem. We investigated the possibilities of using service classes in *fast circuit switched networks*. Switches in a circuit switched network guarantee low, deterministic delay and low delay variance for CBR connections. Circuit switched networks, however, traditionally don't support variable bitrate channels.

We provide a solution for statistical multiplexing in a TDM channel between a source generating VBR traffic with low delay needs and sources with flexible bitrate needs using UBR service classes.

The idea is demonstrated on a specific networking technology. Two solutions are discussed in detail. In the first case one TDM channel is subdivided to many TDM subchannels and UBR sources are multiplexed via TDM (Time Division Multiplexing). In the other method data sent by different UBR sources into a TDM channels is separated by their packet header so it can be regarded as packet switching in TDM.

A performance evaluation of the proposed solutions concerning the mean queue length and mean waiting time of the VBR and UBR sources at a given network node is presented. A comparison study of the solutions is also given in the paper.

The paper is structured as follows. In Section 2 we introduce the fast circuit switched networking technology, which is the basis of our investigations. In Section 3 we investigate the mean values of the properties of the circuit switched system where the whole channel is used by a single source. In Section 4 we describe the channel sharing methods and provide the analysis and comparison of the solutions. In Section 5 we conclude the paper.

2. The Investigated Fast Circuit Switched Network

We have chosen DTM (Dynamic Synchronous Transfer Mode) as the subject of our investigations. DTM is a new broadband network architecture developed at the Royal Institute of Technology in Stockholm and proposed as a next generation networking concept of high speed networks [4]. It is a fast circuit switched technology. The operation is based on multirate and unicast or broadcast channels with short setup delay. It is designed for unidirectional medium with multiple access. The total medium capacity is shared between all connected nodes. Previous proposals and implementations are based on dual-bus topology. The architecture can be extended to include a large number of connected buses using switching nodes. Performance analysis of fully connected mesh topology was also investigated in [4].

The most important elements of DTM networks are nodes and hosts. *Nodes* are networking devices connected to unidirectional buses, set in both directions. *Hosts* can be, for example, end-devices or higher level connectivity devices (e.g.: IP router). They are connected to the DTM networks via nodes. Host-host communication is based on the assistance of nodes. Nodes are responsible for resource allocation, connection establishment and release along the bus.

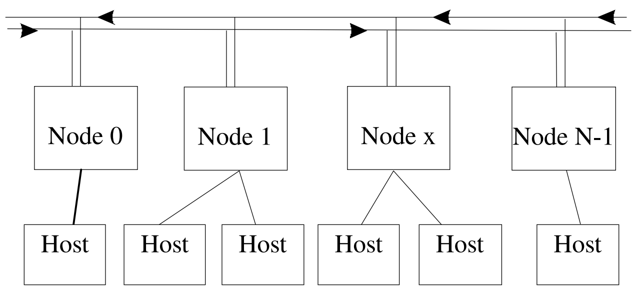

Figure 1 : Structure of a DTM bus

Buses can operate at different bit-rates so as with the existing computer and telecommunication networks, a hierarchical structure spanning from the local networks to the wide area can be constructed.

Communication channels on the physically shared medium are realized by time division multiplexing scheme. The total capacity of the bus is divided into cycles of 125 microseconds, which are further divided into slots. A slot consists of a 64 bit data-word and some additional management bits. The sequence of slots at the same position in successive cycles is called a DTM channel.

There are two types of slots (and DTM channels): data and static slots.

Data slots are used for data transfer. The bit-rate of a DTM connection is specified by the number of data channels it occupies in a cycle. Data channels are assigned to nodes can be either free or used by a connection. Each channel has exactly one owner at a time. If a node owns a channel then it has full control on its use: it can setup a connection in it, release a connection using the channel, and pass the channel ownership to another node.

At system startup, data channels are allocated to the nodes. The owners of the channels change dynamically during the operation. Nodes can ask for channels from others if they have not enough free data channels to serve a new request. This procedure is called channel reallocation.

The other type of slots, called static slots, is used for broadcast control channels between nodes. Nodes send control information in their static slots and listen to all the other static channels to receive control information.

DTM uses distributed channel reallocation algorithms [5]. At the reception of a connection setup request from the host, the node first checks its local pool to see if it has enough channels to satisfy the request. If so, it immediately sends a connection establishment message to the destination node. Otherwise, the node first has to request more channels from the other nodes on the bus. It sends a request for data slots in its static slot. A node that receives this request and has unused data channels, may offer some of its unused channels to the sender's node.

The idea of servicing applications with different requirements and sources with different characteristics was addressed in [4]. Burst switching has been proposed [2] to gain a better bandwidth utilization. If we suppose that the sources behave accordingly to the train model [12], higher throughput can be achieved using burst switching. However, the application area of the proposed solution is limited to non real-time applications. That is, there is no QoS guarantee for the whole call because different bursts have different setup times and any burst can be blocked within the call.

We discuss a solution where the burst switching approach is not used. As a first step let us see the mean parameters of a VBR source with real-time requirements when it uses a full (CBR) DTM channel. We supposed that the DTM channel uses one slot in each cycle, but it is not a constraint of the system.

3. Servicing VBR Sources

In the following networking scenario we examine the average queue length and waiting time for a VBR source that generates traffic in a one-slot DTM channel.

For a given VBR source served by a channel, the queue length has the form of

$$X_{k+1} = (X_k - 1)^+ + Y_{k+1} = X_k - I_{\{X_k \geq 1\}} + Y_{k+1} \qquad (1)$$

where k is the cycle number, Y_k is the number of 64 bit data-words arrived in cycle k, and X_k is the queue length in cycle k. We model the VBR traffic Y_k by batch Bernoulli sources with general batch size distribution B [15]. This model allows us to capture the behavior of both bursty and smooth VBR sources by setting B to be binomial (for smooth VBR traffic) or to be Pascal (for bursty VBR traffic) [15].

$\{Y_k\}$ is the sequence of independent and identically distributed random variables, thereby the sequences of $\{X_k\}$ form a Markovian chain. If $E\{Y\} < 1$ then $\{X_k\}$ is stable.

The average queue length in this scenario (see [10,14]) is

$$E\{X\} = \frac{E\{Y\}(1-2E\{Y\}) + E\{Y^2\}}{2(1-E\{Y\})} = \frac{E\{Y\}}{2} + \frac{\mathrm{var}\{Y\}}{2(1-E\{Y\})} \quad (2)$$

The average waiting time of an arriving 64-bit word (see [10,14]) is

$$E\{D\} = \frac{1}{2} + \frac{\mathrm{var}\{Y\}}{2E\{Y\}(1-E\{Y\})} = \frac{1}{2} + \frac{k}{2(1-\rho_{VBR})} \text{ (cycles)} \quad (3)$$

where $\rho_{VBR} = E\{Y\}$ is the load generated by the VBR source and the peakedness is $k = \frac{\mathrm{var}\{Y\}}{E\{Y\}}$

If the source is bursty and delay sensitive (later referred to as VBR source) then we have to limit its load in order to keep the delay below a certain level. Consider the following example: the VBR source has an extremely large peakedness (k=100) value, and the average queuing delay must be below 10 ms, therefore the maximum load limit for the source is 0.375. This means that the utilization of the DTM channel is very low. We can increase it by adding sources with flexible bandwidth and delay demands to the same DTM channel. Flexible sources are referred to as UBR sources in the following pages.

4. Servicing UBR and VBR Sources in a DTM Channel

Sources can use the DTM channel when it is not used by the VBR source. We examined solutions where more UBR sources are multiplexed with a single VBR source in order to increase the utilization of the DTM channel while the quality of the VBR connection is not degraded.

However, we face two problems:

1. How can we differentiate between the connections?
2. How fast can we switch back to the VBR source?

We have two answers to the first question. They will be presented in section 4.1 and 4.2.

The second question is relevant because switching must be performed very fast in order to keep the delay variation of the VBR channel low. That is why all the VBR and UBR sources must use the same DTM channel during the whole connection. If we assigned different slots to every burst of the connection then switching could take several milliseconds. That is, if the node doesn't have free data channels when a burst arrives from the VBR source after an idle period it must ask other nodes for them. It is different for every burst so it effects the delay variance of the VBR source. Consequently, we suppose that the sources are connected to the same DTM channel.

The management of sources using the DTM channel is easier and the switching time between connections is shorter if the sources are connected to the same node. The receiver hosts can reside at different nodes. But in this case a node has to listen to a common channel and to filter the data of its hosts. The topology restriction is shown in Figure 2.

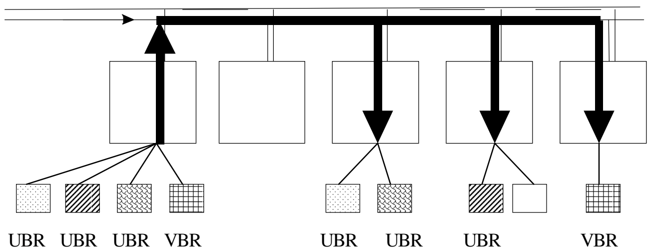

Figure 2 : Sources of a DTM channel are connected to the same node

A DTM channel shared between the sources can be implemented in many ways. We examined two solutions. We supposed in both cases that the capacity of the DTM channel is enough to serve one VBR and several UBR channels.

4.1 Circuit Switched Solution

In the circuit switched solution the DTM channel is further divided into subchannels using time division multiplexing. One DTM channel is divided into M subchannels as it is shown in Figure 3.

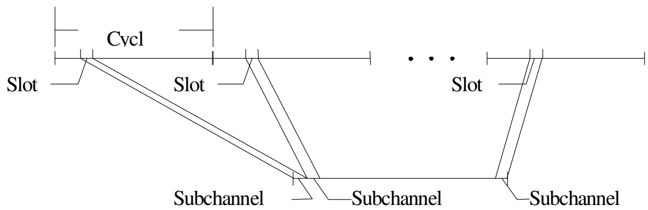

Figure 3 : Definition of subchannels

M successive cycles will be referred to as frames as it is shown in Figure 4.

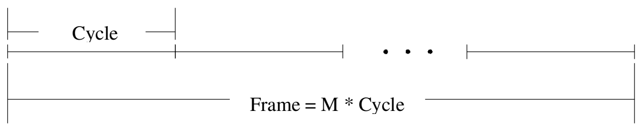

Figure 4 : Structure of a frame

The use of VBR and UBR channels requires modifications in the operation of both sender and receiver and in the slot structure.

The VBR source can use the whole DTM channel with high priority. Each of the M UBR sources is assigned to one of the M subchannels. UBR sources are allowed to send into their subchannels if it is not used by the VBR source.

An additional “address” bit has to be added to every slot to show whether it is used for VBR or UBR traffic.

At the receiver side, the receiver node of the VBR channel identifies the VBR data based on the address bit. The UBR receivers listen to the appropriate subchannel and identify their data based on the address bit.

The described scenario can be modeled with the queuing scheme shown in Figure 5.

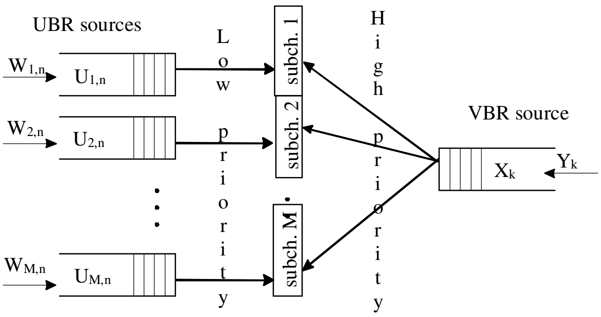

Figure 5 : Queueing model of the circuit switched solution

We can suppose that the VBR source doesn't have to wait for the UBR sources. Accordingly, the results of Section 3 can applied to this scenario. The average waiting time and queue length for the UBR sources are discussed below.

The evolution equation for the queue length is

$$U_{i,n+1} = U_{i,n} + W_{i,n+1} - I_{\{U_{i,n} \ge 1, X_{nM+i}=0\}} =$$

$$= \left(U_{i,n} - I_{\{X_{nM+i}=0\}} \right)^{+} + W_{i,n+1} \qquad (4)$$

where k is the number of cycles passed, n is the number of frames passed (M cycles = 1 frame), $W_{i,n}$ is the number of 64-bit words arrived from UBR source *i* in frame *n*, $U_{i,n}$ is the queue length of UBR source *i* in frame *n*, Y_k is the number of 64-bit words arrived from VBR source in cycle *k* and X_k is the queue length of the VBR source in cycle *k*.

We assume that the sequences of $\{W_{i,n}\}$ are independent and identically distributed random variables. For modeling UBR traffic we can also apply a batch Bernoulli model.

Proposition 1

The average queue length in the dedicated buffer of UBR source *i*

$$E\{U_i\} = \frac{E\{W_i\}(1 - E\{W_i\}) + \mathrm{var}\{W_i\}}{2(1 - E\{Y\} - E\{W_i\})} \qquad (5)$$

Detailed proof to Proposition 1 can be found in Appendix A.

The load generated by UBR source i is

$$\rho_{UBR,i} = E\{W_i\} \qquad (6)$$

and peakedness is

$$k_i = \frac{\mathrm{var}\{W_i\}}{E\{W_i\}} \qquad (7)$$

Using (6), (7) and (5) we can write the average queue length of the dedicated buffer of UBR source *i* as

$$E\{U_i\} = \frac{\rho_{UBR,i}\left(1 + k_i - \rho_{UBR,i}\right)}{2\left(1 - \rho_{VBR} - \rho_{UBR,i}\right)} \qquad (8)$$

From (8) and Little's theorem the average waiting time for UBR source *i*:

$$E\{D_i\} = \frac{E\{U_i\}}{E\{W_i\}} = \frac{1 + k_i - \rho_{UBR,i}}{2\left(1 - \rho_{VBR} - \rho_{UBR,i}\right)} \text{ (frames)} =$$

$$= M \frac{1 + k_i - \rho_{UBR,i}}{2\left(1 - \rho_{VBR} - \rho_{UBR,i}\right)} \text{ (cycles)} \qquad (9)$$

The utilization of subchannel *i* is $\rho_{VBR} + \rho_{UBR,i}$.

We can conclude from (9) that the average delay of the UBR sources is proportional to the number of subchannels M in one DTM channel. The average delay does not change if the other subchannels are not used because UBR sources don't interact.

We examined the behavior of the mean delay function in case of the traffic example described in the VBR source analysis ($k_{VBR} = 100$; $\rho_{VBR} = 0.375$). We assumed that there are 8 subchannels in the system. The delay is shown as a function of load at different traffic characteristics in Figure 6.

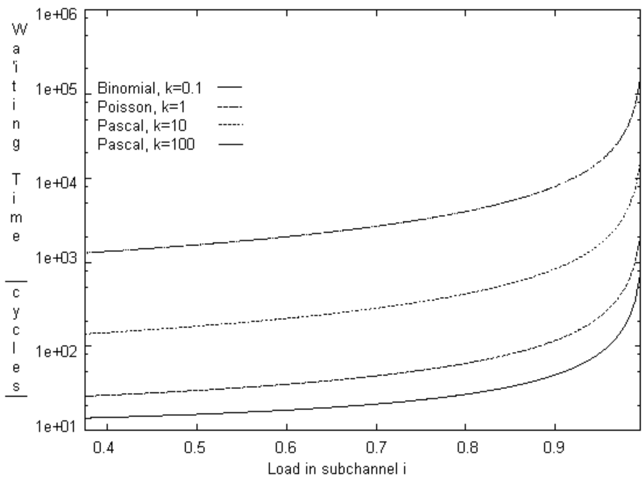

Figure 6 : Average waiting time of UBR sources in the scenario

We can conclude from the graph that the average waiting time greatly increases if the load of the subchannel is above 0.95. If the UBR source is also extremely bursty (k=100) the average delay can be extremely large (above 80000 cycles=10s). If the UBR source characteristic is smooth then the average delay is acceptable (0-20/40 ms).

The other investigated parameter was the average queue length. The amount of memory required for the DTM channel is related to the sum of queue lengths. The average queue length of one UBR source is independent of the number of subchannels. Consequently, the required buffer size is proportional to the numbers of used subchannels N. For planning we have to calculate with worst case parameters. In this case we have to use N=M value for buffer dimensioning. The mean of the sum of UBR queue lengths is shown as a function of load at different traffic characteristics in Figure 7 (N=M=8).

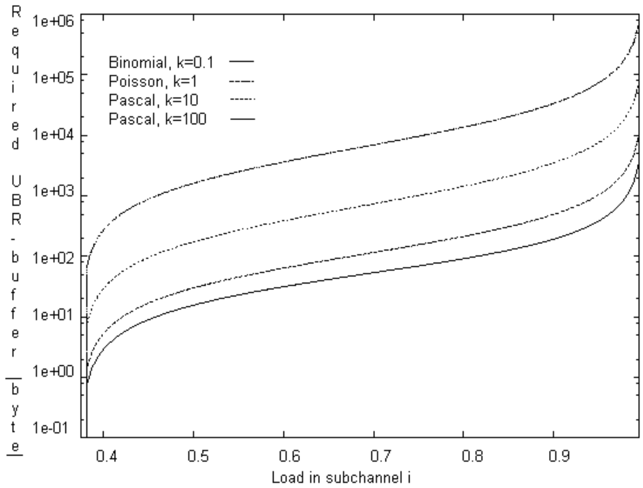

Figure 7 : Sum of average queue lengths of UBR sources in the scenario

4.2 Packet switched solution

An alternative solution for the same problem is packet switching. In many cases we can suppose that the UBR sources generate packetized data. In this case, the capacity not used by the VBR source can be shared in a different way between the UBR sources. The operation of the system is determined by the following rules:

- The slot structure is the same as in case of circuit switching.
- Rules for sending and receiving the data of VBR source are the same as they were shown at the circuit switched solution. It is based on the "address bit".
- The data of UBR sources can be transmitted if the channel is not used by the VBR source. UBR packets are treated as a unit. They are separated by special delimiter words in the same data channel. If the node started to send a UBR packet then it should not proceed to another UBR packet until it is finished.
- The receiver node of a UBR channel considers only the slots in the DTM channel which have the proper address bit. If it finds a start delimiter and it contains the identifier of its UBR connection then it forwards the information to its host until the end delimiter slot arrives. In order to make easier the task of the nodes, the length of the packets must be constant.

We can imagine a scenario when the packet switching solution can be applied: The DTM network is used as a transmission network for ATM networks. Hosts generating UBR traffic are ATM switches. UBR and ABR ATM connections are set up on top of the UBR DTM connections. Real-time VBR ATM connections are set up on top of the VBR DTM connections.

The queuing model of this system is shown in Figure 8.

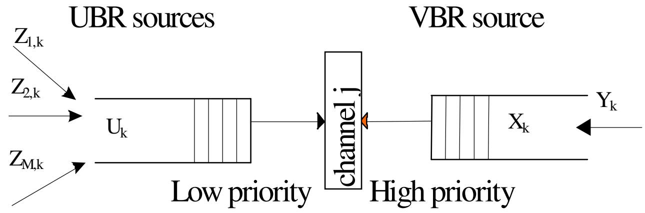

Figure 8 : Queueing model of the packet switched multiplexing solution

The evolution equation for the packet switched solution has the form of

$$U_{k+1} = U_k + \sum_{i=1}^{N} Z_{i,k+1} - I_{\{U_k \ge 1, X_k = 0\}} \tag{10}$$

where k is the cycle number, $Z_{i,k}$ is the number of 64 bit words arrived from UBR source i in cycle k, $Z_k = \sum_{i=1}^{N} Z_{i,k}$, U_k is the queue length in cycle k, Y_k is the number of 64 bit words arrived from the VBR source in cycle k, X_k is the queue length of the VBR source in cycle k and N is the number of UBR sources attached to the DTM channel.

<u>Proposition 2</u>

Average length in the common queue of the UBR sources:

$$E\{U\} = \frac{E\left\{\sum_{i=1}^{N} Z_i\right\}\left(1 - E\left\{\sum_{i=1}^{N} Z_i\right\}\right) + \mathrm{var}\left\{\sum_{i=1}^{N} Z_i\right\}}{2\left(1 - E\{Y\} - E\left\{\sum_{i=1}^{N} Z_i\right\}\right)} \tag{11}$$

Proof for Proposition 2 can be found in Appendix B. Average queue length for independent, identically distributed UBR sources is given by

$$E\{U\} = \frac{NE\{Z\}(1 - NE\{Z\}) + N\,\mathrm{var}\{Z\}}{2(1 - E\{Y\} - NE\{Z\})} =$$

$$= \frac{\rho_{UBR}(1 + k - \rho_{UBR})}{2(1 - \rho_{VBR} - \rho_{UBR})} \tag{12}$$

where $k = \frac{\mathrm{var}\{Z\}}{E\{Z\}}$ and the aggregated load of UBR channels is $\rho_{UBR} = E\left\{\sum_{i=1}^{N} Z_i\right\}$

The average waiting time for UBR sources comes from (11) and Little's theorem:

$$E\{D\} = \frac{E\{U\}}{E\left\{\sum_{i=1}^{N} Z_i\right\}}$$

$$E\{D\}=\frac{E\left\{\sum_{i=1}^{N}Z_i\right\}\left(1-E\left\{\sum_{i=1}^{N}Z_i\right\}\right)+\mathrm{var}\left\{\sum_{i=1}^{N}Z_i\right\}}{2E\left\{\sum_{i=1}^{N}Z_i\right\}\left(1-E\{Y\}-E\left\{\sum_{i=1}^{N}Z_i\right\}\right)}\ \text{(cycles)} \quad (13)$$

If UBR sources are independent and identically distributed:

$$E\{D\}=\frac{1+k-\rho_{UBR}}{2(1-\rho_{VBR}-\rho_{UBR})}\ \text{(cycles)} \quad (14)$$

If the load of the DTM channel ($\rho_{VBR}+\rho_{UBR}$), the aggregated load generated by the UBR sources (ρ_{UBR}) and the distribution of the independent, identically distributed sources are given then from (14) we can conclude that the average waiting time is independent of the number of multiplexed sources (N). We can also see that with these assumptions and at fixed M and N values, the average waiting time (14) and average queue length formulas (12) are proportional to (8) and (9), respectively. Consequently, the delay and buffer size curves have the same form with a different scaling (their values are M and N times larger in the circuit switched solution) if we use the same assumptions.

4.3 Comparison of the Circuit Switched and Packet Switched Solutions

In order to be able to compare the circuit switched and packet switched solutions we defined a gain function in the following form:

$$G(M,N,\rho_{UBR},\rho_{VBR},k)=\frac{E\{D\}_{CS}}{E\{D\}_{PS}} \quad (15)$$

where CS stands for circuit switching and PS for packet switching.

If

- all of the M subchannels of the circuit switched solution is used by UBR connections
- there are M independent identically distributed UBR sources connected to the DTM channel in the packet switched solution (N=M)
- all the sources behave similarly

then

$$G\big|_{N=M}=M\ . \quad (16)$$

The packet switched solution has more advantages than it is expressed by (16):

- There is no “hard wired” M value
- N can be changed without the limitation of M
- and the bandwidth allocated by the UBR connection can be any value within the capacity limits of the DTM channel.

We demonstrate the first advantage and compare it to the circuit switched network below.

Let us assume that only one UBR connection is set up in the cases of both circuit switched and packet switched solution with the same average bit-rate (N=1). If there are M subchannels at the circuit switched solution then $\rho_{UBR}(PS)=\rho_{UBR,i}(CS)/M$ because the load at the packet switched solution is an aggregated value. Let us use the notion $\rho=\rho_{UBR,i}(CS)$. We can express the gain function as follows

$$G\big|_{N=1}=\frac{E\{D\}_{CS}}{E\{D\}_{PS}}=M\left(\frac{1+k-\rho}{1+k-\rho/M}\right)\left(\frac{1-\rho_{VBR}-\rho/M}{1-\rho_{VBR}-\rho}\right) \quad (17)$$

The G function is shown in Figure 9 as a function of M at different ρ and constant k=1 settings. The parameters of the VBR connection are the same as in the previous examples. We can see from the graph that G can be approximated as a linear function of M. The derivative of G function is as follows

$$\frac{\partial G}{\partial M}\bigg|_{N=1}=\left(\frac{1+k-\rho}{1-\rho_{VBR}-\rho}\right)\left(1-\frac{k-\rho_{VBR}}{1+k}\left(1-\frac{1}{\left(\frac{1+k}{\rho}M-1\right)^2}\right)\right) \quad (18)$$

In case of realistic settings (e.g.: for UBR sources k=1 and $\rho=0.5$), the expression $\frac{1}{\left(\frac{1+k}{\rho}M-1\right)^2}$ can be neglected in case of any values of M (even if M=1). We can approximate the slope of the G curve and the G function as follows

$$\frac{\partial\tilde{G}}{\partial M}\bigg|_{N=1}=\left(\frac{1+k-\rho}{1-\rho_{VBR}-\rho}\right)\left(\frac{1-\rho_{VBR}}{1+k}\right)=$$
$$=\left(1-\frac{\rho}{1+k}\right)\left(1+\frac{\rho}{1-\rho_{VBR}-\rho}\right) \quad (19)$$

$$\tilde{G}\big|_{N=1}=\frac{(1+k-\rho)(1-\rho_{VBR})M-\rho(k+\rho_{VBR})}{(1-\rho_{VBR}-\rho)(1+k)} \quad (20)$$

We can calculate some limiting values of $\tilde{G}$ in interesting conditions.

$\lim_{\rho\to 0}\tilde{G}\big|_{N=1}=M$ means that in the case of low load conditions we got the same result as if all the subchannels were used.

$$\lim_{k>>1}\tilde{G}\big|_{N=1}=\frac{1-\rho_{VBR}-\rho/M}{1-\rho_{VBR}-\rho}=M\frac{Free\_channel\_capacity\_in\_PS}{Free\_subchannel\_capacity\_in\_CS}$$

that means that the result is M times the ratio of the free channel capacity in the packet switched system and the free subchannel capacity of the circuit switched system.

The ratio of the free capacities is always larger than 1, so $\tilde{G}$ is larger than M.

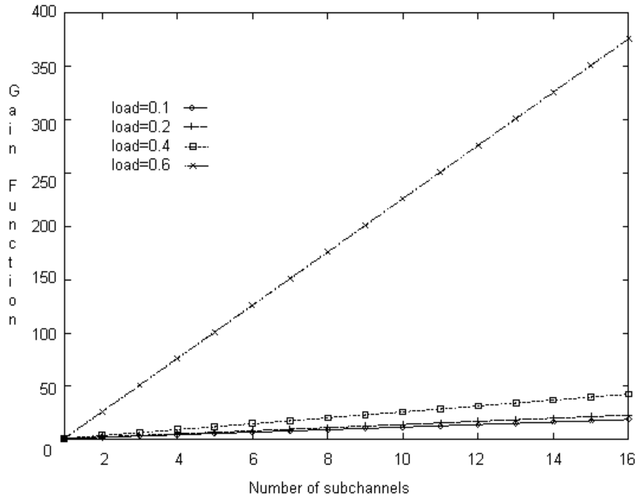

Figure 9 : Gain function: Effect of the number of subchannels at different loads

We also examined the shape of G function as a function of ρ at different k settings while the value of subchannels M equals to 16. It can be seen in Figure 10.

We can conclude from Figure 10 and function (19) and (20) that the value of G is dependent on the load value. The basic reason of this load sensitivity is caused by the gradient of the waiting time curve is much sheerer close to its saturation point because while the single used subchannel of the circuit switched system is overloaded, the packet switched system is far from its saturation point.

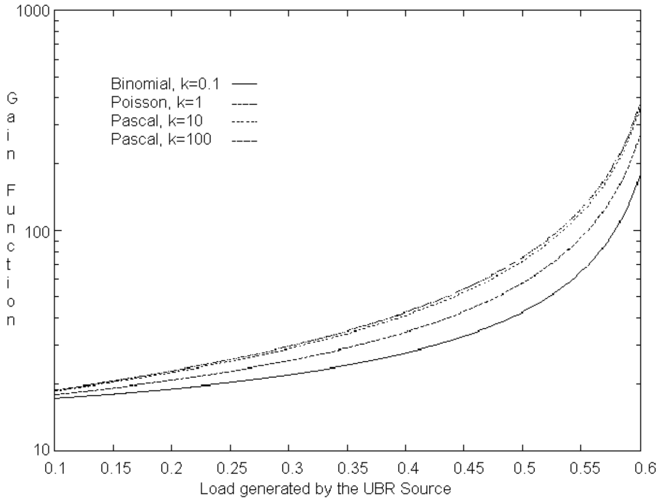

Figure 10 : Gain function: Effect of the load at different k values

Figure 10, function (19) and (20) show that the peakedness of the sources has a minor effect on the value of gain function.

We can conclude that if there are unused circuit switched subchannels then the packet switched solution provides an additional decline in the value of average waiting time.

The above comparison emphasized the superior properties of the packet switched system as [18]. However, it has drawbacks as well. Its implementation is more difficult because of the complex receiving algorithm and the fast operation of the network. Only a small fraction of DTM data channels can be used for multiple service classes. Otherwise, the receivers will not be able to process the control information in the data slots.

5. Conclusion and Further Work

In this paper we proposed two approaches (called packet switching and circuit switching solution) to introduce VBR and UBR services via a fast circuit switched network. We have chosen the DTM broadband network architecture for our investigation as a promising fast circuit switched technology. The methods can be applied to other circuit switched networks as well. We have carried out the performance analysis of the proposals and derived the mean queue length and mean waiting times for both the VBR and UBR traffic classes at a given network node. We found that the channel utilization can be very low in the case of bursty VBR sources but servicing UBR sources can increase it. Our results show that the burstiness of the UBR sources has a significant effect on both the mean queue length and mean waiting time of this source even in case of low traffic load. The comparison study demonstrated the superior properties of the proposed packet switched solution compared to the circuit switched solution.

We introduced two kinds of service classes but other service classes can also be used. CBR can be provided easily by assigning one or more DTM channels or subchannels to a CBR connection. ABR class can be constructed from the UBR and CBR classes.

We analyzed the solutions based on the mean values [7,11,19] of the waiting time and queue length. In the case of real-time applications the value of delay variation and equivalent loss probabilities are also important measures [16]. The investigation of these characteristics and considering more sophisticated input traffic models are the goals of our future research.

6. Appendix A : Proof to Proposition 1

If we use the notion of $V_{i,n+1} = I_{\{X_{nM+i}=0\}}$ we get the well-known evolution equation from (5)

$$U_{i,n+1} = \left(U_{i,n} - V_{i,n+1}\right)^{+} + W_{i,n+1} \qquad (21)$$

where (see [10])

$$E\{U_i\} = \frac{E\{W_i\}(1 - E\{W_i\}) + \mathrm{var}\{W_i\}}{2(E\{V_i\} - E\{W_i\})} \qquad (22)$$

From the steady state of the mean queue length for VBR source (1) we can conclude

$$E\left\{I_{\{X_k \geq 1\}}\right\} = E\{Y_{k+1}\}$$

Now we can write an expression for $E\{V_i\}$

$$E\left\{I_{\{X_k \geq 1\}}\right\} = P(X_k > 0)$$

$$E\{V_i\} = E\left\{I_{\{X_{nM+i}=0\}}\right\} = E\left\{I_{\{X_k=0\}}\right\}$$

$$E\{V_i\} = P(X_k = 0) = 1 - E\{Y\} \qquad (23)$$

We got our result.

7. Appendix B : Proof to Proposition 2

We can write the evolution equation in a form of

$$U_{k+1} = (U_k - V_{k+1})^+ + Z_{k+1}$$

using the following equations

$$U_k - I_{\{U_k \geq 1, X_k=0\}} = \left(U_k - I_{\{X_k=0\}}\right)^+ = (U_k - V_{k+1})^+$$

We can calculate the mean value of the queue length in the buffer of UBR sources as follows

$$E\{U\} = \frac{E\left\{\sum_{i=1}^{N} Z_i\right\}\left(1 - 2E\left\{\sum_{i=1}^{N} Z_i\right\}\right) + \mathrm{var}\left\{\sum_{i=1}^{N} Z_i\right\} + E\left\{\sum_{i=1}^{N} Z_i\right\}^2}{2\left(E\{V\} - E\left\{\sum_{i=1}^{N} Z_i\right\}\right)} =$$

$$= \frac{E\left\{\sum_{i=1}^{N} Z_i\right\}\left(1 - E\left\{\sum_{i=1}^{N} Z_i\right\}\right) + \mathrm{var}\left\{\sum_{i=1}^{N} Z_i\right\}}{2\left(1 - E\{Y\} - E\left\{\sum_{i=1}^{N} Z_i\right\}\right)}$$

using (23) and this is our result.

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