Revenue Optimized IPTV Admission Control using Empirical Effective Bandwidth Estimation

Alan Davy, Member, IEEE, Dmitri Botvich, Member, IEEE, and Brendan Jennings, Member, IEEE

Abstract—The paper presents an admission approach for IPTV service providers that is designed to minimize QoS violations whilst effectively utilizing available bandwidth. Central to the approach is an empirical method of estimating the effective bandwidth required to satisfy QoS targets for admitted traffic flows. The paper describes this method and specifies two admission control algorithms based on the use of effective bandwidth estimates. The first algorithm employs a simple evaluation of whether there is sufficient bandwidth available to ensure, with an appropriate degree of confidence, that QoS targets will not be violated if a requested flow is admitted. The second algorithm utilizes information relating to the cost, duration and request frequency of specific IPTV content to prioritize higher revenue flows within the admission control process. Results of a simulation study (employing real traffic traces of long-lived flows) indicate that the proposed algorithms ensure that an adequate, but not overly generous, amount of bandwidth is allocated to ensure that QoS targets for accepted flows are met. Furthermore, they demonstrate the potential advantage of using content specific information in the admission control process to maximize generated revenue.

Index Terms—Effective Bandwidth, Quality of Service, Aggregated traffic, Admission Control.

I. INTRODUCTION

Admission control is a technique used by service providers to ensure customers’ traffic flows are allocated sufficient bandwidth to ensure service level agreement constraints, relating to packet-level Quality-of-Service (QoS), are maintained during periods of high network load. The goal of the service provider is to ensure QoS for accepted traffic flows whilst maximizing bandwidth available for newly arriving flows. For Internet Protocol Television (IPTV) service delivery traffic flows are generally streaming movies or TV programs, which are typically high-bandwidth and have associated with them stringent QoS targets. Therefore, admission control plays a vital role, since bad admission decisions can significantly degrade QoS, not only for the newly accepted flow, but also for already accepted and ongoing flows.

A key feature of any admission control algorithm is how well it predicts the level of resources required to admit a requesting flow. If a new flow request is accepted, the associated packet level QoS targets should be met, without affecting QoS of already admitted flows. Fundamental to achieving this is the accurate prediction of required effective bandwidth (the minimum amount of bandwidth required by a traffic stream to maintain specified QoS related targets [1]) of the aggregated traffic already admitted to the network. If the admission control algorithm predicts that aggregated effective bandwidth should the flow be accepted will be greater than the available bandwidth, the flow should be rejected. Clearly, the more accurate the estimation of effective bandwidth, the more effectively the admission control algorithm operates. As described later, current effective bandwidth estimation approaches are typically based on theoretical analyses of traffic properties (see for example [1], [2], [3]) and make simplifying assumptions such as constant packet sizes and inter-arrival times.

To overcome the limitations of existing effective bandwidth estimation approaches we have proposed an empirical approach, which we use in this paper as the basis of two IPTV-focused admission control algorithms. The first, which we term Empirical Admission Control (EAC), provides an accurate means of predicting the amount of bandwidth required to ensure admitted traffic flows will maintain agreed packet-level QoS targets for the consequent aggregated set of traffic flows. The second, which we term Revenue Maximizing Empirical Admission Control (RMEAC), extends EAC by using information relating to the cost, duration and request arrival rate of IPTV content to provide an admission control regime that seeks to maximize the revenue that is generated for the service provider by the accepted flows. We compare the performance of EAC with respect to bandwidth utilization and QoS control to a number of comparative admission control (AC) algorithms, through simulation of a simple IPTV network focusing on a service provider wishing to control QoS over limited bandwidth.

The paper is organized as follows: §2 provides background information on the following areas: IPTV service delivery; the effect QoS violations has on IPTV services and customer perception of quality; alternative approaches to controlling QoS for IPTV services; admission control techniques in general; and approaches to estimating effective bandwidth. §3 defines our admission control framework, outlining the effective bandwidth estimation approach and specifying the EAC and RMEAC algorithms. §4 defines the IPTV architecture studied, discussing topology settings, traffic characteristics, user profiles, and QoS violation measurement. §5 details three admission control algorithms for comparison namely Parameter Based Admission Control (PBAC) [4], [5], Experience based Admission Control (EBAC) [6], [7], [8], [9], [10], and...
Measurement and Traffic Descriptor based Admission Control (MTAC) [11], [12]. In §6 we evaluate the performance of EAC in comparison to PBAC, EBAC and MTAC, showing that the empirical estimation approach facilitates superior admission control decision making. We also evaluate the operation of RMEAC, demonstrating its potential to increase revenue in comparison to EAC in situations where there is high demand for profitable content items. Finally, §7 draws conclusions and outlines areas for future work.

II. BACKGROUND AND RELATED WORK

IPTV is a term used to describe the delivery of services such as linear broadcast video content, unicast video-on-demand, in addition to interactive service on video content (such as electronic program guides), over an IP network infrastructure. Within this domain we limit our scope to unicast video-on-demand service delivery, specifically on the control of QoS targets on packet delay. These QoS targets are typically quite stringent; for example, the DSL-Forum has outlined packet delay targets of $10^{-7}$s for IPTV[13].

A problem with streaming video in times of network congestion is the effect random packet loss and delay has on traffic. As highlighted in [14], at times of congestion, packets are dropped from interfaces at random, affecting the quality of possibly all video streams passing through the network. This can have a profound effect on the perceived quality of video by customers [15]. A number of approaches have been developed to manage packet delay and loss of video traffic under congestion conditions. One approach is to selectively adapt the quality of a subset of streams to maintain the level of packet delay and loss of the rest of the traffic [16], [17]. The disadvantage from an IPTV perspective is that strict QoS targets on packet delay and loss are imposed on all traffic, thus any reduction in quality is undesirable. A second approach is the use of admission control techniques, which seek to ensure that adequate bandwidth is available within the network to sustain the high QoS targets for every flow that is accepted.

Admission control approaches can be broadly divided into two groups: (1) parameter based admission control and (2) measurement based admission control. Parameter based admission control [4], [5] is based on the assumption that a priori knowledge exists for the bandwidth requirements of each traffic source. However, such information can not always be established; indeed, often only the peak or mean rate of the traffic is known. On the other hand, measurement based admission control [18], [19] makes decisions based on measurements taken in real time from the network; it attempts to learn the characteristics and requirements of flows admitted and bases future decisions on this knowledge. In general measurements such as mean throughput and variance of traffic aggregates are collected and used as input to analytic techniques for estimating effective bandwidth. However, this approach is susceptible to measurement inaccuracies that lead to inaccurate effective bandwidth predictions.

Hybrids of parameter and measurement approaches have also been developed; for example: Experience Based Admission Control (EBAC) [6], [7], [8], [9], [10] and Measurement Based and a priori Traffic Descriptor Admission Control (MTAC) [11], [12]. These hybrid techniques use both measurements taken from the network and knowledge of submitted traffic descriptors to predict effective bandwidth requirements of flows. For evaluation purposes we evaluate our EAC algorithm against the MTAC, EBAC and a basic parameter based admission control algorithm (which we refer to as PBAC).

III. ADMISSION CONTROL FRAMEWORK

Our admission control framework is founded on estimation of effective bandwidth of traffic by analysis of collected packet traces. An effective bandwidth estimation is calculated through analysis of a trace relating to an aggregate of traffic flows collected over a set time interval. This value is used as the estimate of effective bandwidth for that aggregate for the coming interval. If there are one or more outstanding flow requests then the effective bandwidth of the aggregated flows following their admission is conservatively estimated as the effective bandwidth of the current aggregate plus the cumulative peak throughputs of the requesting flows (we assume that these values are available as supplied traffic descriptors). This estimation provides the information necessary to assess whether admission of flows will result in QoS targets for accepted flows being met. In this section we first describe our method for estimating effective bandwidth using collected traces and then specify the EAC and RMEAC admission control algorithms.

A. Empirical Estimation of Effective Bandwidth

Effective bandwidth can be defined for different types of QoS targets; for example: delay targets, loss targets, or both delay and loss targets combined. Our effective bandwidth estimation process (introduced in [20], [21], [22]) can be applied to all types of QoS targets; however in this paper we address delay targets only. A delay target specifies both the nominal maximum delay experienced on the network and delay targets on packet delay. These QoS targets are typically quite stringent; for example, the DSL-Forum has outlined packet delay targets of $10^{-7}$s for IPTV[13].

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### TABLE I

**NOTATION FOR THE ESTIMATION OF EFFECTIVE BANDWIDTH**

<table>
<thead>
<tr>
<th>Notation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T(x_i,t_i)$</td>
<td>A packet within a trace list of packet size $x_i$ and corresponding arrival times $t_i$.</td>
</tr>
<tr>
<td>${T_M}$</td>
<td>The set of all packets contained within trace $T_M$.</td>
</tr>
<tr>
<td>$M$</td>
<td>The total number of packets in trace $T_M$.</td>
</tr>
<tr>
<td>$\text{delay}_{\text{max}}$</td>
<td>Maximum allowable packet delay target in seconds.</td>
</tr>
<tr>
<td>$\text{P}_\text{delay}$</td>
<td>Packet delay target of traffic allowed to violate $\text{delay}_{\text{max}}$.</td>
</tr>
<tr>
<td>$R$</td>
<td>FIFO Queue service rate.</td>
</tr>
<tr>
<td>$p$</td>
<td>Corresponding proportion of violating traffic for service rate $R$.</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Margin of accuracy used to find the effective bandwidth value for a particular proportion of violations.</td>
</tr>
<tr>
<td>$R_{\text{eff}}$</td>
<td>FIFO queue service rate interpreted as an estimate of Effective Bandwidth.</td>
</tr>
<tr>
<td>$\delta_{\text{max}}$</td>
<td>Maximum queue volume, before traffic is delayed greater than $\text{delay}_{\text{max}}$.</td>
</tr>
<tr>
<td>$\delta_{\text{time}}$</td>
<td>Time at which FIFO will complete processing of packets currently in the queue.</td>
</tr>
<tr>
<td>$\delta_{\text{vol}}$</td>
<td>Current volume of the FIFO queue buffer.</td>
</tr>
<tr>
<td>$\text{TOTAL}_{\text{vol}}$</td>
<td>Total volume of traffic that has been processed through the FIFO queue.</td>
</tr>
<tr>
<td>$\text{DELAY}_{\text{vol}}$</td>
<td>Volume of traffic delayed greater than the target $\text{delay}_{\text{max}}$.</td>
</tr>
</tbody>
</table>
Algorithm 1: Algorithm for estimation of effective bandwidth via replaying collected traces through a simulated FIFO queue.

**Input:** $delay_{max}, p_{delay}, \{T_M\}, \beta$

**Output:** $R$

**Function** `calcViolations(delay_{max}, R, T_M)`

Set $\delta_{vol} = 0$;
Set $\delta_{time} = 0$;
Set $TOTAL_{vol} = 0$;
Set $DELAY_{vol} = 0$;

Set $\delta_{max} = delay_{max}R$;

forall $T(x_i, t_i)$ in $T_M$ do
   $TOTAL_{vol} = TOTAL_{vol} + x_i$;
   if $t_i \geq \delta_{time}$ then
      $\delta_{time} = t_i + \frac{\beta}{R}$;
   Elseif $t_i < \delta_{time}$ then
      $\delta_{vol} = (\delta_{time} - t_i)R + x_i$;
      $\delta_{time} = \delta_{time} + \frac{\beta}{R}$;
   if $\delta_{vol} > \delta_{max}$ then
      $DELAY_{vol} = DELAY_{vol} + (\delta_{vol} - \delta_{max})$;
   end
Set $p = \frac{DELAY_{vol}}{TOTAL_{vol}}$;
return $p$.
// End Function `calcViolations()`

Set $\epsilon = p_{delay}\beta$;
Set $R_{low} = calcMean(\{T_M\})$;
Set $R_{high} = calcPeak(\{T_M\})$;
Set $R_{mid} = R_{low} + \frac{R_{high} - R_{low}}{2}$;

Set $p_{mid} = calcViolations(delay_{max}, R_{mid}, \{T_M\})$;
while ($p_{delay} - \epsilon < p_{mid} < p_{delay} + \epsilon$) do
   if $p_{mid} < p_{delay}$ then
      $R_{high} = R_{mid}$;
   else
      $R_{low} = R_{mid}$;
   Set $R_{mid} = R_{low} + \frac{R_{high} - R_{low}}{2}$;
   Set $p_{mid} = calcViolations(delay_{max}, R_{mid}, \{T_M\})$;
end while
return $R_{mid}$.

the proportion of traffic that is allowed exceed this nominal maximum delay. An example of a QoS delay target would be $(50ms, 0.001)$, that is, only 0.1% of traffic is allowed to be delayed by more than 50ms. As effective bandwidth depends on the QoS target, for different QoS targets the effective bandwidth will vary significantly.

Our effective bandwidth estimation algorithm operates as follows. Let $delay_{max}$ be the nominal maximum delay and let $p_{delay}$ be the percentage of traffic which can exhibit delay greater than $delay_{max}$. We define the effective bandwidth $R_{eff}$ of a traffic source for delay QoS target $(delay_{max}, p_{delay})$ as the minimal rate $R$ such that if we simulate a FIFO queue with unlimited buffer and processing rate $R$, the percentage of traffic which will exhibit delay greater than $delay_{max}$ will be less than $p_{delay}$.

To estimate the effective bandwidth of a particular traffic source on the network, we take a recorded packet trace of that source. We observe that if we simulate a FIFO queue (initially assumed to be empty) with the same inputted traffic trace $\{T_M\}$ for different queue rates $R_1 > R_2$ and estimate the percentages $p_1$ and $p_2$ of traffic delayed more than $delay_{max}$ for different rates respectively, then $p_1 \leq p_2$. This means that the percentage of traffic, $p$, delayed more than $delay_{max}$ is a monotonically decreasing function of processing rate $R$. Based on this observation, we employ a simple bisection algorithm for a recorded packet trace to find the minimal value of a queue rate such that the percentage of traffic delayed more than $delay_{max}$ is less than $p_{delay}$.

Alg. 1 outlines the binary search algorithm used to estimate the effective bandwidth of a supplied traffic trace $T_M$. Initially $R_{low}$ and $R_{high}$ are set to the mean and peak throughput of the supplied trace respectively, as the effective bandwidth lies between these two values. The justification for this is that if a packet trace is processed through a queue with service rate equal to its peak rate, the packets within the trace will experience no queue delay (assuming the peak rate was found using an appropriate measurement interval). A detailed discussion on measurement intervals and their effect on peak measurements can be found in [23]. The FIFO queue model depicted in Alg. 1 assumes an infinite queue, initially empty. The algorithm sets a specified target FIFO queue volume $Q_{max}$ for service rate $R$ and delay target $delay_{max}$. If the volume of the queue $Q_{vol}$ exceeds this limit, all traffic beyond this limit will be delayed $DELAY_{vol}$. When all packets have been processed through the queue, the algorithm will return the proportion of delayed traffic, $p$, over the total volume of traffic processed $TOTAL_{vol}$. It should be noted that this effective bandwidth estimation approach assumes that all traffic flows within a trace are of the same QoS class, that is, they have the same delay target. For IPTV we believe this assumption is valid since all IPTV traffic for a given service provider will be subject to the same QoS targets and will therefore be assigned to the same QoS traffic class at the ingress nodes of a network.

| **TABLE II** |
| **NOTATION USED FOR EAC ALGORITHM DEFINITION** |
| **Notation** | **Description** |
| $t_i$ | The content item for which the flow admission request relates. |
| $p(i^*)$ | The peak throughput rate of item $i$. |
| $B_{TOT}(t, t + t')$ | The total bandwidth leased by the service provider. |
| $B_{eff}(t, t + t')$ | The interval of time for which effective bandwidth is estimated. |
| $\{B_{effN}\}$ | A set of previously measured effective bandwidth levels. |
| $N$ | The number of previously measured effective bandwidth levels stored. |
Algorithm 2: Empirical Admission Control (EAC) Algorithm

Input: \(i^*, \{B_{eff_0}\}, B_{TOT}\)

Output: result (accept|reject)

Set \(B_{eff}(t, t + t') = \max(B_{eff_j} : j \rightarrow 1 \ldots N)\);

if \((p(i^*) + B_{eff}(t, t + t') \leq B_{TOT})\) then
    result = accept
else
    result = reject
return result

B. Empirical Admission Control (EAC) Algorithm

The EAC algorithm, specified in Alg. 2, is invoked on the reception of a request for content item \(i^*\). To process this request, knowledge of \(N\) past effective bandwidth measurements \(\{B_{eff_0}\}\) are used, along with the amount of total bandwidth available to the service provider, \(B_{TOT}\). The algorithm estimates the future level of effective bandwidth \(B_{eff}(t, t + t')\) by choosing the maximum previous effective bandwidth value from \(\{B_{eff_0}\}\); this ensures a conservative estimation of the future effective bandwidth level. If the peak rate \(p(i^*)\) of the requested item \(i^*\), plus the predicted effective bandwidth \(B_{eff}(t, t + t')\) is less than the total available bandwidth \(B_{TOT}\), the request is accepted, otherwise it is rejected.

Alternative approaches could be employed to predict an appropriate effective bandwidth value, such as using a simple moving average, exponentially weighted moving average, or a time exponentially weighted moving average (as employed by Martin and Menth [24]). These approaches can lead the algorithm to be less conservative, although the memory of the latter two approaches can be configured to lead to more conservative behavior. However, we believe that our more conservative approach is justified, as the potential gain in having bandwidth available to accept one or more additional flows is outweighed by the risk of adversely affecting the QoS of all accepted flows through underestimation of the effective bandwidth of their aggregate traffic flow.

C. Revenue Maximizing Empirical Admission Control (RMEAC) Algorithm

The EAC algorithm is agnostic of both the revenue generated by each flow admission and the revenue lost through flow rejection. We now propose an admission control algorithm that allows knowledge associated with the IPTV content to be used within the admission decision process. The objective is to use historical information about content item request arrivals, together with associated cost and resource requirements, to maximize expected revenue. We base this algorithm on the work of Jennings et al. [25], who defined a revenue optimization algorithm for load control in Intelligent Network service delivery environments. The Revenue Maximising Empirical Admission Control algorithm is specified as follows:

Assume there are \(I\) individual items of content made available by the service provider. Let \(i = 1, \ldots, I\) denote an arbitrary item of content. Let \(p(i)\) denote the peak bandwidth per second required by item \(i\) and let \(r(i)\) denote the revenue generated by an accepted request for item \(i\). Let \(T_i\) denote the duration in seconds of flows associated with the streaming of item \(i\).

Let \(B_{TOT}\) denote the total bandwidth available between the service provider and the network provider. Let \(B_{eff}(t)\) denote the estimated combined effective bandwidth of the flows accepted at time \(t\) (this can be estimated on an interval-by-interval basis as with the EAC algorithm). Every time a request for item \(i^*\) arrives, the admission control algorithm estimates, given its knowledge of the duration and time of acceptance of currently accepted flows, the time interval for which the current level of effective bandwidth of accepted flows (not including that of the new request) will be maintained; this time interval is denoted \((t, t + t')\). Note that the algorithm assumes that no flows are prematurely terminated for any reason.

Every time a request for an item arrives the algorithm iteratively computes a provisional allocation of the currently unallocated bandwidth to items for interval \((t, t + t')\) in a manner that seeks to maximize the revenue generated for the service provider. Provisional allocations are based on the revenue values for each item, the probability of the request for item \(i^*\), plus the predicted effective bandwidth \(B_{eff}(t, t + t')\) is less than the total available bandwidth \(B_{TOT}\). The algorithm estimates the marginal cost associated with provisional allocation of an item \(i\).

\(|\pi_i(t, t + t')|\) Variable used to calculate probability of arrivals of an item assuming a poisson arrival process, within each iteration of the algorithm.

\(|\Pi_i(t, t')|\) Variable used to calculate probability of arrivals of an item assuming a poisson arrival process, within each iteration of the algorithm.

TABLE III

<table>
<thead>
<tr>
<th>Notation</th>
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</tr>
</thead>
<tbody>
<tr>
<td>(I)</td>
<td>The number of individual items of content available to the Service Provider.</td>
</tr>
<tr>
<td>(i)</td>
<td>A particular content item.</td>
</tr>
<tr>
<td>(p(i))</td>
<td>The peak bandwidth per second required by item (i).</td>
</tr>
<tr>
<td>(r(i))</td>
<td>The amount of revenue generated by accepting item (i).</td>
</tr>
<tr>
<td>(T_i)</td>
<td>The duration in seconds of flows associated with the streaming of item (i).</td>
</tr>
<tr>
<td>(q_i(-t', t))</td>
<td>The number of requests for item (i) during the time period ((-t', t)).</td>
</tr>
<tr>
<td>(n_i(t, t + t'))</td>
<td>The number of requests for item (i) that have been provisionally allocated by the algorithm.</td>
</tr>
<tr>
<td>(u_i(t, t + t'))</td>
<td>The marginal utility of accepting a request for item (i) during interval ((t, t + t')).</td>
</tr>
<tr>
<td>(i^*)</td>
<td>The item to which the flow admission request relates.</td>
</tr>
<tr>
<td>(v(i))</td>
<td>The marginal cost associated with provisional allocation of an item (i).</td>
</tr>
<tr>
<td>(\delta_i(t, t + t'))</td>
<td>The marginal utility per marginal cost of item (i).</td>
</tr>
<tr>
<td>(\pi_i(t, t + t'))</td>
<td>Variable used to calculate probability of arrivals of an item assuming a poisson arrival process, within each iteration of the algorithm.</td>
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item during the interval. If the admission control request is for item $i^*$ then the probability of the arrival of at least one request for item $i^*$ in the interval is set to 1 (since this request has just arrived). The marginal utility can therefore be expressed as:

$$u_i(t, t + t')_{|v(i)} = q_i(t-t', t)w_u e^{-q_i(t-t', t)}$$

and the marginal utility per marginal cost of provisionally allocating an item $i$, denoted $v(i)$, is the associated maximum bandwidth consumption of item $i$ over its specified duration:

$$v(i) = p(i)T_i$$

At each iteration the algorithm selects a provisional allocation to an item $i'$, decreasing the currently available bandwidth for a request for item $i'$ during $(t, t + t')$, denoted $\delta_i(t, t + t')$, is then:

$$\delta_i(t, t + t') = u_i(t, t + t')/v(i)$$

The marginal utility per marginal cost of provisionally allocating bandwidth for a request for item $i$ during $(t, t + t')$, denoted $\delta_i(t, t + t')$, is:

$$\delta_i(t, t + t') = u_i(t, t + t')/v(i)$$

The marginal cost associated with provisional allocation of an item $i$, denoted $u_i$, is the associated maximum bandwidth consumption of item $i$ over its specified duration:

$$u_i = p(i)T_i$$

We evaluate the performance of EAC and RMEAC against a number of previously proposed admission control algorithms. The algorithms we have chosen are similar to EAC and RMEAC in the sense that they too use a measurement of traffic characteristics and service request traffic descriptors. The algorithms we describe are the EBAC [6], [7], [8], [9], [10] , MTAC [11], [12], and a basic form of PBAC [4], [5].

**A. Experienced Based Admission Control (EBAC)**

EBAC operates by taking into consideration a measured peak to mean ratio of currently admitted traffic, denoted $U(t)$. Based on a collection of these measurements, the algorithm chooses an appropriate up to date reciprocal of this ratio, denoted $\varphi(t)$ (known as the over provisioning factor), suitable for inclusion in its admission control logic. The algorithm gains experience by using a complex approach to estimating the current over provisioning factor. Previous peak to mean ratios are calculated and stored in a time exponentially weighted moving histogram. By choosing the $95^{th}$ percentile of this histogram, the most up to date over provisioning factor can be calculated. The approach taken for estimating this value is depicted in Alg. 4. The peak measurements used within the algorithm are explicit peak rates supplied with the content item request. The algorithm aims to reserve adequate resources for admitted traffic by learning peak to mean ratios of traffic.

```plaintext
Algorithm 3: RMEAC admission control algorithm

Input: $i^*, B_{eff}(t)$

Step 1: Initialization
Calculate $t + t'$ as the time at which the first termination of the currently accepted flows is expected to occur;

forall items $i \in 1 \ldots I$ do

Set $q_i(t-t', t)$ to the number of requests for item $i$ in the interval $(t-t', t)$;
Set provisional allocation $n_i(t, t + t') = 0$;
Set $\pi_i(t, t + t') = e^{-q_i(t-t', t)}$;
Set $\Pi_i(t, t + t') = 1 - \pi_i(t, t + t')$;
if $i = i^*$ then
  Set marginal utility $u_i(t, t + t') = r(i)$;
else
  Set marginal utility $u_i(t, t + t') = r(i)\Pi_i(t, t + t')$;
  Set marginal cost $v(i) = p(i)T_i$;
Set remaining bandwidth
$B(t, t + t') = B_{TOT} - B_{eff}(t)$;

Step 2: Identify Optimal Provisional Allocation
if $B(t, t + t') > 0$ then
forall items $i \in 1 \ldots I$ do
  List all candidates that maximize $\delta_i(t, t + t')$;
if list contains item $i' = i^*$ then
  Accept request for item $i^*$;
STOP;
else
  Randomly select candidate allocation $i'$ from the list;

Step 3: Perform Allocation
if $B(t, t + t') - p(i') \geq 0$ then
Set $n_{i'}(t, t + t') = n_{i'}(t, t + t') + 1$;
Set $B(t, t + t') = B(t, t + t') - p(i')$;
else
  Reject request for item $i^*$;
STOP.

Step 4: Update Internal Variables
Set $\pi_{i'}(t, t + t') = \pi_{i'}(t, t + t') \frac{q_{i'}(t-t', t)}{n_{i'}(t, t + t')}$;
Set $\Pi_{i'}(t, t + t') = \Pi_{i'}(t, t + t') - \pi_{i'}(t, t + t')$;
Set $u_{i'}(t, t + t') = r(i')\Pi_{i'}(t, t + t')$;

Step 5: Loop Statement
if $B(t, t + t') > 0$ then
  GOTO Step 2;
else
  Reject request for item $i^*$;
  STOP.
```

Algorithm 4: EBAC Computation of the Over Provisioning Factor

**Input:** $F(t), M(t)$
**Output:** $\phi(t)$

Set $R(t) = \sum_{i \in F(t)} p(i)$;
Set $U(t) = \frac{M(t)}{R(t)}$;
Insert $U(t) \rightarrow P(t, U)$;
Set $U_p(t) = \min \{ u : P(t, U \leq u) \geq p_u \}$;
Set $\phi(t) = \frac{1}{U_p(t)}$;
**return** $\phi(t)$

Algorithm 5: EBAC Admission Decision Logic

**Input:** $i^*, F(t), \phi(t), \rho_{\text{max}}, B_{\text{TOT}}$  
**Output:** result (accept/reject)

if $p(i^*) + \sum_{i \in F(t)} p(i) \leq B_{\text{TOT}} \cdot \phi(t) \cdot \rho_{\text{max}}$ then
result = accept;
else
result = reject;
**return** result.

To take QoS into consideration, the algorithm sets a maximum link utilization threshold $\rho_{\text{max}}$. This threshold is calculated using a well known queuing system method of estimating effective bandwidth [3] of traffic with constant packet size, and constant inter arrival times. The approach assumes that the traffic arrives on the link following an $\text{N}\cdot\text{D}/\text{D}/1-\infty$ queuing system, with $\text{N}$ homogeneous flows, each sending packets of an expected size $E[B]$ and expected packet inter-arrival times $E[A]$. The rate of a particular flow $C_f$ is calculated as:

$$C_f = \frac{E[B]}{E[A]}$$

and the packet delay distribution of this system is calculated as:

$$P(W \leq t) = 1 - e^{-2x(t/N+1-\rho)}$$

where $x = t \cdot B_{\text{TOT}} / E[B]$ and $\rho = \frac{N \cdot E[B]}{C_f}$

The algorithm relies on this probability distribution to estimate the threshold, heavily depending on the queue system assumptions. It uses this to estimate the required maximum link utilization $\rho$ needed to avoid QoS violations as:

$$\rho_{\text{max}} = \max_{\rho} \rho : P(W > W_{\text{max}}) \leq p_W$$

Taking these considerations into account, the admission control algorithm depicted in Alg. 5 grants or rejects admission.

B. Measurement and a priori Traffic Descriptor based Admission Control (MTAC)

MTAC [11], [12] estimates the required effective bandwidth of traffic based on the assumption that traffic arriving at the admission point follows Gaussian characteristics. The equation below is used to estimate the effective bandwidth of currently admitted traffic, where $m$ is the mean aggregate bit rate, $\sigma$ is the standard deviation of the aggregate bit rate and $\epsilon$ is the upper bound on allowed queue overflow probability.

$$C_{\text{est}} = m + a' \sigma$$

where

$$a' = \sqrt{-2ln(\epsilon) - ln(2\pi)}$$

MTAC also uses a precaution factor to ensure it behaves more conservatively as the network approaches congestion; this factor is calculated as follows. A single reference flow is defined by a reference mean $m_{\text{ref}}$ and reference standard deviation $\sigma_{\text{ref}}$. For the total link capacity $B_{\text{TOT}}$, the number of reference flows $T_{\text{ref}}$ that can be simultaneously admitted for a given target bound on (the Packet Loss Ratio), is calculated. Using mean and standard deviation measurements collected, the total number of reference flows $N_{\text{ref}}$ within the admitted traffic is calculated. This is achieved by estimating both the number of reference flows that can produce the measured mean throughput, denoted $N_m$, and the number of reference flows that can produce the measured standard deviation $N_\sigma$. The calculations are as follows:

$$N_{\text{ref}} = \frac{(N_m + N_\sigma)}{2}$$

$$N_m = \left\lceil \frac{M_{\text{measured}}}{m_{\text{ref}}} \right\rceil$$

$$N_\sigma = \left\lceil \frac{\sigma_{\text{measured}}^2}{\sigma_{\text{ref}}^2} \right\rceil$$

The precaution factor, denoted $P_F$, defines the relationship between estimated number of reference flows $N_{\text{ref}}$ within the measured traffic, and the total number of reference flows $T_{\text{ref}}$ allowed within the total link capacity $B_{\text{TOT}}$:

$$P_F = \frac{N_{\text{ref}}}{T_{\text{ref}}}$$

Admission is simply based on whether the estimated bandwidth multiplied by the precaution factor is less than the total available bandwidth; if not, the flow is rejected (as outlined in Alg. 6).

C. Parameter Based Admission Control

As a comparison to the worst case scenario, we model a simple parameter based admission control algorithm (similar in nature to those defined in [4], [5]). The algorithm’s decision depends completely on the peak rate $p(i)$ of content items, as supplied by the traffic descriptor. No measurement is involved in this process. On receiving a content item request, the algorithm decides on admission if the admission test holds in Alg. 7. This test is simply whether the sum of the peak rates of all admitted flows, plus that of the new requesting flow, is less than the level of reservable bandwidth $B_{\text{TOT}}$. 
Algorithm 6: MTAC Admission Decision Logic

Input: $p_{new}, B_{TOT}, \epsilon, M_{measured}, \sigma_{measured}, P_F$
Output: result (accept|reject)

Set $a'_{PLR} = \sqrt{-2\ln(\epsilon) - \ln(2\pi)}$;
Set $B_{ext} = M_{measured} + p_{new} + a'_{PLR} \sqrt{\sigma^2_{measured}}$;
if $(B_{ext} P_F) \leq B_{TOT}$ then
result = accept;
else
result = reject;
return result.

Algorithm 7: PBAC Admission Decision Logic

Input: $i^*, B_{TOT}, \{F(t)\}$
Output: result (accept|reject)

if $p(i^*) + \sum_{j \in \{F(t)\}} p(j) \leq B_{TOT}$ then
result = accept;
else
result = reject;
return result.

V. Evaluation IPTV Scenario Description

From an IPTV admission control perspective, the entities we are interested in are the customer, the service provider and the network operator. A number of projects that have proposed business related scenarios for delivery of video-on-demand service over QoS enabled IP networks [26], [27], [28]. Within these projects, the concept of wholesale bandwidth is used to describe the arrangement where the service provider leases QoS guaranteed bandwidth from the network operator, an arrangement governed via an agreed Service Level Agreement (SLA). In turn, the service provider delivers QoS guaranteed services to its subscribed customers, as governed by a service provider-to-customer SLA (constrained by the limits of its own agreement with the network provider). Failure to meet these SLA targets usually results in loss of revenue through discounting. We define packet level QoS targets related to these agreements within our IPTV scenario and focus on how the service provider ensures its customers receive guaranteed QoS on traffic in line with their SLA(s).

The service provider has a maximum amount of bandwidth available at its disposal. We assume that within this limit, traffic will meet QoS packet delay targets as specified by the service provider to network operator SLA. For our scenario we assume the service provider leases bandwidth from the network operator assuming that at peak times, 20% of its customer base will be accessing offered content items (via unicast video-on-demand). As delivery of content can consume a large quantity of bandwidth, if the assumed peak in access is exceeded without adequate bandwidth management there will be degradation in QoS experienced by all customers, resulting potentially in significant revenue loss and customer dissatisfaction. In times of increasing network load, routers employ techniques such as Random Early Detection (RED), or Weighted Random Early Detection (WRED), which, when throughput reaches a particular threshold within a traffic class, drop packets randomly to avoid congestion. Packets are dropped randomly within the traffic aggregate; therefore, since users are not distinguished between within the traffic aggregate, all users flows will experience degraded QoS. This potential problem is particularly relevant for IPTV, given the relatively strict QoS targets for example, a packet loss ratio of $10^{-7}$s is specified by the DSL Forum [13]. The service provider should therefore employ an admission control strategy to avoid QoS violations, whilst maximizing bandwidth utilization to the degree possible.

A. Simulation Model

We now describe the simulation model used to evaluate the operation of the proposed admission control algorithms. Fig. 1 depicts a service provider, a network operator and a number of customers. Each customer is connected to the network through xDSL, with a downstream maximum throughput of 24Mbps. The service provider has a single point of connection to the network, through which all service traffic is aggregated; this is an OC-3 link with maximum bandwidth capacity of 155Mbps. It is at this ingress point that the effective bandwidth of aggregated traffic is estimated, and the service provider performs admission control on service requests. All traffic measurement is performed at this point and we assume that the required network dimensioning and traffic engineering has been performed by the network operator to ensure that traffic within the service provider’s leased bandwidth capacity will be delivered within agreed SLA targets. The service provider wishes to perform admission control on bandwidth up to 90% of the capacity of the link to ensure there is a 10% margin of precautionary bandwidth available. To ensure all video traffic is treated with common QoS targets, all flows are aggregated into a common traffic class; we assume that DiffServ is used for this purpose.

1) User Profile: The diurnal properties of the user group are modelled using typical assumptions of low and peak periods of activity. Specifically peak demand periods are assumed to exist during the evening, after work hours, while low demand periods occupy early morning and normal working hours. We assume that all customers are within the same time zone, so that our model represents a reasonably accurate representation of user intensity levels throughout a given 24 hour period. Fig. 2 demonstrates our configured content item request arrival rate intensities. Within a particular hour period, we use a standard poisson arrival process to generate arrivals with the
TABLE IV
CONTENT ITEM CHARACTERISTICS FOR EVALUATION IPTV SCENARIO

<table>
<thead>
<tr>
<th>i</th>
<th>req. arr. rate</th>
<th>( R(i) )</th>
<th>( p(i) )</th>
<th>( T_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>60/hr</td>
<td>$9</td>
<td>2.9 Mbps</td>
<td>1 1/4 hrs</td>
</tr>
<tr>
<td>2</td>
<td>200/hr</td>
<td>$3</td>
<td>2.7 Mbps</td>
<td>45 mins</td>
</tr>
<tr>
<td>3</td>
<td>60/hr</td>
<td>$1</td>
<td>2.6 Mbps</td>
<td>30 mins</td>
</tr>
</tbody>
</table>

expected mean arrival rate calculated from the corresponding hour period within Fig. 2.

2) Service Popularity and the Pareto Distribution: The Pareto distribution is commonly used to model a wide range of statistical characteristics such as distribution of wealth within a population. It can also capture other characteristics following the 80 : 20 rule where 80% of traffic generated within the network is contributed to 20% of available services [29]. We follow this rule and model the popularity of our available services on it. The effect this will have on traffic generated is that requests for the most popular content items will contribute to a high percentage of the overall requests.

3) Traffic Models and Characteristics: We use a number of the video frame traces, discussed in [30], to simulate realistic video traffic. The traces have been generated from several video sequences of typically 60 minutes. For admission control purposes we measure the peak rate of each video trace. Choosing an appropriate interval over which to measure the peak rate of a trace is essential as too large an interval can reduce the accuracy of the estimate, whereas too small an interval can lead to unnecessarily high peak rate measurements. We choose a measurement interval of 0.05s to measure peak throughput, this choice being based on the resolution at which we are measuring Quality of Service violations. Table IV, depicts the properties of each service within our simulation. This includes the content item rank, duration, cost and peak rate. An important simplifying assumption we make is that once a request for a content item is accepted, the customer will view that item for its complete duration without breaks (pausing).

4) Pricing Model: A simple pricing model is used where the most popular services generate the most revenue. For example, recently released feature films are typically priced higher than older content items. Within our model, the popularity of a item mirrors its frequency of requests. As requests are based on the Pareto distribution, we use this to provide a pricing structure for the modeled items. Based on this, we divide the items into three classes: class 1 represents the most requested items and are assigned a common cost of $9, the subsequent class 2 have an associated cost of $3, and the remaining class 3 have the lowest cost of $1.

5) QoS Violation Measurement: We measure QoS violations within the network by collecting a packet trace at a point following admission control and processing it through our FIFO queue algorithm. We set the FIFO queue service rate to the maximum reserved bandwidth rate. The algorithm will capture the proportion of traffic delayed greater than the specified QoS delay target. If this proportion is greater than the specified target, the traffic is in violation of the agreed service level agreement.

VI. EXPERIMENTAL RESULTS

The initial objective of our analysis is to demonstrate the advantage of using EAC, to the other defined admission control algorithms with respect to QoS assurance and bandwidth utilization in times of network congestion. The analysis evaluates the performance of each algorithm based on bandwidth utilization, proportion of traffic violations, and number of admissions. Following the analysis of EAC, we offer a comparison of its operation to that of RMEAC. We initially provide a set of results demonstrating the operation of RMEAC, followed by an analysis of the algorithm performance in comparison to EAC with regards to bandwidth utilization, QoS violations, and crucially, revenue generated by admitted content item requests.

A. Aggregated Traffic Flows

A primary advantage of basing admission control on an accurate measurement of effective bandwidth is the ability to account for the statistical multiplexing effect when traffic is aggregated on a link. As traffic is multiplexed, the required effective bandwidth for the aggregated traffic is reduced in proportion to the overall mean throughput of service flows admitted [31]. Awareness of this within EAC, allows the algorithm to more accurately predict the level of bandwidth necessary to ensure QoS targets on traffic are maintained, without over estimation of bandwidth requirements. The disadvantage of other approaches analysed is that they do not reflect the same behavior.

To demonstrate this effect, we set up a simple experiment where 32 flows admitted to the network steadily over a 5 hour period. We record the prediction of bandwidth required by each AC to perform admission control, divided by the current mean throughput (we refer to this as the effective bandwidth coefficient). Fig. 3 shows the relationship between estimated effective bandwidth coefficient and the number of aggregated flows. From this figure we see that:

- MTAC demonstrates a strict linear relationship between measured mean throughput and required bandwidth. This would have the disadvantage of under provisioning bandwidth for lower numbers of admitted flows.
settings outlined in section V. We observe that:

• PBAC depicts a linear response to increasing flows. Similar to MTAC, it does not respond to the statistical multiplexing effect.
• EBAC demonstrates a similar response to MTAC. As flows are added, the ratio of required bandwidth to mean throughput is estimated based on the link maximum utilization threshold. As this parameter is statically defined within the algorithm, it remains unchanged as the number of traffic flows admitted increase.
• EAC demonstrates a decrease in effective bandwidth coefficient as flows are added, reflecting the effect that multiplex gain has on the provisioning of required resources.

B. Admission Control of IPTV Content Items

Based on the outlined scenario, we perform admission control on the generated service requests over a number of simulation runs, each using one of the proposed admission control algorithms. The experiments evaluate the proportion of QoS violating traffic and bandwidth utilization for a set QoS target on packet delay of (0.02s, 0.0001). Fig. 4 depicts the bandwidth utilization based on admission control per algorithm and Fig. 5 depicts the QoS violations incurred by the respective algorithms. The results demonstrate the performance of each algorithm in response to the scenario settings outlined in section V. We observe that:

• PBAC has the lowest maximum bandwidth utilization of \( \sim 25Mbps \). While not incurring any QoS violations, this is considered an undesirable under-utilization of available resources;
• MTAC has a much higher maximum utilization of bandwidth at \( \sim 75Mbps \). This may be seen as a desirable utilization of available bandwidth; however this approach does incur significant QoS violations, as can be seen in Fig 5. MTAC predicts required bandwidth levels of admitted traffic based on a Gaussian distribution using a packet loss ratio of 0.0001. This leads to an under-estimation of required resources, thus leading to QoS violations as a result of admitting too many service requests;
• EBAC also has a high maximum bandwidth utilization of \( \sim 85Mbps \), but also incurs significant QoS violations. As this algorithm depends on a weak approach to controlling QoS, it allows content items to be accepted up to a maximum link threshold of 58.4% utilization. The approach assumes constant packet size and inter arrival times of packets, which over-estimates the maximum link utilization in this case;
• EAC utilizes an acceptable \( \sim 50Mbps \) of maximum bandwidth utilization, while incurring no QoS violations for this particular scenario, demonstrating an appropriate control of bandwidth with respect to QoS targets.

Within a QoS controlled network, it is important to be able to control the level of violations of set QoS targets. If QoS targets change, the admission control algorithm must respond in kind to the changes. We demonstrate here the effectiveness of EAC in responding to changing QoS requirements. Fig. 6 shows for a particular QoS target of (0.04s, 0.001), the utilization of bandwidth for each AC. We observe the following:

• PBAC performs exactly the same under the relaxed QoS target as for the more stringent QoS target. The reason for this response is because it does not take QoS targets into consideration when making admission decisions.
• MTAC is configured to use a relaxed packet loss ratio of 0.001 for this experiment. As a result, the estimated bandwidth requirements for admitted traffic is under-
C. Analysis of RMEAC versus EAC

We have demonstrated ability of EAC to utilize available bandwidth while meeting strict QoS constraints. We have demonstrated EACs ability to control QoS of admitted traffic while ensuring that an adequate, but not overly generous, amount of bandwidth is used. However, an additional goal of a service provider is to maximize revenue generated over available bandwidth while maintaining QoS targets of admitted traffic. Thus, in times of high demand for content items the service provider is likely to desire that traffic flows carrying high-revenue content items are prioritised over those of lower revenue. In this section we show how the RMEAC algorithm meets this objective.

We now demonstrate the operation of RMEAC under an artificial scenario in which a sudden burst in demand for a particular content item occurs. Figs. (8 - 13) demonstrate the operation of RMEAC in comparison to EAC. There are three classes of content items, with the characteristics listed in Table IV. Initially service requests for items belonging to each of the three classes are equally distributed. At 1.25 hours into the simulation, we simulate a sudden burst in requests for an item in one of the three classes. We now discuss the result of a burst occurring within each class, the effect that RMEAC has on the admitted flows, and a comparison to the same event as controlled by the EAC algorithm.

1) Burst in service class 1: Fig. 8 demonstrates the resulting throughput per content item class over the duration of the experiment. When a burst of requests arrive for items in class 1, requests from the other classes are given less priority based by RMEAC. As available bandwidth reduces, service admissions from the lower priority classes are almost completely throttled. Throughput reaches a maximum utilization of $\sim 50 \text{Mbps}$, with no QoS violations. When the burst reduces and normal operation is restored, services from the other lower revenue classes are again granted admission.

Fig. 9 demonstrates the same experiment conditions with admission controlled by EAC. EAC does not prioritize higher value services but rather operated on a first-come-first-served basis. The effect here is that a limited number of services from the other lower class services are admitted, resulting in lower revenue generated in total to that of RMEAC.

2) Burst in service class 2: Fig 10 depicts the results for a burst in service requests of content item class 2 occurs. Here, RMEAC utilizes a similar level of bandwidth as the previous example, again with no QoS violations. However, instead of flows relating to the class with the burst in requests dominating the entire bandwidth, RMEAC protects requests for the higher revenue class 1, and throttles requests from the lower revenue class. This experiment demonstrates the gain of RMEAC over EAC. EAC does not prioritize class 1 items, and thus loses out on revenue gaining opportunities.

3) Burst in service class 3: Fig. 12 depicts the bandwidth utilization from each class after a burst in requests for an item in class 3. The results demonstrate that requests from the two higher revenue classes are both protected, thus prioritizing these over requests for the lower revenue class 3 items. As shown in Fig. 13, EAC again does not prioritize requests for higher revenue items, resulting in a reduction in possible revenue gain.
VII. CONCLUSION

This paper has proposed two admission control algorithms focussed on the IPTV application domain. Both algorithms are founded on an empirical method of estimating the effective bandwidth of a set of aggregated traffic flows, which was shown to be superior to a number of other estimation approaches. In particular, the empirical estimation approach has the ability to reflect the significant effect of statistical multiplexing when flows are aggregated over the same link; therefore, it leads to more accurate effective bandwidth estimations. More accurate effective bandwidth estimations in turn allow specification of admission control algorithms that avoid QoS violations, but, crucially, in doing so allocate close to the minimal necessary amount of bandwidth. This allows service providers efficiently utilize the bandwidth they may lease from a network operator, whilst ensuring that their customers receive satisfactory QoS levels.

The two algorithms we proposed were (1) EAC, which uses a simple decision process based on the availability of sufficient bandwidth following the admission of a new content item request and (2) RMEAC, which involves a more complex decision process which evaluates the likelihood of the arrival of higher-revenue item requests in the time it will take to serve the current item request; if this likelihood is sufficiently high the current request will be rejected even if sufficient bandwidth is available. Experimental results showed that EAC out-performed a selection of previously-proposed admission control algorithms in terms of reaching the appropriate trade-off between ensuring QoS targets are met and not over-allocating bandwidth. Further results showed that, in certain conditions, RMEAC can out-perform EAC in terms of max-
imizing the revenue generated for the service provider by admitted traffic flows.

In future work we plan to extend both EAC and RMEAC to operate effectively in a distributed environment where a service provider must manage multiple traffic ingress points sharing limited bandwidth. In such circumstances admission of traffic flows into the network must be coordinated as to avoid incurring QoS violations at any point within the network. In addition we will investigate the effect of relaxing some of the simplifying assumptions made in this paper; for example, the assumption that all admitted flows are not interrupted by customers.

REFERENCES


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