An Analytical Evaluation of VoD Traffic Treatment within the EF-enabled DiffServ Ingress and Interior Nodes

Y. Koucheryavy, D. Moltchanov, J. Harju

Institute of Communication Engineering, Tampere University of Technology,
P.O. Box 553, FIN-33101, Tampere, FINLAND
{yk, moltchan, harju}@cs.tut.fi
http://www.cs.tut.fi/tlt/

***Abstract* - The differentiated services (DiffServ, [1]) expedited forwarding (EF, [2]) per-hop behavior (PHB) is targeted on applications which need strict guarantees of end-to-end delay and should not suffer from packet losses. It makes EF PHB an appropriate choice for loss-free timely delivery of delay and loss intolerant traffic. It is expected that the substantial part of such sort of traffic will be generated by video-on-demand (VoD) services. In order to provide transmission service which is based on EF PHB to VoD traffic, several traffic conditioning functions have to be implemented within the DiffServ ingress nodes. These conditioning functions are based on traffic profiles. In this paper we show how to compute EF PHB traffic profiles for VoD traffic, which are based on simple token bucket mechanism and consider the effect of traffic profile violations. We evaluate both aggregated traffic and per-source quality of service (QoS) degradations caused by traffic profile violations. In order to compute the parameters of EF PHB queue within the DiffServ ingress node we approximate the output stochastic process from the first queuing system by arrival curve. We also consider the VoD traffic treatment within DiffServ interior nodes and show how to compute parameters of EF queues within those nodes.**

I. INTRODUCTION

VoD service is expected to be a one of the very popular applications in broadband multi-service networks. From the traffic transmission point of view, VoD service can be classified as one of the most delay and loss intolerant client-server application. Traffic generated by such sort of applications needs strict quality of service (QoS) guarantees in terms of bandwidth, losses, delays and jitter.

In order to satisfy the demands of real-time traffic nature of VoD service, an appropriate network transmission facility should be provided. Currently, Internet does not provide any QoS guarantees to its applications. It provides the best-effort service only, which does not satisfy the demands of real-time applications. As a result, a work on IP QoS has been initiated. IETF has proposed two QoS frameworks: Integrated Services (IntServ, [3]) and Differentiated Services (DiffServ, [1]). IntServ approach is based on connection admission control (CAC) procedures and uses explicit resource reservation technique. IntServ can provide deterministic QoS guarantees and for this purpose it requires a signaling protocol in order to inform the appropriate network elements about the necessary resource reservation. DiffServ approach is based on service differentiation principle. It aggregates flows with the same QoS requirements and assigns to them the same treatment at the routers along the path of aggregated traffic flow. The service differentiation is achieved by implementing several simple per-hop behaviors (PHBs) in the routers. DiffServ provides probabilistic QoS guarantees to aggregated traffic flows and uses a sort of static CAC algorithms which is based on service level agreements (SLAs). DiffServ approach is more preferable compared to IntServ because of its simplicity and high scalability. In this paper we assume that the network implements DiffServ QoS framework.

IETF DiffServ working group has standardized two PHB groups. These are Assured Forwarding PHB (AF PHB, [4]) and Expedited Forwarding PHB (EF PHB, [2]). EF PHB is targeted on applications which require strict guarantees of end-to-end delay and should not suffer from packet losses.

It is known that in order to satisfy the demands of real-time traffic nature of VoD service MPEG traffic should have the necessary amount of reserved bandwidth and/or some type of priority in service. Because of strict QoS requirements of MPEG traffic and the ability of EF PHB to provide both priority in service and adequate bandwidth reservation [2], we propose to use EF PHB group in order to handle such type of traffic within the DiffServ domains appropriately.

The modern compression algorithms mostly operate in variable bit rate (VBR) mode. VBR mode allows very high compression ratios while the quality of decoded picture remains almost the same during the playback. At the other hand, EF PHB is used to construct transmission services with constant end-to-end bandwidth. From the network dimensioning point of view, it is unwise to transmit VBR compressed video over CBR link. However, currently, this is the almost only way to transmit compressed video over Internet with relatively strict QoS guarantees.

In order to provide transmission service which is based on EF PHB to behavior aggregate, several traffic conditioning functions must be implemented within the DiffServ ingress nodes. These functions are based on traffic profiles. The estimation of traffic profiles parameters is a crucial task in context of configuration of DiffServ ingress nodes.

One of the major advantages of the transmission services which are based on EF PHB consists in their ability to bound the end-to-end delay. The latter requirement can be fulfilled only if the delay of the packets is bounded within the each network node along the path of EF behavior aggregate. The analysis of EF traffic treatment within the DiffServ ingress nodes is of paramount importance since these nodes perform both DiffServ traffic treatment functions - traffic conditioning and queuing.

The full paper is organized as follows. Section II deals with VoD service peculiarities. VoD service network configurations and VoD server configuration are considered there. In Section III MPEG traffic modeling issues are considered. We define stochastic and deterministic models of both single MPEG source and multiplexed traffic from a number of MPEG sources. In Section IV the attention is paid to analysis of VoD traffic treatment within the DiffServ ingress node. We show there how to estimate DiffServ network nodes' parameters and QoS parameters experienced by both single MPEG source and multiplexed traffic from a number of smoothed MPEG sources. The conclusions are given in the last section.

II. VOD CONFIGURATION

A. VoD Service Configuration

Assume that there are N neighboring Internet domains making up a chain and these domains belong to different large internet service provides (ISPs). Every ISP has its own DiffServ implementation in accordance with IETF specifications [1]. In order to provide QoS guarantees to their users, let us assume that these ISPs have installed SLAs between each other (Fig. 1). We believe that this configuration may be the case in the Internet and we call it the "remote" VoD configuration. In this configuration the ISPs may not have its own VoD server or dedicated connection to VoD content provider. Moreover, the nearest VoD server can be located far from the home domain of the VoD user. Anyway, the desired QoS guarantees must be provided between the VoD service entities.

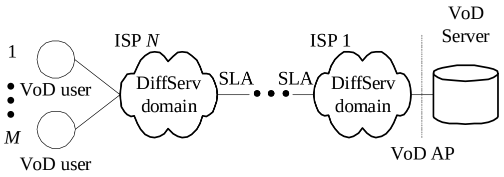

Fig. 1 "Remote" VoD service configuration.

We also assume that a number of VoD custimers in ISP N who wish to use VoD service, however, only ISP 1 has a dedicated connection to VoD content provider. In this case VoD service (and, therefore, QoS guarantees) should be provided across all N domains which belong to different ISPs.

B. VoD Server Configuration

Let us consider the VoD server outline which consists of functional blocks and depicted in Fig. 2. The block "MPEG storage" stores information of MPEG sequences. These sequences are represented by files. Note that the structure of the MPEG storage system has a lot of peculiarities and is outside the scope of this paper. "Rate information" block keeps information about the predefined rates of each MPEG sequence. This information is available from the GoP smoothing algorithm. It has been shown [8] that such algorithm smoothes both burstiness and high peak rate found in MPEG sequences, and does not affect MPEG time structure significantly. During the transmission of video sequence the rate information block enforces the server software to use predefined rates instead of real frame rates. Then, the smoothed MPEG sequence is packetized into IP packets. In order to achieve synchronized transmission we propose to use RTP over UDP protocols configuration. After that the packetized MPEG streams are multiplexed.

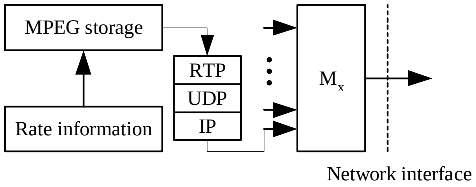

Fig. 2 VoD server functional blocks.

We have introduced several assumptions about the VoD server configuration. We assume that the length of all IP packets which belong to different microflows within the multiplexed MPEG traffic stream is constant and its value lies between acceptable bounds. Thus, the VoD IP packets service time within the DiffServ network node is a constant value and equal to the time to transmit one packet on the outgoing link. This is true at least for DiffServ ingress node. In addition, we also assume that domains do not implement IP packets segmentation procedures along the path between the VoD server and the end-user equipment. In this case the service time of VoD IP packets is constant in each DiffServ network node along the path to destination.

III. VOD TRAFFIC MODELS

A. Stochastic and Deterministic Traffic Modeling

It is known that in order to analyze the network performance we should introduce the traffic models. Let us consider two approaches to network traffic modeling. In accordance with first approach the traffic source or multiplexed traffic from a certain network element is modeled by stochastic process. Since such models should capture most relevant statistical characteristics of real traffic sources, the availability of representative statistical data as well as efficient methods of statistical analysis is of paramount importance. Moreover, in most cases the decision whether our model is a good predictor of traffic source is often taken after the comparison of modeled data with statistical ones. The described approach is very popular and often used in traffic modeling. We called it the "stochastic approach" to traffic modeling.

However, there are some cases when the statistical data of traffic source is unavailable or these data can not be modeled by stochastic process or even we do not know the traffic nature at all. In presence of such uncertainty we can make the assumption that the traffic is unknown but satisfies certain regularity constraints [5]. Note that in most networks such assumption holds – traffic entering the network is constrained by some mechanism (e.g. leaky bucket policer in ATM networks or token bucket in IP networks). In most cases these constraints are represented by simple deterministic model. Using these simple traffic models it is possible to derive the bounds of performance parameters within the wide variety of network elements [5]. It also should be noted that in order to define the deterministic model to which the traffic is constrained, the stochastic models are often needed. We called it the "deterministic approach" to traffic modeling.

In this paper both approaches are used. Note that in our case we should model both the traffic from as single MPEG source and the multiplexed traffic from a number of MPEG sources at the entrance to the network. Since the traffic source is known and statistical data are available [6], firstly, in this paper, we employ the stochastic approach. Our deterministic model of MPEG traffic is based on stochastic model.

B. *Stochastic VoD Traffic Models*

The packet stream at the network interface between the VoD system and the DiffServ ingress node consists of multiplexed traffic from a number of smoothed MPEG traffic sources. We call it the "VoD traffic behavior aggregate". In order to characterize the VoD traffic stochastically we should introduce two stochastic models: the model of single MPEG traffic source and the model of multiplexed traffic from a number of smoothed MPEG traffic sources. In this paper we propose to model both types of traffic by the discrete-time batch Markovian arrival process (D-BMAP).

It was shown [7] that the D-BMAP process matches well the histogram of relative frequencies of single MPEG traffic source and its autocovariance function (ACF). In accompanying paper [8] we show how to derive D-BMAP model of MPEG traffic. Our model has only four states of modulating Markov chain and, therefore, retains the analytical tractability. In that model in order to define the probability distribution function (PDF) of D-BMAP process we can use the histogram of relative frequencies. Since the ACF of the D-BMAP process obeys the geometrical sum distribution it produces fair approximation of the ACF of empirical data [7]. These considerations give us an assurance that these statistical characteristics of the D-BMAP model match their empirical counterparts well.

We also found that the ACF of multiplexed traffic from a number of MPEG sources obeys a near geometrical sum distribution. Thus, the D-BMAP process can also be used to model such type of traffic.

The construction of Markov modulated processes from the empirical data involves the inverse eigenvalue problem. The general solution of inverse eigenvalue problem does not exist. However, up to date several papers have addressed the solution of this problem when some limitation on the form of eigenvalues are set [7,9].

C. *Deterministic VoD Traffic Models*

In order to construct the deterministic traffic model we assume that the stochastic behavior of single MPEG source is unknown but constrained to burstiness regulator (r,b) proposed by Cruz [5], where b is the length of the regulator's queue and r is the constant output rate. The behavior of the (r,b) regulator is similar to the token bucket mechanism. One can use the stochastic model of single smoothed MPEG traffic source to compute these parameters [5].

Since we defined the stochastic models of both single smoothed MPEG traffic source and multiplexed traffic from a number of smoothed MPEG traffic sources we can define their deterministic (r,b) models.

IV. DIFFSERV INGRESS NODE ANALYSIS

A. *Functional Description*

To satisfy the demands of real-time traffic nature of VoD service, such type of traffic should have a necessary amount of reserved bandwidth and/or some type of priority in service. EF PHB has a predefined minimum amount of forwarding resources such as well-defined minimum departure rate (bandwidth) and a predefined amount of buffer space at each node along the path of EF behavior aggregate. Moreover, the process of EF traffic treatment is independent from other traffic treatment within the network nodes [2].

In accordance with DiffServ specification [1], interior network nodes do not implement any traffic conditioning functions. All these functions must be performed by ingress network nodes. Let us consider the DiffServ ingress node which implements EF PHB in addition to the best-effort service. In accordance with EF PHB specification [2], such node must perform two major functions: conditioning the EF behavior aggregate via policing and/or shaping and configuring node so that the EF behavior aggregate has a well-defined minimum departure rate. The functional blocks of DiffServ ingress node which serves the EF behavior aggregate is shown in Fig. 3, where "1" is a traffic conditioning block and "2" is an EF queue at the output port of DiffServ ingress node.

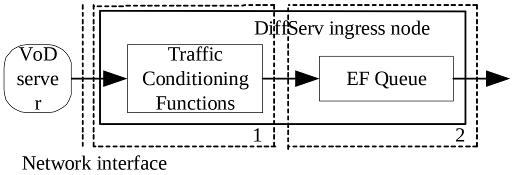

Fig. 3 Functional blocks of DiffServ ingress node which serves EF behavior aggregate.

B. *Token Bucket Parameters Estimation*

The traffic conditioning functions are based on traffic profiles. Traffic profiles specify the temporal properties of traffic stream selected by a classifier [1].

One of the most popular traffic profiles used in current Internet is based on a token bucket policing mechanism. In accordance with this profile each DSCP is assigned to a particular token bucket and during the packets transmission all packets marked with this DSCP should be measured against this token bucket meter.

In general, token bucket can be used for two purposes. Firstly, it shapes incoming traffic up to the some horizon. Shaping bounds of the simple token bucket are given by two parameters: bucket depth (*b*) and token rate (*r*). Token bucket also can serve as traffic marker - DSCP of packets which do not conform to the token bucket specification (*r*,*b*) can be changed. Note that the bucket depth and token rate are often given in bytes rather than in packets. This is because the packet lengths can be variable. In our case since all packets within the VoD traffic behavior aggregate have the same length, we measure the bucket depth and token rate in packets.

Assume that the VoD traffic behavior aggregate after entering the DiffServ ingress node is policed and shaped via simple token bucket mechanism. The token bucket can be represented by equivalent queuing system with single server (Fig. 4). The service rate in such queuing system equals to the token rate *r* and *b* is the capacity of the system. The probability of loss in this queuing system corresponds to the probability of remarking. The remarked packets will not enter the EF queue. We should note that remarking is highly undesirable for MPEG traffic transmission over EF PHB. Consider the token bucket with parameters (*r*,*b*) which allows packets remarking at the DiffServ ingress node. In this case a certain part of arriving packets is remarked to other DSCP. A number of packets which should be remarked depends on (*r*,*b*) parameters of the token bucket and on the arrival process as well. The DSCP to which these packets are remarkered may represent Assured Forwarding PHB classes or best-effort service. In both cases, microflows can experience unpredictable delays, reordering of packets and even losses which are caused by traffic conditioning functions. Therefore, the token bucket mechanism must not allow the packet losses (remarking).

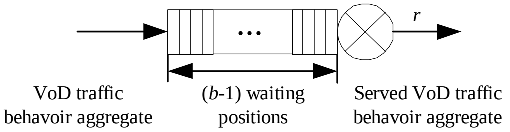

Fig. 4 The token bucket equivalent queuing system.

To provide loss-free transmission of VoD traffic through the DiffServ domain we should provide such (*r*,*b*) that the probability of packets remaking is equal to zero. This probability can be derived from the analysis of simple queuing system D-BMAP/D/1/*b*, where D-BMAP models the arrival process of VoD traffic behavior aggregate, *b* is the capacity of the system, measured in packets. The service time in such system is slotted and the slot length is given by $\Delta = R/r$ where *R* is the length of the IP packet and *r* is the token rate.

Let $\{W^{A}(n),\quad n=1,2,..\}$ be the D-BMAP arrival process which models VoD traffic behavior aggregate. In accordance with D-BMAP the number of arriving packets in each discrete-time interval is modulated by aperiodic irreducible discrete-time Markov chain with M states $\{S^{A}(n), n=1,2,..\}$, $S^{A}(n)\in\{1,2,..,M\}$. Assume that the stationary probabilities of modulating Markov chain are known and given by $\vec{\pi}=(\pi_1,\pi_2,..,\pi_M)$. We define D-BMAP process as a sequence of matrices $D(=0), D(=1), D(=2),..$ each of which contains probabilities of transition from state to state with $0,1,2,..$ arrivals respectively.

The probability of *v* packets loss in the slot in D-BMAP/D/1/*b* system is given by the following expression [10]:

$$\Pr\{L(n)=v\}=\sum_{k=0}^{b}\sum_{i=1}^{M}\sum_{j=1}^{M}\left(x_{ki}\cdot D(=b+v-k)_{ij}\right), \qquad (1)$$

where *b* is the capacity of the system in packets, *M* is the number of states of modulating Markov chain of the D-BMAP process, x_{ki}, $k\in\{0,1,..,b\}$, $i\in\{1,2,..,M\}$ are the elements of stationary distribution of Markov chain $\{S^{[A]}(n), S^{[Q]}(n), n=1,2,..\}$, $S(n)\in\{0,1,..,b\}$.

Since our queuing system must not allow the loss of packets we should consider the probability of at least one packet loss in the D-BMAP/D/1/*b* system. This probability can be derived from (1) and is given by next expression [10]:

$$\Pr\{L(n)\ge 1\}=\sum_{k=0}^{b}\sum_{i=1}^{M}\sum_{j=1}^{M}\left(x_{ki}\cdot\left(D(\ge b+1-k)\right)_{ij}\right), \qquad (2)$$

where $D(\ge k)$, $k\in\{0,1,..,K\}$ are the matrices each of which contains elements which denote the transition of modulating Markov chain from state to state with more than *k* arrivals. Analyzing the expression (2) we should note that the packet losses depend on the arrival process and the capacity of the system (bucket depth, *b*). Note that the D-BMAP arrival process depends on the service time duration Δ which, in turn, depends on the outgoing link rate (token rate). Based on these considerations, we can write next functional dependencies:

$$\begin{aligned}\Pr\{L=v\}&=f\left(b,\Delta,D-BMAP\right),\\ \Pr\{L\ge v\}&=f\left(b,\Delta,D-BMAP\right)\end{aligned} \qquad (3)$$

Thus, using the given arrival process and varying *b* and Δ parameters we can choose the appropriate regions of token bucket parameters (*r*,*b*). Recall that these regions do not allow the loss of the packets of VoD traffic behavior aggregate.

The services which are based on EF PHB, in addition to low losses, must guarantee a bounded delay. However, there must be areas within the chosen token bucket parameters which allow a very high delay of certain packets. Such behavior corresponds to high values of b which, in turn, correspond to low token rates r and depend on their values. Therefore, in order to bound the delay of packets within the token bucket mechanism and obtain the appropriate (r,b) values we should take into account the delay experienced by packets within the D-BMAP/D/1/b queuing system.

The probability that the packet will wait in D-BMAP/D/1/b system during the w time slots is given by [10]:

$$\Pr\{V = w\} = \sum_{k=0}^{w-1}\sum_{r=1}^{\infty}\left(\left(\sum_{i=1}^{M}\sum_{j=1}^{M}\left(x_{ki}\cdot D(=r)_{ij}\right)\right)\cdot\frac{1}{c}\right), \qquad (4)$$

where c is the size of arriving batch.

Using the (r,b) parameters which do not allow packet losses computed at the previous step it is possible to choose the appropriate (r,b) pairs. These pairs should not allow the delay of any packet on more than w time slots within the token bucket mechanism and the delay bound within the token bucket is bounded by $V_{\max}^{tb} = (w\cdot\Delta)$.

All of these computations can be performed before the beginning of SLA establishing procedure. Moreover, in the case when the ISP uses some sort of dynamic resource allocation through bandwidth brokers or some other devices, traffic profiles can be computed by VoD server software dynamically.

C. *Token Bucket Parameters Violation*

Consider the misbehavior of VoD server. Assume that there will be a time instant when the VoD server will not follow the estimated traffic profile without any permissions from the network. In this case it is important to predict the QoS degradation which can be experienced by the VoD traffic behavior aggregate within the token bucket mechanism. In addition, it is crucial to analyze the per-source QoS degradation which is caused by token bucket parameters violation. We consider these tasks consecutively.

Consider the loss of packets of VoD traffic behavior aggregate caused by token bucket profile violation. Assume that the VoD traffic behavior aggregate feeds traffic conditioner at the DiffServ ingress node. Let $(r_{\text{old}},b_{\text{old}})$ be the token bucket profile to which the VoD server should follow. Therefore, the network uses token bucket parameters $(r_{\text{old}},b_{\text{old}})$ which do not allow the remarking of packets in accordance with established SLA. At some time instant the VoD server no longer follow this traffic profile and the packets remarking is occurred within the token bucket mechanism. Since the packets remarking corresponds to packet losses within the equivalent D-BMAP/D/1/b queuing system, we should consider the inverse task to that one, considered in Subsection 4.2. We solve it as follows: given the token bucket parameters $(r_{\text{old}},b_{\text{old}})$, estimate the PDF and mean of losses using the expression (2). Note that using (3) we can derive the probability that there will be an event of at least one packet remarking.

In order to evaluate the per-source QoS degradation consider the tagged VoD traffic source which is multiplexed with $(L$-1) background MPEG traffic sources. These L sources compose the VoD traffic behavior aggregate. We model both the tagged MPEG source and multiplexed traffic from $(L$-1) sources by D-BMAP processes, and therefore, it is possible to define the multiplexed traffic from L sources as a superposition of two D-BMAP processes. In this case we have D-BMAP$^{[TAG]}$+D-BMAP$^{[BACK]}$/D/1/b queuing system which equivalent to the D-BMAP$^{[SUP]}$/D/1/b queuing system where the arrival process is the superposition of tagged and background arrival processes. We use superscripts $^{[TAG]}$, $^{[BACK]}$ and $^{[SUP]}$ to distinguish between those parameters which belong to tagged, background and superposed arrival processes. From the practical point of view, the number of states of superposed process should not exceed several tens.

The probability of v packets loss in the slot by the tagged D-BMAP process within the D-BMAP$^{[TAG]}$+D-BMAP$^{[BACK]}$/D/1/b queuing system is given by next expression [10]:

$$\begin{aligned}&\Pr\{L^{[TAG]}(n) = \nu\} = \\ &= \sum_{i=1}^{b}\sum_{k^{[TAG]}=1}^{\infty}\sum_{k^{[BACK]}=1}^{\infty}\Psi_{\geq i+1}^{k^{[TAG]}+k^{[BACK]}}(\nu)\times \qquad (5)\\ &\times\Omega^{k^{[TAG]},k^{[BACK]},K-i},\end{aligned}$$

where $k^{[TAG]}$ is the number of arriving packet from the tagged process, $k^{[BACK]}$ is the number of arriving packet from the background process, $\Omega^{k^{[TAG]},k^{[BACK]},K-i}$ and $\Psi_{\geq i+1}^{k^{[TAG]}+k^{[BACK]}}(\nu)$ were derived in [10].

The maximum delay experienced by packets of VoD traffic behavior aggregate is equal to the token depth multiplied by time interval to transmit one packet at the token rate $V_{\max}^{tb} = (b\cdot\Delta)$. Using expression (5) we also can get the PDF of waiting time of packets within the queuing system. Moreover, the probability that the arbitrary packet of tagged source will suffer the w slots delay in the queuing system is given by next expression [10]:

$$\begin{aligned}&\Pr\{Q^{[TAG]} = w\} = \\ &= \sum_{i=0}^{b}\sum_{k^{[TAG]}=1}^{\infty}\sum_{k^{[BACK]}=1}^{\infty}\Psi_{=i}^{k^{[TAG]}+k^{[BACK]}}\times \qquad (6)\\ &\times\Omega\left(k^{[TAG]},k^{[BACK]},K-i\right),\end{aligned}$$

where $\Omega\left(k^{[TAG]},k^{[BACK]},K-i\right)$ and $\Psi_{=i+1}^{k^{[TAG]}+k^{[BACK]}}(\nu)$ were derived in [10]

Practically, it is difficult to obtain the values which are given by expressions (5) and (6). However, it may be preferable to carry out such type of preliminary evaluation.

Finally, consider the case when the VoD server violates the traffic profile (r_{old},b_{old}) but the queuing system does not suffer from packet losses. Note that it may take place when the initial token buckets parameters are higher than necessary. In this case the VoD traffic behavior aggregate may still not suffer from packet losses while the bounded delay may increase substantially. The new upper delay bound of VoD traffic behavior aggregate can be derived using (4).

D. EF Queue Parameters Estimation

After the policing and shaping procedures the VoD traffic behavior aggregate enters the EF queue at the output port of DiffServ ingress node. Since EF traffic behavior aggregate must have a well-defined minimum departure rate that is independent of the dynamic state of the node, we can consider EF queue within the DiffServ ingress node in isolation from the other queues within that node. The functional blocks of DiffServ ingress node are shown in Fig. 5 where the blocks correspond to those depicted in Fig. 3.

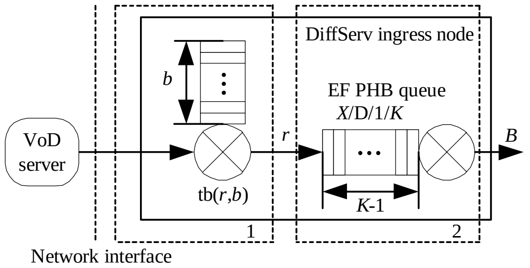

Fig. 5 Functional blocks of DiffServ ingress node serving VoD traffic behavior aggregate.

The services which are based on EF PHB should not allow packet losses and the end-to-end delay should be bounded. Both requirements can be fulfilled only if the delay of the packets is bounded and the packet losses are controlled within the each network node along the path of EF traffic. In Section IV.*B* it has been shown that the appropriate choice of token bucket parameters bounds the delay within the token bucket mechanism. Thus, in order to bound the delay within the DiffServ ingress node to certain value $V_{\max}$, in addition to bounding the delay within the token bucket mechanism $V_{\max}^{tb}$, we also should bound the delay $V_{\max}^{q}$ within the EF PHB queue.

As far as the lengths of all packets are equal and EF PHB has minimum amount of guaranteed departure rate, the EF PHB queuing system can be represented by discrete-time system *X*/D/1/*K*, where *K* is the capacity of the system and *X* is the arrival process from the token bucket.

To define the arrival process to the EF queue at the DiffServ ingress node we should consider the general features of the output process from the D-BMAP/D/1/*b* queuing system. It is known that the output process from the D-BMAP/D/1/*b* queuing system is a D-MAP process. Therefore, the buffer at the output port of the DiffServ ingress node can be modeled by D-MAP/D/1/*K* queuing system. It also should be noted that the derivation of the D-MAP process at the output of the D-BMAP/D/1/*b* queuing system is a very complicated procedure which involves a lot of mathematical calculations.

In order to define the parameters of EF PHB queue (B_0,K_0) we employ arrival/service curves approach [5]. The VoD traffic behavior aggregate's arrival function $R_{in}(t)$, $t \ge 0$ after leaving the token bucket system is constrained to deterministic model (*r*,*b*) (arrival curve) as follows: $R_{in}(t) \le A_{in}(t) = (rt + b)$ for all *t*, where *r* is the token rate and *b* is the bucket depth.

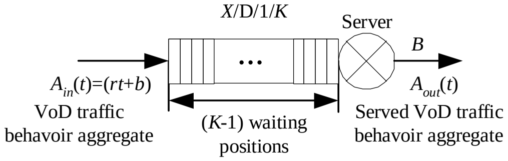

Fig. 6 EF PHB queue.

Let *S*(*t*) be the service curve of the EF PHB queue. By definition the service curve of the EF PHB queue is given by B_0t, where B_0 is the minimum departure rate of the EF PHB at the DiffServ ingress node. Let $A_{out}(t)$ be the arrival curve at the egress of the EF PHB queue (Fig. 6). Therefore, from the above definition it follows that $A_{out}(t) = \min(B_0 \cdot t, A_{in}(t))$. The upper bound of the number of packets within the EF PHB buffer is given by [5]:

$$K_{\max} = \max_{t:t \ge 0}(A_{in}(t) - B_0 t). \tag{7}$$

It is important to note that the maximum delay is equal to the time needed to serve the maximum burst of packets stored in the EF PHB queue. Note that the maximum delay $V_{\max}^{q}$ that a packet can experience waiting in EF PHB queue is bounded by [5]:

$$V_{\max}^{q} = K_{\max} / B_0 . \tag{8}$$

Using the expression (7) it is possible to calculate the region of minimum departure rate which should be assigned to the EF PHB within the DiffServ ingress node and guarantees no losses. Note that that the certain values in this region allow a very high maximum queuing delay of packets. Therefore, we should choose such B_0 which guarantee the delay of packet on no more that $V_{\max}^{q}$ in accordance with (8).

V. VOD TRAFFIC TREATMENT WITHIN INTERIOR NODES

Consider the transmission path of VoD traffic behavior aggregate through the DiffServ domain. After leaving VoD server the VoD traffic behavior aggregate enters the DiffServ ingress node and then passes through a number (say *N*) of DiffServ interior nodes after that it leaves the DiffServ domain. We excluded the DiffServ egress node from the path because its functions can be identical to those, performed by interior nodes.

Considering VoD traffic behavior aggregate transmission path over DiffServ domain we should note that the packet delays and packet losses can occur within the each network node. In order to compute that part of traffic conditioning agreement (TCA) which consists of QoS parameters expectations and should be provided to the user as a valuable part of SLA the configuration parameters of all network nodes should be estimated.

Each DiffServ node which serves VoD traffic behavior aggregate is characterized by two parameters (K_i, B_i), $i \in \{1,2,..,N\}$ while the DiffServ ingress node is described by two pairs (r_0, b_0) and (K_0, B_0). These configuration parameters define the QoS parameters which are experienced by VoD traffic behavior aggregate. Note that in the case when delay and loss of packets can occur in every network node it is almost impossible to predict the performance parameters of the VoD service. We propose two solutions of this problem.

In accordance with the first solution we propose to assign the minimum departure rate within the DiffServ interior nodes as high as required by traffic which leaves DiffServ ingress node. It is possible to compute these rates because after leaving the AF queue VoD traffic behavior aggregate is smoothed and constrained to certain queue parameters (K_0, B_0) and satisfies our deterministic model of VoD traffic behavior aggregate. Thus, within the DiffServ interior nodes we can simply assign $B_i \geq B$, $\forall i \in \{1,2,..,N\}$. By doing so we bound to zero the delay and keep zero losses within the every DiffServ interior node. Therefore, QoS degradation can occur within the DiffServ ingress node only. These QoS degradations depend on DiffServ ingress node parameters (K_0, B_0) and implicitly determine the quality of decoded video.

In context of second approach we firstly should note that there is an opportunity to decrease the requirements on minimum departure rates within the DiffServ interior nodes. Indeed, the VoD traffic behavior aggregate become constrained after the leaving of AF PHB class queue we can use the results obtained in [5] to compute the necessary departure rates and corresponding buffer spaces within DiffServ interior nodes given the end-to-end delay bound we need to provide. Obviously, the transmission service will become more sophisticated since we should fulfill the requirements on delay bounds within each DiffServ interior node. Such case can be seen as the considerable option.

CONCLUSIONS

In this work it has been shown how to derive the simple token bucket parameters of VoD traffic behavior aggregate. Then, under some assumptions, the delay within the DiffServ ingress node which serves the VoD traffic behavior aggregate was evaluated. The effect of token bucket parameters violations and corresponding aggregate and per-source QoS degradations were also derived.

The results obtained in this work are partially based on our previous work [10] and can be used at the network planning phase and at the service planning phase as well. Particularly, the token bucket parameters of MPEG traffic behavior aggregate and the required capacity of DiffServ network nodes can be calculated.

Although the EF PHB is targeted on applications which need strict guarantees the efficiency of such transport for VoD traffic is questionable. However, currently this is the almost only way to transmit compressed video over Internet with some type of guarantees. Therefore, from the network dimensioning point of view, it is crucial to compare the efficiency of EF PHB it terms of network utilization. Particularly, further in our work the efficiency of VoD traffic over EF PHB and AF PHB will be analyzed.

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