An Approach to Measurement based Quality of Service Control for Communications Networks

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***Abstract*—This paper presents a purely empirical approach to estimating the effective bandwidth of aggregated traffic flows independent of traffic model assumptions. The approach is shown to be robust when used in a variety of traffic scenarios such as both elastic and streaming traffic flows of varying degrees of aggregation. The method then forms the basis of two Quality of Service related traffic performance optimisation strategies. The paper presents a cost efficient approach to supplying suitably accurate demand matrix input for QoS related network planning and a QoS provisioning, revenue maximising admission control algorithm for an IPTV services network. This paper summarises these approaches and discusses the major benefits of an appropriately accurate effective bandwidth estimation algorithm.**

***Index Terms*—Effective Bandwidth, Quality of Service, Aggregated Traffic, Demand Matrix, Admission Control, Revenue Optimization.**

I. INTRODUCTION

QUALITY of Service (QoS) control of traffic within a communications network is crucial for successful generation of revenue for the network operator. The network operator wishes to guarantee QoS of traffic while optimising the utilisation of network resources. Central to a network performance optimisation strategy for QoS control is the estimation of effective bandwidth, which is the minimum amount of bandwidth required on a link to maintain QoS targets of a traffic flow [1]. However the estimation of effective bandwidth is a non trivial task. Traditional approaches that are reliant on traffic model assumptions to estimate this value [2], [3] can lead to sub-optimal utilisation of bandwidth resources, if used for performance optimisation.

This paper presents a purely empirical effective bandwidth estimation algorithm independent of traffic model assumptions that can accurately estimate the effective bandwidth of aggregated traffic flows. The paper goes on to demonstrate how such an approach can be used in performance optimisation strategies for QoS control of traffic within the network. The authors focus on aspects of two processes, namely: long-term network planning and short term admission control for IPTV flows. They propose and evaluate a cost effective process for preparing demand matrix input suitable for long term QoS aware network planning. The authors demonstrate that such a solution is both appropriately accurate for long term network planning requirements and cost effective for the network operator to deploy in comparison to a direct network monitoring system deployment. The approach uses the effective bandwidth estimation algorithm to propose a ratio of effective bandwidth to mean throughput demands estimated from accounting data records, known as the effective bandwidth coefficient. The author also proposes and evaluates a revenue maximising admission control algorithm suitable for use within IPTV service delivery networks. The admission control algorithm depends on accurate estimation of effective bandwidth to ensure that QoS targets of admitted traffic flows are maintained. It also utilises information relating to cost, duration and request frequency of specific IPTV content to prioritise higher revenue flows within the admission process.

This paper summarises the contributions of the work presented in [4] with regards to developing and evaluating the techniques discussed. The paper is structured as follows: §II discusses the requirements of effective bandwidth estimation within a communications network and provides a summary of the proposed empirical effective bandwidth estimation algorithm with reference to supporting results; §III summarises the proposed cost effective process of establishing input for QoS aware network planning known as QoSPlan; §IV offers an overview of the proposed revenue maximising admission control algorithm; and finally §V concludes the paper and offers some future research directions.

II. EFFECTIVE BANDWIDTH ESTIMATION WITHIN A COMMUNICATIONS NETWORK

Effective bandwidth is defined as the minimum amount of bandwidth required by a traffic flow to maintain a specified QoS related target [1]. There are many approaches proposed to estimate the effective bandwidth of a traffic flow [2], [3], however the majority of these approaches rely on the formal specification of a traffic model and depend on the traffic within the network being conformant with given traffic model assumptions. Such approaches are generally unsuitable for use within a communications network as traffic can be quite difficult to model over varying time-scales, this is backed up by evidence of self-similarity within traffic [5].

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For example, in [2] Guerin proposes an approach to estimating the effective bandwidth of a traffic flow based on the assumption that packets are arriving at a point following a Gaussian distribution. While in [3] and [6] Roberts proposes an approach to estimating the effective bandwidth of a traffic flow assuming uniform packet size and inter arrival times. These approaches depend on the traffic being well behaved and assumes no deviation from the traffic model assumptions. However as traffic is aggregated at a point, the relationship between the effective bandwidth of traffic and its associated QoS targets begin to vary (also known as statistical multiplexing). As stated in [7] as a result of this, the required effective bandwidth per individual flow decreases as the number of flows aggregated at a point increase. However the approach proposed in [7] is also dependent on traffic model assumptions, and is therefore difficult to capture this effect on realistic traffic. The accurate measurement of effective bandwidth for aggregated traffic flows is vital for controlling QoS of traffic within communication networks. The paper now presents a summary of the purely empirical approach for estimating the effective bandwidth of aggregated traffic flows independent of traffic model assumptions.

A. Empirical effective bandwidth estimation algorithm

The concept of empirically estimating effective bandwidth is primarily based on replaying a collected packet trace through a simulated First In First Out (FIFO) queue at various queue service rates and observing the queue buffer behaviour. The approach depends on the following observation; Let $delay_{max}$ be the nominal maximum packet delay target and let p_{delay} be the proportion of traffic which can exhibit delay greater than $delay_{max}$. If a collected packet trace is processed through the FIFO queue for a particular queue service rate R, then p denotes the proportion of traffic violating $delay_{max}$. For different queue service rates $R_1 > R_2$, and estimated proportion p_1 and p_2 of traffic delayed greater than $delay_{max}$ then $p_1 \leq p_2$ as R_1 is a higher service rate, and therefore more capable of processing the packet trace while minimising delay. This means that the proportion of traffic p delayed more than $delay_{max}$ is a monotonically decreasing function of queue service rate R. Using this observation it is straightforward to design a search algorithm for a recorded packet trace to find the minimal value of a queue rate such that the proportion of traffic delayed more than $delay_{max}$ is less than p_{delay}.

Based on this observation the algorithm [8] proceeds as follows: Initially two queue service rates are set up as the mean and peak throughput of the supplied packet trace. The algorithm will continue while the proportion of violating traffic for service rate R_1, namely p_1, is not equal or equivalent to p_{delay}. p_1 and p_2 are initially calculated by processing the supplied packet trace through the FIFO queue using the associated service rates and traffic delay target. Once $p1$ and p_2 are calculated the search algorithm recognises that p_1 will be much higher than p_2, as more traffic will violate the violation target while using the lower service rate of R_1. Using this observation, the algorithm will evaluate where p_{delay} is in relation to these two search points. The algorithm will continue looping, and refining the values R_1 and R_2 to close in on the violation target. Once R_1 returns a violation proportion within the error region of p_{delay} the algorithm will exit and return the service rate R_1 as the effective bandwidth of the packet trace, specific to the supplied delay and violation target. As this effective bandwidth value does not take into consideration the delay experienced by the packet traversing the network, we treat it as a per hop effective bandwidth estimation and not an end-to-end estimation.

B. Experimental analysis

In order to evaluate the performance of the specified algorithm, a time and space complexity analysis of the algorithm was performed. As the algorithm relies on the simulation of a FIFO queue model to estimate the proportion of QoS violations that a packet trace incurs for a particular queue service rate, each packet within the packet trace must be processed in succession. This operation happens in time O(N), where N is the number of packets within the packet trace. As the algorithm uses a binary search algorithm to choose appropriate service rates dependent on the associated QoS violations experienced, the algorithm must repeat the previous operation in time O(log$M$), where M is the search space of possible QoS violations. M is dependent on both the QoS violation target, p_{delay} and an error resolution parameter, denoted β. This error resolution parameter, calculated as $p_{delay} * \beta$, is used by the algorithm to evaluate whether an appropriate QoS violation target has been found. The algorithm evaluates ± this value of the calculated p against the target p_{delay}. Therefore we can calculate M as $\frac{1}{p_{delay}\beta}$. As the algorithm employs a binary search strategy to locate the QoS violation target and corresponding queue service rate, the theoretical number of algorithm iterations can be found as follows:

$$\log_2(\frac{1}{p_{delay}\beta})$$

Within [4] the author demonstrates that the algorithm performs in line with the above theoretical statement, thus demonstrating that by varying either the packet trace size or the search space, the performance of the algorithm can be improved.

The author also evaluated the proposed algorithm against two comparative approaches to estimating effective bandwidth of traffic flows. The two approaches chosen were the Gaussian estimation [2] and the Roberts estimation [3]. The algorithms were evaluated on estimating the effective bandwidth of a set of aggregated traffic flows for a set of QoS targets of packet delay. As the volume of aggregated traffic flows increased from 1 to 64, the empirical effective bandwidth estimation algorithm demonstrated a decrease in effective bandwidth requirements per traffic flow. However the other two approaches demonstrated a static effective bandwidth estimation per traffic flow, regardless of the volume of aggregated traffic flows. The reason behind this is that the latter two approaches depend on set traffic model assumptions, and as the traffic characteristics of flows are modified as a result of statistical multiplexing at the point of aggregation, the algorithms fail to compensate for this.

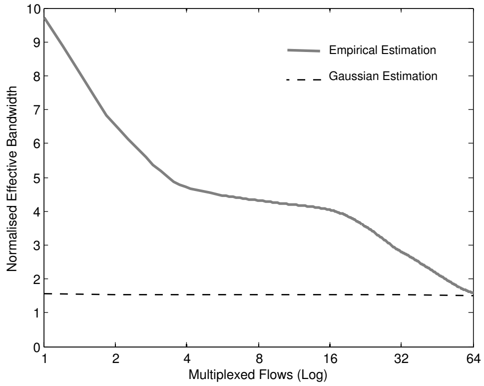

Fig. 1. Empirical versus Gaussian estimation of effective bandwidth of aggregated traffic flows (Elastic).

Fig. 1 depicts a graph of normalised effective bandwidth per traffic flow as estimated by the empirical effective bandwidth estimation algorithm and the Gaussian estimation algorithm. A further evaluation of these results are demonstrated in [4]. The remainder of this paper discusses the usefulness of an accurate approach to estimating effective bandwidth with respect to QoS control within a communications network.

III. COST EFFECTIVE DEMAND MATRIX PREPARATION FOR QOS AWARE NETWORK PLANNING

The process of network planning typically involves the use of dedicated network monitoring hardware to gather and collate large amounts of network traffic data, which is then analysed to identify an optimal network configuration design reflecting estimated demand and specified QoS requirements. Use of dedicated hardware means that this approach can be relatively expensive, incurring costs in hardware procurement and maintenance, in addition to significant training and operational costs. This paper now presents an alternative process for supplying the appropriately accurate traffic demand information, required to support QoS related network planning activities. The process called QoSPlan, [9], [10] is designed to address network operator requirements of supplying viable QoS related data to the network planning process at minimal cost. An investigation into the accuracy and cost efficiency of QoSPlan under different traffic scenarios through a comparison with a direct network monitoring system is discussed.

A. The QoSPlan process

Vital to any network planning process is the establishment of a network wide view of traffic demands between edge routers, this is commonly termed the demand matrix [11]. The demand matrix maps the throughput of traffic between two edge node pairs on a network for a particular traffic class. As the objective of QoSPlan is to supply this input to the network demand matrix with minimal additional hardware deployments, QoSPlan focuses on harnessing the network operators' currently deployed systems to establish this input. Network operators traditionally generate revenue through charging for the usage of bandwidth over their network and therefore generally deploy a network accounting system. QoSPlan analyses collected accounting system data to establish suitable input to the network planning process. It is designed as an extension to existing network accounting system deployments. However, as identified in [10], a demand matrix prepared in such a manner does not take effective bandwidth requirements of these traffic demands into consideration, therefore QoSPlan introduces an additional step to take this into consideration. QoSPlan uses an estimated effective bandwidth coefficient to relate the estimated traffic demands within the demand matrix to corresponding effective bandwidth requirements of traffic. The architecture is illustrated in Fig. 2. Two separate phases have been developed to establish the necessary input required for QoS aware network planning; the estimation of a demand matrix per traffic class from accounting system data; and the estimation of appropriate effective bandwidth coefficients from a set of collected packet traces. A method of establishing an appropriately accurate demand matrix from accounting data is presented in [8] and further analysed and evaluated in [4] and [10].

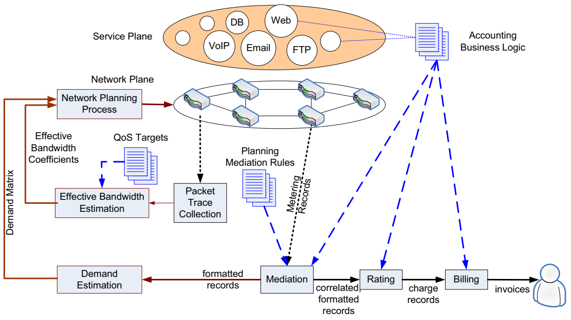

Fig. 2. QOSPlan Architecture

The effective bandwidth coefficient serves as a method of taking the QoS requirements of traffic into consideration. The approach is to collect a number of short packet traces from each traffic class at a number of ingress points from around the network. The empirical effective bandwidth estimation algorithm is used to calculate the effective bandwidth of each packet trace collected. This approach is perfectly suited to this scenario as the effective bandwidth algorithm is independent of any traffic model, and only requires packet traces to operate along with supplied QoS targets on packet delay. The approach now establishes a generalised effective bandwidth to mean traffic demand ratio. This is termed the effective bandwidth coefficient and is established as follows: the mean throughput, $mean_i$, is calculated for each packet trace collected, as is the associated effective bandwidth for that packet trace $R_{eff,i}$ where i identifies the packet trace being evaluated from the set of collected traces, $i \in \{1..I\}$; using these values we estimate the effective bandwidth coefficient k_i as:

$$k_i = \frac{R_{eff,i}}{mean_i}$$

The effective bandwidth coefficient k_i is calculated for all packet traces collected per traffic class. The set of coefficients

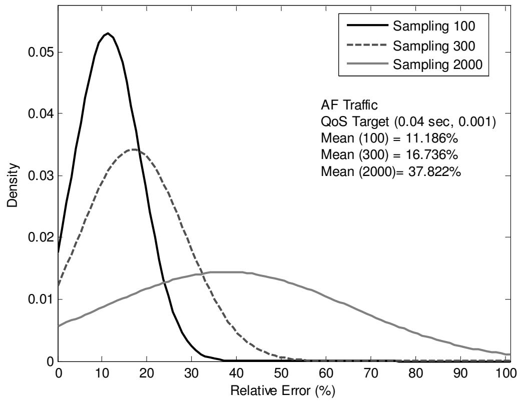

Fig. 3. Directly measured effective bandwidth versus QoSPlan estimated effective bandwidth for AF traffic.

calculated allows one to generalise a relationship between estimated network mean demands and effective bandwidth requirements based on supplied QoS targets per traffic class within the network. Further considering a set of I coefficients $k_1, \cdots, k_I$, the approach first excludes any k_i with too low a mean rate using some appropriate threshold value. The reason for this is that for low levels of traffic aggregation, the effective bandwidth to mean throughput ratio would be quite high in comparison to higher levels of aggregation. This is due to the effect statistical multiplexing has on the effective bandwidth of aggregated traffic flows, as discussed earlier in section II. The contribution of the low mean throughput to overall network demand, is minimal in respect to the effect its associated coefficient may have on the set of coefficients. The next step is to calculate a suitable representative coefficient of effective bandwidth K as the 95^{th} or 99^{th} percentile of the remaining set of coefficients.

B. *Experimentation and results*

A number of experiments were performed to evaluate the accuracy of QoSPlan in establishing viable input for network planning in comparison to a dedicated network monitoring system. The experimental analysis demonstrated that various packet sampling strategies employed during the collection of accounting records, in particular IP flow records [12], can impact on the accuracy of traffic demand estimated from the collected accounting data records. The study demonstrated that QoSPlan can supply appropriately accurate, QoS related traffic demand data suitable for long term network planning, with a global relative error of up to 10% for particular settings in comparison to a dedicated network monitoring system. A sample of the results presented in [4] can be seen in Fig. 3.

Based on a set of anecdotal cost assumptions, an economic analysis between the deployment costs of QoSPlan versus a dedicated monitoring system deployment was presented in [4] and [10]. The study demonstrates that a clear difference in the cost of deploying both approaches for networks of different sizes, with the QoSPlan deployment costs incurring savings of up to 80% in comparison to a direct monitoring system deployment. This is a result of the greater level of reuse of existing system data (such as accounting system data) in the QoSPlan deployment and the requirement for installation of significantly more hardware in the direct monitoring system deployment.

IV. QOS BASED IPTV ADMISSION CONTROL

Admission control is a technique used by service providers to ensure customers traffic flows are allocated sufficient bandwidth to ensure Service Level Agreements (SLA) relating to packet-level QoS are maintained during periods of network congestion. The goal of the service provider is to guarantee QoS for accepted traffic flows while maximising bandwidth available for newly arriving flows. In the context of IPTV service delivery, admission control plays a vital role, as flows (streaming movies and TV programmes) are typically high-bandwidth and must meet stringent QoS targets, so bad admission decisions can significantly degrade QoS for all accepted flows.

A key performance metric of any admission control algorithm is its ability to predict the level of resources required to admit a requesting flow. If a new flow request is accepted, the outlined packet level QoS must be guaranteed, without affecting QoS of already admitted flows. Fundamental to this process is the prediction of required effective bandwidth of the aggregated traffic following admission of the new flow. If the admission control algorithm predicts that aggregated effective bandwidth, should the flow be accepted, will be greater than the available bandwidth, the flow must be rejected. Clearly, the more accurate the estimation of effective bandwidth, the more effective the admission control algorithm operates as a whole. An admission control algorithm based on an empirical estimation of effective bandwidth, which maximises revenue for the service provider, is now presented.

A. *Revenue Maximising Admission Control Algorithm*

The admission control algorithm, further specified in [13], [14], uses empirical effective bandwidth estimation of admitted traffic to ensure QoS targets of admitted traffic are maintained, and uses knowledge associated with the IPTV content within the admission decision process to maximise revenue for the service provider. The objective is to use historical information about content item request arrivals, together with associated cost and resource requirements, to maximise expected revenue. The revenue maximisation algorithm is base on the work of [15], who defined a revenue optimisation algorithm for load control in Intelligent Network service delivery environments.

The algorithm assumes there is a set of I individual items of content made available by the service provider to the customer. 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.

Each time a request for an item arrives, the admission control algorithm iteratively computes a provisional allocation of the currently unallocated bandwidth to item for interval $(t, t + t')$ in a manner that seeks to maximise the revenue generated for the service provider. Provisional allocations are based on the revenue values for each item, the probability of the arrival of requests for those items in the interval $(t, t+t')$, and the peak bandwidth required for each item. The algorithm assumes that requests for items arrive following Poisson arrival process [1], hence the number of arrivals for item i in the interval $(t-t', t)$, denoted $q_i(t-t', t)$, can be taken as an estimate of the number of arrivals for the interval $(t, t + t')$. As the iterations progress, the number of requests for item for which bandwidth has been provisionally allocated, denoted $n_i(t, t+t')$, is stored.

At each iteration the provisional allocation of bandwidth to an item i is the one that maximises the marginal utility to marginal cost in comparison to the other possible allocations. The marginal utility, denoted $u_i(t, t + t')$, is defined as the revenue associated with accepting a request for that item, times the probability of an arrival of an additional request for the 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:

$$u_i(t, t + t')|_{i \neq i^*} = r(i) \sum_{w=n_i(t,t+t')+1}^{\infty} \frac{q_i(t-t', t)^w}{w!} e^{-q_i(t-t', t)}$$

$$u_{i^*}(t, t + t')|_{n_{i^*}(t,t+t')=0} = r(i^*)$$

$$u_{i^*}(t, t + t')|_{n_{i^*}(t,t+t') \neq 0} = \\ r(i^*) \sum_{w=n_{i^*}(t,t+t')+1}^{\infty} \frac{q_{i^*}(t-t', t)^w}{w!} e^{-q_{i^*}(t-t', t)}$$

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

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

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

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

At each iteration the algorithm selects a provisional allocation to an item i', decreasing the currently available bandwidth for the interval, denoted $B(t, t + t')$, by $p(i')$. The algorithm terminates when the provisional allocation is for item $i' = i^*$, in which case the request for item i^* is accepted, or when the value of $B(t, t + t')$ is too small to make a given provisional allocation, in which case the request for item i^* is rejected.

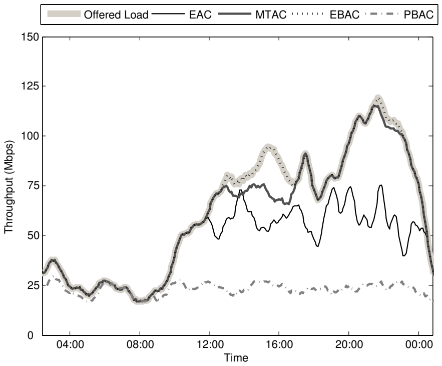

Fig. 4. Bandwidth utilization of admission control algorithms with relaxed QoS targets.

B. *Experimentation and results*

The authors performed a number of experiments to evaluate the performance of the admission control algorithm, further discussed in [14]. The experiments evaluate the performance of the algorithm against three comparative admission control algorithms under a number of different traffic scenarios employing real traffic traces of long-lived flows. The algorithms within the comparison included the Parameter Based Admission Control algorithm (PBAC) [16], the Measurement based a priori Traffic Descriptor based Admission Control algorithm (MTAC) [17] and the Experience Based Admission Control algorithm (EBAC) [18]. From the perspective of QoS control the admission control algorithm demonstrated that an adequate, but not overly generous, amount of bandwidth is allocated to ensure that QoS targets for accepted flows are met. A sample of the results depicted in [14] are shown in Fig. 4 which demonstrates bandwidth utilisation of each of the admission control algorithms within the experiment.

To evaluate the revenue maximising algorithm, the admission control algorithm was compared against an admission control algorithm with no revenue maximising decision logic within the admission control process (this less sophisticated algorithm is termed the empirical effective bandwidth estimation algorithm or EAC). A scenario where a number of IPTV services of different values and request arrival rates were used to evaluate whether higher revenue services were protected by RMEAC during timed of network congestion in comparison to that of EAC under identical conditions. A sample of the corresponding results are depicted in Fig. 5 and Fig. 6.

The figures depict that for an increase in service requests from a particular service group, RMEAC preserves the admission of these services during times of congestion as they are considered more valuable to the service provider, as apposed to an admission control algorithm that does not take IPTV service related information into consideration. This scenario demonstrates the possible gain in revenue of RMEAC over EAC, as EAC does not priorities higher valued flow requests, and thus loses out on revenue gaining opportunities as depicted

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[1] The Poisson arrival process is 'memoryless' meaning, so the measured mean arrival rate for the previous interval is as good an estimate for the following interval as any.

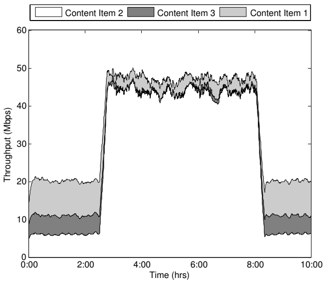

Fig. 5. Burst in requests for content item class 2 (RMEAC).

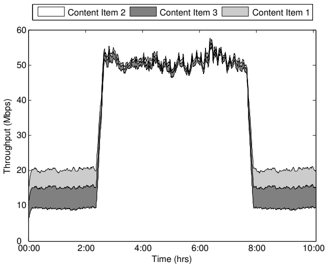

Fig. 6. Burst in requests for content item class 2 (EAC).

on figure 6. In this case, RMEAC demonstrates a gain of 16.4% in revenue, demonstrating the ability of RMEAC to increase revenue while maintaining QoS control and appropriate bandwidth utilisation.

V. CONCLUDING REMARKS AND FUTURE WORK

This paper has provided a summary of the work presented within the lead author's thesis [4] and associated publications [8], [9], [10], [13], [14]. The paper defines a purely empirical effective bandwidth estimation algorithm independent of traffic model assumptions. The approach can accurately estimate the effective bandwidth of aggregated traffic flows of various traffic types such as elastic and streaming traffic. This method then forms the basis of two traffic performance optimisation strategies for long term network planning and short term admission control. The paper demonstrated that with the benefit of an accurate effective bandwidth estimation algorithm, a cost effective method of supplying appropriately accurate QoS related input for network planning. The paper also demonstrated that an admission control algorithm can use the effective bandwidth estimation algorithm to maintain QoS targets of admitted traffic, and with this improve revenue generation by the service provider through employing a revenue maximising algorithm utilising IPTV specific information such as item cost and request arrival frequency. It is envisaged that such an effective bandwidth estimation algorithm can have a wide range of applications within the domain of QoS control for communications networks, such as traffic engineering and routing. The effective bandwidth estimation algorithm itself has room for improvement. At the moment the algorithm is an off-line approach which can limit its applicability to some memory and time constrained scenarios. The objective is to investigate the development of an online effective bandwidth estimation algorithm, independent of traffic model assumptions.

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