# A Top-Down Approach to VoD Traffic Transmission Over DiffServ Domain Using the AF PHB Class

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*Abstract*-**Based on the Differentiated Services (DiffServ, [1]) model we develop implementation-ready transmission service for video-on-demand (VoD) traffic. In order to satisfy the demands of real-time nature of VoD traffic we propose to use assured forwarding (AF, [4]) per-hop behavior (PHB) group. We provide specific traffic profile parameters which adequately fit to VoD traffic requirements. Using these parameters and AF PHB class we show how to construct a well-defined transmission service that is suitable for VoD traffic delivery. Our service is analytically tractable. It means that using the quality of service (QoS) parameters which should be provided to VoD traffic we can evaluate the required capacity not only within the DiffServ ingress node, but within the interior nodes too. Our transmission service is designed in such way that it is fully characterized by the parameters of DiffServ ingress node, bounds the losses and delay along the path of behavior aggregate and allows us to predict the QoS degradation which can be experienced by both behavior aggregate and single microflows.**

## 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 (inelastic) 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.

Nowadays, it is quite clear that multi-service broadband networks will preferably use IP protocol at the network layer while the transport layer will be shared between TCP and UDP. However, to date most research activities in the area of video traffic transmission have been concentrated on asynchronous transfer mode (ATM) networks. Yet, ATM is just one possible way to implement a wide area subnetwork in the global Internet. Concerning the VoD traffic delivery in the Internet, we have to pay attention to the IP level mechanisms, in addition to the properties of various network technologies used below IP.

In order to satisfy the demands of real-time nature of VoD traffic, 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 needs of real-time applications. As a result, the work on IP QoS has been initiated. IETF has proposed two QoS frameworks: Integrated Services (IntServ, [2]) and Differentiated Services (DiffServ, [1]). IntServ 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 [2]. DiffServ employs different approach. 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 PHBs in the routers [1]. As a result, DiffServ provides probabilistic guarantees to aggregated traffic 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. Assured Forwarding PHB (AF PHB, [3]) is designed for a range of applications which need different QoS guarantees. There are four classes of PHB identification codes within the AF PHB group. Within the each class there are three distinct DiffServ codepoints (DSCP) with different packet drop precedence. Expedited Forwarding PHB (EF PHB, [4]) is targeted on applications which require strict guarantees of end-to-end delay and should not suffer from packet losses.

The modern compression algorithms mostly operate in variable bit rate (VBR). VBR mode allows very high compression ratios while the quality of decoded picture remains almost the same. At the other hand it is known that the VoD traffic should have the necessary amount of reserved bandwidth and/or some type of priority in service. Since EF PHB is used to construct transmission services with constant end-to-end bandwidth it is inappropriate from the network dimensioning point of view to transmit VBR traffic over CBR channel. Because of the ability to provide priority in service and adequate bandwidth reservation, in order to handle such type of traffic within the DiffServ domains appropriately we propose to use AF PHB group.

It is known that the loss-free transmission is preferable for VoD traffic, however, keeping in mind the high peak rate and drastic short-term rate changes found in MPEG sequences it is not wise to provide a loss-free transmission. Moreover, the development of effective forward error correction (FEC) algorithms and evolution of MPEG native destination-based error concealment techniques allows us to reduce the requirements on packet losses. At the same time delay requirements remain very strict. Thus, it is necessary for VoD traffic transmission service to provide low losses and bound the end-to-end delay of packets. Both requirements can be fulfilled only if the loss of packets is controlled and the delay of the packets is bounded within the each network node along the path of behavior aggregate. Therefore, it is crucial to develop simple transmission service which satisfies the abovementioned requirements of VoD traffic.

In this paper we propose transmission service for VoD traffic within the DiffServ IP network. The QoS parameters which can be provided by our transmission service are fully characterized by the parameters of DiffServ ingress node, particularly, by the queue length and link share which are assigned to single AF PHB class.

Our transmission algorithm can allow the loss of packets and can provide the necessary delay that satisfies the needs of real-time nature of VoD traffic. In addition, it provides a clear way to tune those parameters which directly affect losses and delays within the DiffServ nodes. Moreover, the service maintains the way to compute all parameters analytically.

In context of our transmission service, the analysis of AF traffic treatment within the DiffServ ingress node is of paramount importance since these nodes perform both traffic treatment functions which are defined by AF PHB specification [3] - traffic conditioning and queuing.

Our paper is organized as follows. Section 2 deals with VoD service peculiarities. VoD service configuration, VoD server configuration and VoD traffic generation are considered there. VoD traffic modeling issues are considered in Section 3. Stochastic and deterministic VoD traffic models are defined there. Section 4 presents our transmission service and includes corresponding performance evaluation. The conclusions are drawn in the last section.

## II. VOD CONFIGURATION

### A. VoD Service Configuration

Assume that there are $N$ neighboring Internet domains making up a chain. Consider that 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 these ISPs have installed SLAs between each other. Such configuration is depicted in Fig. 1. We believe that this configuration may be the case in the Internet and we called it the "remote" VoD configuration. In this configuration the ISPs may not have their 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.

We also assume that there are several users 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.

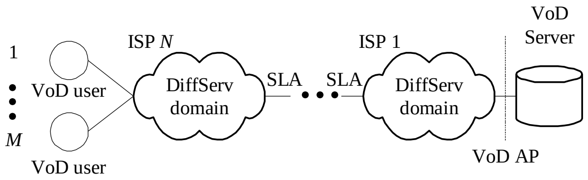

Fig. 1. VoD service configuration.

### B. VoD Server Configuration

VoD server functional configuration is depicted in Fig.2. MPEG storage stores information of MPEG sequences. These sequences are represented by files. Rate information block keeps information about the predefined rates of each MPEG sequence. This information is available from the GoP smoothing algorithm. The 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.

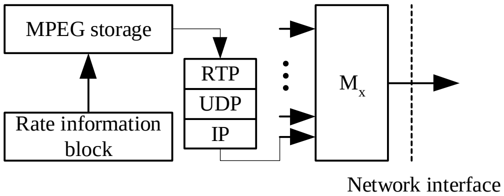

Fig. 2. VoD server configuration.

We introduce 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 $R$ lies between acceptable bounds. Thus, the VoD IP packets service time 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 for each VoD IP packets is constant in every DiffServ network node along the path to destination.

In this paper it is supposed that the VoD server performs host marking procedure as defined in [1] and all VoD packets which enter the network have an appropriate DSCP codepoint already.

### *C. VoD Traffic Generation*

Basically, VoD traffic consists of large MPEG file transfers and can be characterized by high peak rates and drastic short-term rate changes (burstiness). These features can cause undesirable losses within the network nodes' buffers or packets remarking within the traffic conditioners during the traffic transmission through the network. To deal with these problems in this paper we assume that the MPEG traffic is smoothed at the group of pictures (GoP) level as follows:

$$K^{(m)}(h) = \frac{1}{m} \sum_{i=(h-1)m+1}^{hm} X(i), \quad m = 1, l_{GoP}, 2l_{GoP}, .., N, \qquad (1)$$

where $N$ is the number of frames in the sequence, $l_{GoP}$ denotes the length of the GoP, $X(n)$, $n = 1,2,..,N$ denotes the sizes of individual frames and $K^{(m)}(h)$, $m = 1, l_{GoP}, .., N$, $h = n/m, (n/m)-1, .., 1$, $h \in \{1,2,..,l_{GoP}\}$ denotes the sizes of smoothed sequence.

In our study GoP has twelve frames structure (*IBBPBBPBBPBB*, [6]) and, therefore, we consider only those patterns which length is divisible by twelve. In this paper we set $m = l_{GoP} = 12$.

Note that the outlined approach does not require any computational resources during the transmission of video sequences, provides a predefined deterministic delay and efficiently employs frame structure of the MPEG sequence. We believe that this approach can be used in real VoD systems because of its simplicity.

## III. VOD TRAFFIC MODELING

### *A. Stochastic and Deterministic Traffic Modeling*

In order to analyze the network performance we should introduce the models of different types of traffic. Let us consider two approaches to 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 mostly used in traffic modeling. We called it the "stochastic approach" to traffic modeling.

However, there are some cases when the statistical data of traffic sources is unavailable or these data can not be modeled by stochastic process or even we do not know the traffic nature. 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 which describes the model of unknown traffic. 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 models of network traffic to which the traffic is constrained the stochastic models are often needed. We called it the "deterministic approach" to traffic modeling.

Further, in this paper both approaches are used. In our case we should model the multiplexed MPEG traffic at the entrance to the network. Since the traffic source is known and statistical data are available [6], firstly, in this paper, we employ a 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 network node consists of multiplexed traffic from a number of smoothed MPEG traffic sources. We called it the "VoD traffic behavior aggregate". In this paper we propose to model both the traffic from as single MPEG source and the multiplexed traffic from a number of MPEG sources by the discrete-time batch Markovian arrival process (D-BMAP).

It was shown [7] that the D-BMAP process matches the probability distribution function (PDF) of the single MPEG traffic source and its autocorrelation function (ACF) well. In order to define the PDF of number of arrivals of D-BMAP process we can use an empirical histogram of relative frequencies. Since the ACF of the D-BMAP process obeys the geometrical sum distribution it produces good 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 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 [7,8].

### C. Deterministic VoD Traffic Models

In order to construct the deterministic traffic model we assume that the stochastic behavior of VoD traffic behavior aggregate is unknown but constrained to burstiness regulator ($r$,$b$) as 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 traffic model or empirical traffic pattern to compute the parameters of the model [5].

## IV. TRANSMISSION SERVICE

### A. Definition of the Service

VoD traffic transmission service should have the necessary amount of reserved bandwidth and/or some type of priority in service. We propose to assign to VoD traffic a whole AF PHB class since each AF PHB class has a predefined minimum amount of forwarding resources such as bandwidth and buffer space at each node along the path of AF behavior aggregate. Because of predefined amount of forwarding resources, we can assume that the process of AF traffic treatment is independent from other traffic treatment within the network nodes.

Let us consider the DiffServ ingress node which implements AF PHB. In accordance with specification [3] such node must perform two major functions: conditioning the behavior aggregate and configuring node so that the behavior aggregate has a minimum departure rate and certain amount of buffer space. The queuing model of DiffServ ingress node which serves the VoD traffic behavior aggregate is shown in Fig. 3 where "1" is the traffic conditioning block, "2" is the AF class queue, $r_0$ and $b_0$ are the parameters of traffic conditioning block, $(K_0 - 1)$ is the length of the buffer and $B_0$ is the outgoing link share which is assigned to AF PHB class as the minimum departure rate.

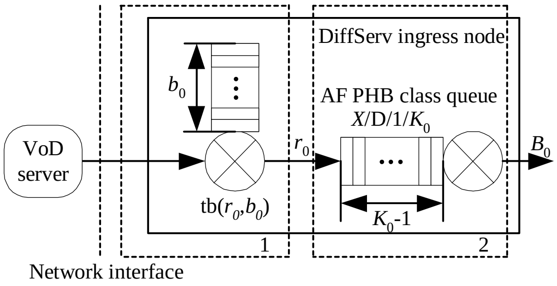

Fig. 3. A model of behavior aggregate's treatment within the DiffServ ingress node.

The DiffServ interior network nodes should perform the queuing functions only. The queuing model of DiffServ interior node is presented in Fig. 4 where $(K_i - 1)$ is the length of buffer and $B_i$ is the outgoing link share which is assigned to AF PHB class as the minimum departure rate.

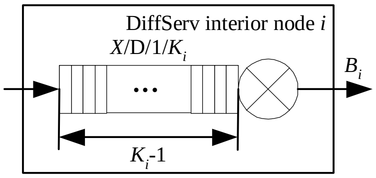

Fig. 4. A model of behavior aggregate's treatment within the DiffServ interior node.

Let us 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. Note that we excluded the DiffServ egress node from the path of VoD traffic behavior aggregate because its functions can be identical to those, performed by interior nodes.

Considering VoD traffic behavior aggregate transmission over DiffServ domain we should note that the packet losses may occur within the each network node and the remarking of packets may occur within the traffic conditioning mechanism. In order to compute the certain part of SLA which consists of QoS parameters expectation 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 $(K_0, B_0)$. Thus, we should provide appropriate values of $(r_0, b_0)$, $(K_0, B_0)$ and $(K_i, B_i)$, $i \in \{1,2,..,N\}$. These configuration parameters define the QoS parameters which are experienced by VoD traffic behavior aggregate. Note that for the case when loss of packets may occur in every network node it is almost impossible to predict the performance parameters of the VoD service.

In this paper we propose to replace the problem of whole network transmission path analysis by the problem of configuring the DiffServ ingress node only. In other words 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 this 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 VoD traffic behavior aggregate. Thus, within the DiffServ interior nodes we simply assign $B_i \geq B$, $\forall i \in \{1,2,.., N\}$. By doing so we bound to zero both delay and losses within the DiffServ interior nodes. 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.

It is allowed to use more than one VoD server within our transmission service. The only requirement is that the additional VoD traffic behavior aggregates should satisfy the deterministic model (*r*,*b*). In this case we can use those results provided in [5] to compute the minimum departure rate $B_i$ $\forall i \in \{1,2,.., N\}$ within the DiffServ interior nodes.

We also note that an opportunity to decrease the requirements on minimum departure rates within the DiffServ interior nodes exists. 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. However, such case can be seen as the considerable option of proposed service.

Thus, in order to define the required capacity for AF class which serves VoD traffic behavior aggregate we should analyze the treatment of VoD traffic behavior aggregate within the DiffServ ingress node.

### *B. Token Bucket Parameters*

The traffic conditioning functions implemented within the DiffServ ingress nodes 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 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. Token bucket traffic profile defines rules for determining whether a particular packet is in-profile or out-of-profile. Out-of-profile packets are those packets which arrive when insufficient tokens are available in the bucket. Different conditioning actions may be applied to in-profile and out-of-profile packets.

The bucket depth and token rate are often given in bytes. This is because the packet lengths can be variable. In our case when all packets within the VoD traffic behavior aggregate have the same length, we measure the bucket depth and token rate in packets without the loss of generality.

Assume that the VoD traffic behavior aggregate after entering the DiffServ ingress network node is policed and shaped via simple token bucket mechanism. Token buckets allow packets remarking in accordance with negotiated traffic profiles. It is highly undesirable for MPEG traffic transmission over AF PHB service. Let us consider the token bucket which allows packets remarking. In this case a certain part of arriving packets will be remarked to other DSCPs. A number of packets which should be remarked depends on the token bucket parameters and on the arrival process as well. The DSCPs to which these packets are remarkered may represent lower drop precedence within the AF PHB class or even DSCP corresponding to the best-effort service. Since these remarked packets may belong to different microflows which produce behavior aggregate, in the case of congestion these microflows can experience unpredictable delays, reordering of packets and even losses which are caused by traffic conditioning functions.

To deal with the abovementioned problems we propose to use simple traffic conditioning functions. We allow all traffic from VoD traffic behavior aggregate to enter the corresponding AF PHB class queue without any remarking and shaping. However, DiffServ ingress node should still monitor VoD traffic behavior aggregate for (*r*,*b*) parameters declared in traffic conformance agreement (TCA). These parameters should be defined in such way that every packet generated by VoD server in accordance with declared traffic profile should proceed to AF PHB class queue. Therefore, the rate of the token bucket should be set to the maximum rate of VoD traffic behavior aggregate and the bucket depth should be set to the packet length *R*. The traffic conditioning functions are still needed to prevent potential VoD server misbehavior - all packets which violate the traffic profile will be remarked.

### C. Estimation of the AF Class Queue Parameters

In order to fully characterize our transmission service we should define the AF class queue parameters ($B_0$,$K_0$) which should be assigned to the VoD traffic behavior aggregate within the DiffServ ingress network node. These parameters depend on the desired QoS parameters. We assume here that these QoS parameters are expressed in terms of losses and delays. The number of losses can be given by mean number of lost packets or by PDF of lost packets. The delay requirements can be expressed in terms of mean delay, PDF of the delay or delay bound. In most cases it is sufficient to fulfill the requirements which are given by mean number of losses and delay bound.

In order to introduce the model of AF PHB class queue we should consider the queue management (QM) algorithm. AF PHB specification [1] proposes to use some sort of active QM algorithm within each class of AF PHB. An example of such algorithm is random early detection (RED, [9]) and its extensions to the case of several drop precedence levels. RED-like algorithms monitor the instantaneous congestion level and compute smoothed congestion level in order to determine when packets should be discarded. These algorithms work well in presence of TCP connections which use congestion avoidance mechanism [10]. It can be demonstrated that in presence of UDP flows the efficiency of algorithm significantly decreases [11]. Since the VoD traffic transmission does not implement congestion avoidance mechanisms we propose to use simple droptail QM. This algorithm make use of “first come, first served” (FCFS) queuing discipline.

Since the packet lengths within the VoD traffic behavior aggregate are constant and AF PHB class has fixed minimum amount of bandwidth and buffer space we can model the AF PHB class queue as a discrete-time queuing system $X$/D/1/$K_0$, where $(K_0-1)$ is the length of the buffer and $X$ denotes the arrival process from traffic conditioner. Since the traffic conditioning functions does not affect a time structure of the VoD traffic behavior aggregate, the arrival process to the queue is the D-BMAP process which models the VoD traffic behavior aggregate. Finally, the queuing system can be represented as D-BMAP/D/1/$K_0$ (Fig. 5).

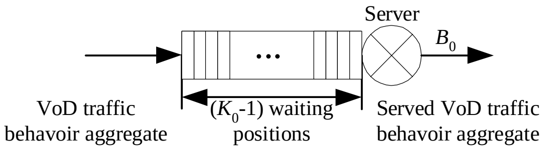

Fig. 5. AF PHB class queue.

The time in D-BMAP/D/1/$K_0$ system is slotted and the slot duration time is given by $\Delta = R\cdot 8/B_0$, where $R$ is the length of packet and $B_0$ is the outgoing link share which is assigned to AF PHB class as the minimum departure rate.

Consider the system at the end of arbitrary time slot. For such system the following equation holds [12]:

$$\begin{aligned} &S^Q(n+1)=\max(0,S^Q(n))+,.\\ &+\min(W^A(n+1),K_0-S^Q(n)) \end{aligned} \qquad (2)$$

where $W^A(n+1)$ denotes the number of arrivals in ($n$+1)th slot, $S^Q(n)\in\{0,1,..,K_0\}$ is the state of the system.

The complete description of the system requires a two dimensional Markov chain $\left\{S^A(n),S^Q(n),n=1,2,..\right\}$ embedded at the moments of packet departures, where $S^A(n)\in\left\{1,2,..,M\right\}$ is the state of the arrival process in time slot $n$. One can use some iteration algorithm [12] to compute the steady state probabilities that $k$ packets are in the system and the arrival process is in the state $j$:

$$\begin{aligned} x_{kj} = \lim_{n\to\infty}\Pr\left\{S^Q(n)=k,S^A(n)=j\right\},\ j\in\left\{1,2,..,M\right\},\\ k\in\left\{0,1,..,K_0\right\}. \end{aligned} \qquad (3)$$

The probability that $v$ packets lost in the slot in D-BMAP/D/1/$K_0$ system is given by next expression [13]:

$$\Pr\{L=v\}=\sum_{k=0}^{K_0}\sum_{i=1}^{M}\sum_{j=1}^{M}\left(x_{ki}\cdot\left(D(=b+v-k\right)_{ij}\right), \qquad (4)$$

where $M$ is the number of states of modulating Markov chain of the D-BMAP process, $x_{ki}$ are the elements of stationary distribution, $D(=k)$, $k\in\{1,2,..\}$ are the matrices elements of which denote the transition of modulating Markov chain from state to state with $k$ arrivals.

In most cases it is not mandatory for VoD traffic to provide loss-free transmission. However, if it is necessary we should consider the probability of at least one packet loss in the D-BMAP/D/1/$K_0$ system [13]:

$$\Pr\{L\geq 1\}=\sum_{k=0}^{K_0}\sum_{i=1}^{M}\sum_{j=1}^{M}\left(x_{ki}\cdot\left(D(\geq b+1-k)\right)_{ij}\right), \qquad (5)$$

where $D(\geq k)$, $k\in\{1,2,..\}$ are the matrices elements of which denote the transition of modulating Markov chain from state to state with more than $k$ arrivals.

Analyzing the expressions (4) and (5) we should note that losses depend on the arrival process and the capacity of the system $K_0$ and on service time duration $\Delta$ (outgoing link share $B_0$). Thus, we can write next functional dependencies:

$$\begin{aligned} &\Pr\{L=v\}=f\left(K_0,B_0,D-BMAP\right),\\ &\Pr\{L\geq v\}=f\left(K_0,B_0,D-BMAP\right). \end{aligned} \qquad (6)$$

Therefore, using the given arrival process and varying $B_0$ and $K_0$ parameters we can choose the appropriate regions of AF class queue pair $(B_0, K_0)$. Recall that these regions fulfill the requirement on losses.

In addition to losses it is also necessary to fulfill the requirements on delay. However, there must be areas within the chosen queue parameters which allow a very high delay of certain packets. Such behavior corresponds to very high values of $K_0$ and low minimum departure rates $B_0$. Thus, in order to fulfill the requirements on delay and obtain the appropriate values of $(B_0, K_0)$ we should take into account the delay experienced by packets within the D-BMAP/D/1/$K_0$ queuing system.

The probability that the packet will wait in D-BMAP/D/1/$K_0$ system during $w$ time slots is given by [13]:

$$\Pr\{V = w\} = \sum_{k=0}^{w-1}\sum_{r=1}^{\infty}\left(\left(\sum_{i=1}^{M}\sum_{j=1}^{M}\left(x_{ki}\cdot\left(D(=r)\right)_{ij}\right)\right)\cdot\frac{1}{r}\right), \qquad (7)$$

where $r$ is the size of arriving batch.

Using the $(B_0, K_0)$ parameters which do not allow packet losses computed at the previous step it is possible to choose the appropriate $(B_0, K_0)$ pairs. These pairs will not allow the delay of any packet on more than $w$ time slots.

Note that 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 (BB) or some other devices, traffic profiles and AF PHB class queue parameters can be computed by VoD server software dynamically.

The given parameters enable us to compute those SLA parameters which can be negotiated with users. These parameters should include less sophisticated ones compared to those mentioned before. They can include mean delay and mean losses and probably the quantiles of their PDFs and/or other user friendly parameters. These parameters can be estimated using (4), (5) and (7).

We also should note that there are some cases when we are given the VoD traffic behavior aggregate and AF class queue parameters $(B_0, K_0)$, and we have to compute the QoS parameters. It may be the case when the VoD service should be implemented within the limited resource environment. Note that this problem is the inverse to that one which has been treated. We propose to solve it as follows. Using the expression (4) and (5) we estimate the PDF of number of lost packets and the probability of at least one packet loss. Then, applying (7) we estimate the PDF of delay of packets.

The extension of the latter task states that we should evaluate the number of sources composing the VoD traffic behavior aggregate which can be successfully delivered to their destinations given the AF class queue parameters $(B_0, K_0)$ and desired QoS guarantees. This task is similar to latter one except for the arrival process dimension.

## D. *Per-Source QoS Degradation*

Since the VoD service is the microflow-oriented one the behavior aggregate's performance parameters does not provide full description of the service. From this point of view, it is crucial to analyze per-source QoS degradation which can be caused by AF PHB class queue.

In order to evaluate per-source QoS degradation we consider the tagged MPEG traffic source which is multiplexed with ($N$-1) background MPEG traffic sources. These $N$ sources altogether compose the VoD traffic behavior aggregate. We model both the tagged MPEG source and multiplexed traffic from ($N$-1) sources by D-BMAP processes, and therefore, it is possible to define the multiplexed traffic from $N$ sources as a superposition of two D-BMAP processes. In this case we have D-BMAP$^{[TAG]}$+D-BMAP$^{[BACK]}$/D/1/$K_0$ queuing system which is equivalent to the D-BMAP$^{[SUP]}$/D/1/$K_0$ queuing system where the D-BMAP$^{[SUP]}$ arrival process is the superposition of tagged and background arrival processes. We use superscripts $^{[TAG]}$, $^{[BACK]}$ and $^{[SUP]}$ to distinguish between parameters which belong to three types of defined arrival processes. Note that 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/$K_0$ queuing system is given by next expression [13]:

$$\Pr\{L^{[TAG]} = \nu\} = \sum_{i=1}^{K_0}\sum_{k^{[TAG]}=1}^{\infty}\sum_{k^{[BACK]}=1}^{\infty}\Psi_{\geq i+1}^{k^{[TAG]}+k^{[BACK]}}(\nu)\times \qquad (8)$$
$$\times\Omega^{k^{[TAG]},k^{[BACK]},K_0-i},$$

where $k^{[TAG]}$ and $k^{[BACK]}$ are the number of arriving packet from the tagged process and from the background process respectively, $\Omega^{k^{[TAG]},k^{[BACK]},K_0-i}$ and $\Psi_{\geq i+1}^{k^{[TAG]}+k^{[BACK]}}(\nu)$ were derived in [13].

The probability that the arbitrary packet of tagged source will suffer the $w$ slots delay is given by [13]:

$$\Pr\{Q^{[TAG]} = w\} = \sum_{i=0}^{K_0}\sum_{k^{[TAG]}=1}^{\infty}\sum_{k^{[BACK]}=1}^{\infty}\Psi_{=i}^{k^{[TAG]}+k^{[BACK]}}\times \qquad (9)$$
$$\times\Omega\left(k^{[TAG]}, k^{[BACK]}, K_0 - i\right),$$

where $\Omega\left(k^{[TAG]}, k^{[BACK]}, K_0 - i\right)$ and $\Psi_{=i+1}^{k^{[TAG]}+k^{[BACK]}}(\nu)$ are derived in [13]. During the transmission through the network the tagged source can experience only those losses and delays which are given by (8) and (9).

We also should note that practically, it is hard to obtain the values which are given by expressions (8) and (9). However, it may be preferable to carry out such type of preliminary evaluation.

## CONCLUSIONS

In this paper in order to define our transmission service we took into account a lot of peculiarities of VoD service. These are VoD service configuration, VoD server configuration, traffic generation and modeling issues. After that we proposed a implementation-ready transmission service within the DiffServ IP networks.

We proposed to use the special traffic profile parameters which adequately fit to VoD traffic requirements. Using these parameters and AF PHB class we have shown how to construct a well-defined transmission service that is suitable for VoD traffic delivery.

Our service is analytically tractable. It means that using the QoS guarantees which should be provided to VoD traffic behavior aggregate, we can evaluate the required capacity not only within the DiffServ ingress nodes but within the interior nodes too. Moreover, our transmission service is designed in such way that it is fully characterized by DiffServ ingress node parameters, bounds the delay within the network nodes along the path of behavior aggregate and allows us to predict the QoS degradation which is experienced by both behavior aggregate and single microflows. We also showed how to compute these valuable parameters.

It also should be noted that our analysis gives worst-case results because some additional bandwidth may be allocated to AF PHB class in accordance with fair sharing algorithm which can be implemented by DiffServ nodes along the path of VoD traffic behavior aggregate [3].

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