Traffic characterization for flexible service delivery in next-generation converged access networks

Evangelos A. Kosmatos, Theofanis G. Orpahnoudakis, Helen C. Leligou, Eleftherios Tsampasis

Abstract**—** The evolution towards converged access networks and the importance of quality of experience at an affordable cost brings the need for access networks that can offer a wide range of services not currently available to the desired extent. Legacy networks used explicit signaling that traversed all nodes along the path to book resources before the launch of the media stream. This approach does not scale and cannot provide adequate resource control and Service Level Agreement (SLA) management in scalable and autonomous packet networks. Still, the need to reserve resources in advance remains since real-time services have limited, if any, means of adjusting their rates to the prevailing network conditions. Hence, in order to preserve customer satisfaction, the traditional preventive approach that reserves resources for the duration of the session is the only option. This paper proposes a measurement based approach to derive the flow resource needs and then trigger the Resource and Admission Control enriching the network with implicit admission control. We evaluate the proposed methodology against other approaches that employ measurement based Effective Bandwidth estimation and demonstrate its noticeable performance in terms of achievable resource utilisation, accuracy and practical feasibility

Keywords**—**DBA, Effective Bandwidth, Leaky Bucket, MAC, PON, TDMA.

I. INTRODUCTION

An emerging type of service in converged access networks is wireless backhauling provided by access network providers to Mobile Network Operators (MNOs). The growing popularity of mobile data services necessitates a rapid rise in network capacity not only on the air interface to the end user but also in the backhaul network. The latter is quite important in the mobile operator business model affecting capital investment, operational expenses, service deployment and customer experience. Fiber infrastructure is inevitably the only long-term solution and the deployment of Passive Optical Networks (PONs) presents an opportunity for a cost-effective, scalable and future proof solution. In this paper we investigate the use of Passive Optical Networks (PONs) for mobile backhaul and propose a resource allocation framework building on the efficiency of PONs to share resources, dynamically allocate bandwidth in real-time and enhance efficiency by improved statistical multiplexing. The novelty of the proposed approach lies in the translation of the new possibilities offered by PON into negotiable SLA parameters for the benefit of the MNO.

The purpose of this paper is to assess the traffic-handling capabilities of TDMA PONs under such a mixed initial traffic scenario and provide appropriate mechanisms for the efficient estimation of the real time LTE Base Stations (BSs) bandwidth needs. To provide Quality of Service (QoS) in a cost efficient manner, enough network resources have to be reserved for each customer and associated traffic flow to fulfill its needs. Most usually QoS is generally expressed in terms of packet loss, delay and delay variation whereas the network resources that can be employed to control the available QoS level to a packet flow are a guaranteed service rate and available buffer space (in case the service cannot be readily available and packets need to be delayed in queuing points). Some form of flow admittance process and the corresponding admission control are also required in order to guarantee the QoS levels of flows according to pre-established SLAs. The objective of flow characterization, admission control and corresponding resource reservation as described throughout this paper is to trigger appropriate measures to guarantee the required QoS level to all accepted flows. This can be achieved through a number of mechanisms including appropriate configuration of service rates in intermediate traffic management entities (schedulers and shapers), congestion indication and packet marking, appropriate configuration of buffer management entities (e.g. early drop techniques) and in case of heavy congestion (i.e. when the QoS of pre-established flows is at risk) connection blocking.

The autonomic network operation and SLA management should also take into account the mixed service provisioning model that frequently arises, since mobile backhauling will not be the only service delivered over a single PON network. In most cases PONs are expected to be shared among several residential and business users including MNOs. Future Internet-based networks are expected to evolve as data-centric networking platforms providing services beyond today's

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expectations for shared workspaces, Peer-to-Peer (P2P), distributed data storage, cloud and grid-computing, broadcasting and multi-party real-time media-rich communications and many types of e-services such as sophisticated machine-machine interaction between robots, e-health, and interactive e-learning. Many of these new network models have been designed to work transparently on overlay networks and have no means of communicating with the network layer. In the mixed use and as traffic picks up, the obvious simple initial approach of over-provisioning exhausts its usefulness and the role of the TDMA part of the PON become prominent for a good utilization and hence profitability. To bring QoS in such architectures, there is a need to obtain estimates of their resource needs by indirect methods, since real-time services have poor means of adjusting their rates to the prevailing network conditions without compromising customer satisfaction. Thus, the traditional preventive approach that needs a priori estimates of resource needs for the duration of the session is the only option.

When explicit signaling is not available, ways to deduce the flow needs from measurements have to be defined. These needs refer to the network resources and more precisely to the bandwidth and buffer space needs of atomic but also already bundled flows that are directed to specific core interfaces and queuing points. The characterization is crucial for efficiently utilizing the available infrastructure. When the type and descriptors of a specific flow are known in advance, then admission control and policing become quite straightforward.

In this paper we propose a resource allocation framework based on the operation of distributed agents that can automate the procedures of SLA management, estimation of resources and adaptation to dynamic traffic load profiles. A resource estimation algorithm is proposed and compared against other approaches proposed in the literature. A performance assessment is conducted by using simulations for the selection of the most appropriate bandwidth estimation algorithm in terms of high bandwidth utilisation, low percentage of violations and practical feasibility.

The structure of the paper is as follows: in Section II we describe the high-level architecture, the basic requirements and the motivation behind our work. In Section III we describe the main principles for autonomic bandwidth estimation and the algorithms that can be implemented to achieve this. In Section IV we present comparative simulation results for a broad range of such algorithms and provide our concluding remarks in Section V.

II. TDMA PON Architecture and Resource Allocation Framework

The typical case of a proposed mixed mobile and fixed user backhaul is depicted in Fig. 1. There are two dominant TDM PON standards that can be used for the mixed backhaul network: GPON [1] and EPON [4]. Both foresee the support of different QoS levels embedded in TDMA PONs for a successful performance, but operators must be well aware of the idiosyncrasies of priorities and MAC functions. There is

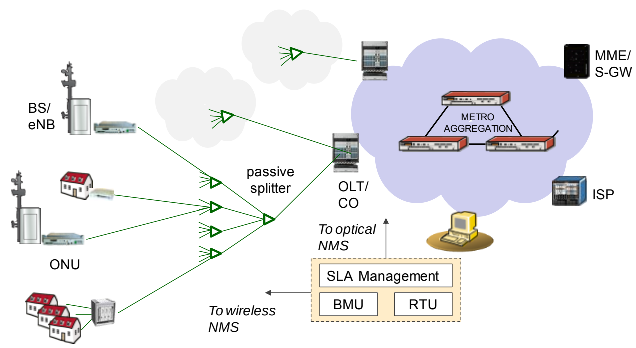

Fig. 1 Typical mixed PON architecture

no space herewith to dwell on the way the PON MAC operates and the reader can find relevant information in [1], [2] for the GPON and [3], [4], [5] for EPON. The architecture illustrated in Fig. 1 allows Mobile Network Operators (MNOs) and other business users pressed with the need to raise the capacity of the backhaul by taking advantage of a probably already deployed residential TDMA PON at a fraction of the cost of a dedicated fiber. On the other hand, the fixed local loop operator, can exploit the benefits of bringing services to business customers leasing a significant percentage of the PON bandwidth. At the crucial initial stage of deployment this may significantly raise system utilization bringing forward the financial break-even point building on the synergy created by multiplexing on a shared medium. To this end, the BS cannot be treated as a normal business user connected to the PON with a static Service Level Agreement (SLA), neither can the mobile operator see this link as a fixed pipe the way it was up to now. Such an approach would not fully exploit neither the bandwidth management properties of the PON nor the existing multiplexing gain opportunities. Instead, special tools need to be provided to take advantage of the capabilities of the PON Dynamic Bandwidth Allocation (DBA) mechanisms ([6], [7]) to the benefit of both operators.

This task is assigned to a novel functional unit charged with carrying out the extended bandwidth management with interfaces towards both the BS and the PON as shown in Fig. 1. This unit coordinates the SLAs between the two operators and handles the relevant alarms and other events.

In this work we focus on two important issues that are part of the dynamic SLA provisioning. The first is to provide algorithms for the efficient real time estimation of the BS bandwidth needs and functions to implement dynamic SLAs. The second is to provide guidelines for the selection of the appropriate estimation algorithm based on the results of performance assessment by simulations.

As mentioned, the full exploitation of the multiplexing gain opportunity requires a much more elaborate BW management scheme than is warranted for the residential traffic. Static SLA negotiation would provide the initial requirements based on agreements between PON and business customers, MNOs, residential customers (depending on the region, the number of customers, etc.). However, to achieve optimal usage of PON resources offering services on a pay per use model a dynamic

SLA renegotiation framework is required.

Therefore a central issue in this framework is how to respond to the different timescales of the traffic change and for this two hierarchical levels are envisaged. One handles the pre-arranged SLAs and the slow long-term changes (BW Management Unit-BMU) and the other handles the fast changes in an autonomic manner (real-time measurement box-RTM) as shown in Fig. 1. Starting from the initial SLA requirements and utilizing the long-term estimator and Real-time measurement based resource allocation units, the operator should perform a detailed exercise to determine the network resources needed on daily, weekly and monthly basis per customer category, type of service, geographical region and the respective (re)configuration in order to offer the customers the optimal QoS. Concluding on this exercise, the Resource Management system can then reserve the required resources and interact with blocks of the SLA Management, and Performance Management and monitoring to verify that the usage of the network resources does not violate the thresholds set. The latter are strictly linked with SLA terms, and are based on the PON operator's business plan.

The first objective of the new functionality is to let each operator have control of his side of the negotiation so the mobile operator will issue bandwidth requests and the PON operator will respond with what is in a position to satisfy. This way a service bandwidth framework will be established defining the upper and lower limits of the traffic agreement. However, the autonomic part will very quickly set short term parameters within this framework that enable better exploitation of the joined systems.

III. Bandwidth Estimation in the TDMA PON

The autonomic subsystem RTM is responsible for the collection of real-time measurements, the traffic characterization and the traffic estimation. The main element of the RTM is the estimation unit which is based on a set of algorithms for the efficient estimation of the traffic demands. In the literature, the most promising algorithms for bandwidth estimation can be divided in two main categories: the algorithms which are based on the paradigm of Effective Bandwidth (EF) and the algorithms which are based on the leaky bucket model.

A. *Effective Bandwidth Algorithms*

The concept of effective bandwidth [8] can be utilized to estimate the amount of bandwidth that should be allocated to a source in order to meet a QoS requirement. The definition of effective bandwidth is expressed by the following equation:

$$eb(s,t) = \frac{1}{st} logE\left[e^{sX[0,t]}\right] \quad (1)$$

where X[0, t] express the amount of traffic load that arrives in the interval [0, t]. The s parameter cannot be estimated using measurements and should be calculated by making the assumption of a large buffer and using the Large Deviations Theory. Therefore the direct estimation of effective bandwidth based on (1) is not practical and a number of studies are proposed in literature for the indirect evaluation of effective bandwidth, the most promising of them are based on empirical estimation of effective bandwidth. A comparison of several different empirical estimators is described in [9].

The Gaussian approximation algorithm [10] is computationally simple and therefore it is easy to be implemented. It makes the assumption of a bufferless link and therefore is considered to be the upper bound of the estimated value. The definition of Gaussian approximation algorithm is expressed by the following equation:

$$C_{EB} = \mu + \sigma\sqrt{-2lnP - ln2\pi} \quad (2)$$

where μ is the mean arrival rate of the traffic, σ is the standard deviation of the arriving traffic, and P is the packet loss percentage QoS parameter.

The Courcoubetis approximation algorithm [11] provides another effective bandwidth formula based on Large Deviation Theory, assuming a large buffer size. However, Courcoubetis approximation does not consider the self-similarity of traffic (e.g. video flows). The Courcoubetis approximation is defined as:

$$C_{EB} = \mu + \frac{IDs}{2B} \quad (3)$$

where μ is the mean arrival rate of the traffic, ID is the index of dispersion, s is the space parameter, and B is the buffer size of the queue.

The Norros approximation algorithm [12] takes into consideration the mean arrival rate of the traffic, the buffer size of the queue and the self-similarity of the flow as well by estimating the Hurst parameter. The Norros approximation is defined as:

$$C_{EB} = \mu + \left[B^{H-1}k(H)\sqrt{-2a\mu \ \ln P}\right]^{\frac{1}{H}} \quad (4)$$

where $k(H) = H^H(1-H)^{1-H}$, μ is the mean arrival rate of the traffic, B is the buffer size of the queue, H is the Hurst parameter of the traffic , a is the coefficient of variation of the traffic, and P is the packet loss percentage QoS parameter of the flow.

B. *Leaky Bucket Algorithms*

Algorithms based on the leaky bucket model attempt to characterise and estimate traffic load by estimating the appropriate leaky bucket parameters (r, b) such that all packets could be sent out immediately upon their arrivals. This token bucket model can be extended by the addition of a queue at its input. This queue is used to hold packets while they are waiting for enough tokens to be accumulated in the bucket. The first work to compute token bucket parameters from the traffic pattern was done by C. Partridge and M. Garrett in 1994 [14]. For a fixed r, they proposed a single pass algorithm (called Send-Now) to derive the minimal value of b for the no-queuing case. In [15] the Send-Now algorithm is compared to the proposed No-Delay TB algorithms, resulting in both linear complexity and equal estimation results. In [16] the Send-Now algorithm is extended with the k parameter. In the first phase, the flow is calculated for an interval I, allowing the measurement of the average and maximum bitrate of the period. Then the algorithm calculates the bucket size b based on average and maximum bitrate and the selected k value between the two thresholds. In addition, an alternative algorithm based on LB is used in a packet shaping scheme in [13].

C. *Reverse Leaky Bucket Algorithm*

The effective bandwidth algorithms either assume a bufferless link or large buffers, therefore fail to estimate efficiently the traffic load in cases of small or medium buffer lengths. In addition, the algorithms based on the leaky bucket model estimate both r and b parameters and therefore are subject to technical limitations, since the leaky bucket implementation cannot be flexible enough to quickly and easily adapt the size of the bucket. An increment in bucket size may require changing the technical specifications of the network entity. This may be impractical, since usually the selection of bucket size is made during the initialization phase of the system and only infrequent changes take place during normal operation.

The proposed Reverse Leaky Bucket (RLB) algorithm (illustrated by means of pseudo-code in Fig. 2) alleviates the technical limitations of leaky bucket algorithms producing efficient estimations independently of the buffer size. Contrary to the approaches described above, RLB operates given a predefined bucket size, which could be e.g. determined by worst case delay requirements. Thus, each implementation could select appropriate values taking into account system (e.g. available memory) or QoS parameters (e.g. delay).

```
b = bucket_size
r = 0

for (i = 1 to n)
        c = c + r*Δt_i
        if (b < c)
           c = b
           tb = 0
        else
           tb = tb + Δt_i
        if (l_i <= c)
           c = c - l_i
        else
           r = r + (l_i-c)/tb
```

Fig. 2: Pseudo-code of RLB algorithm

The RLB algorithm estimates the optimum (minimum) rate of the flow so that no violations would be observed (red packets) during a subsequent measurement by a token bucket policer for a given value of parameter b. The b parameter is the bucket size, the r parameter is the estimated bitrate, Δt_i is the interarrival time between the current and previous packet and l_i is the packet size.

IV. Performance Assessment by Simulation

In this section computer simulation results are presented to compare the bandwidth estimation algorithms in terms of performance and on this basis to investigate the feasibility of their use as bandwidth estimators in a TDM PON environment serving both residential / professional users and mobiles BSs. In detail, the following algorithms are implemented in the simulation environment:

- Gaussian Approximation algorithm
- Courcoubetis Approximation algorithm
- Leaky Bucket (LB) algorithm, the one presented in [16] for three values of the k parameter, k = {0, 0.5, 1}
- Reverse Leaky Bucket (RLB) algorithm, the one presented in the previous section.

A. *Simulation model and parameters*

Two sets of simulation scenarios were defined. The first set comprised packets generated from a single (primary) traffic source and the second set extended the first scenario including the superposition of a second packet stream generated by a secondary traffic source activated during selected time intervals, as shown in Fig. 3. The generated packet flows were transmitted to an output link via a First In First Out (FIFO) queue. The FIFO service rate was controlled by the input traffic monitoring and bandwidth estimation unit, which implemented the selected algorithm each time and emulates the role of the RTM unit. At the FIFO output a flow policer monitored the egress traffic flow again configured with the parameters that have been the result of the input flow characterization unit. Therefore, the resulting flow service would emulate the result of the bandwidth estimation process implemented at the PON RTM unit and will provide insight to the impact that this process has on the QoS perceived by the user and the potential SLA violations that it may cause.

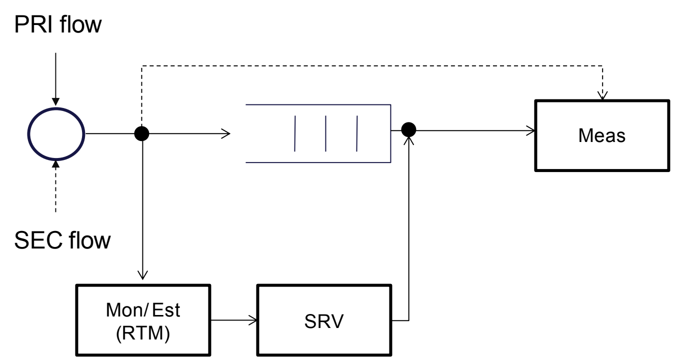

Fig. 3: Simulation model

The objective of the simulations was to evaluate the accuracy of the estimation methodology and the performance of each algorithm. The selected performance metrics included the following:

- the resources reserved (i.e. effective bandwidth) by the PON system to guarantee the negotiated QoS parameters (which determines the upper bound of user flows that can be admitted to the systems under the specific QoS parameters i.e. the maximum system utilization)
- the percentage of packets of the output packet flow that would be classified as out of profile by the egress leaky bucket policer configured to police the output traffic flow based on the estimation parameters of the RTM system
- the queuing delay caused by the system (that could cause potential deviations from negotiated SLA parameters)

	Flow parameters			
	Type	**Model**	**Burst Factor (BF)**	**Average rate (Mb/s)**
Primary flow	VBR	on-off	BF=3	25
Secondary flow	VBR	on-off	BF=3	5

Table 1: Simulated input flow parameters

In each scenario of the first set (single flow set), a VBR data flow of 25Mb/s bandwidth based on on-off packet model and with burst factor BF=3 was generated (Table 1). The burst factor (BF) is expressed by the equation:

$$BF=(T_{on}+T_{off})/T_{on} \quad (2)$$

where T_{on} is the time period of packet transmission and T_{off} is the idle period. The main objective of first set of scenarios is to assess the algorithms in terms of efficient calculation of the effective bandwidth.

During the simulation time, each algorithm iteration is further divided into two phases: the estimation phase and the assessment phase (Fig. 4). During the estimation phase measurement collection and algorithm execution are realised. Therefore at the end of the estimation phase, each algorithm has produced its estimation (e.g. effective bandwidth, leaky bucket size) for the next period. As mentioned above during the assessment phase, the performance of the selected algorithm is examined in terms of producing the most efficient estimation. In order to calculate the performance, a policing unit is used with peak rate equal to the efficient bandwidth calculated by the algorithm and bucket size equal to the predefined or calculated bucket size (depending on algorithm type). During this phase, the percentage of violations (red packets) is metered. The percentage of packet violations determines the effectiveness of the algorithm in estimating the forthcoming bandwidth. High percentage of red packets implies failure of the algorithm on estimating a reasonable effective bandwidth, while zero red packets implies ideal algorithm performance. In addition the actual flow bandwidth is compared to the calculated effective bandwidth.

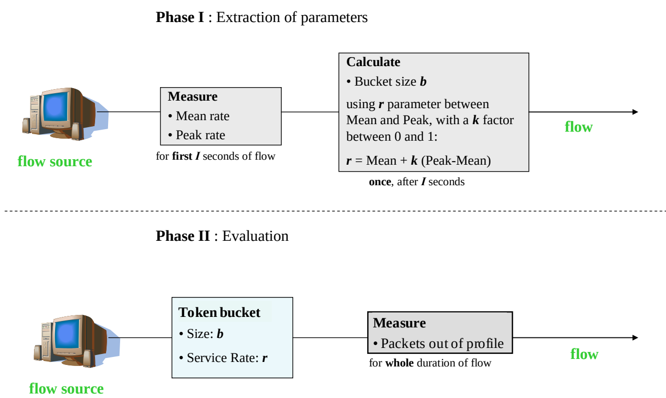

Fig. 4: Measurement phases

In the second set of scenarios (primary and secondary flow set), two VBR flows of 25Mb/s and 5Mb/s respectively were generated. Both flows are based on the on-off traffic model with burst factor BF=3. The main objective of this second set of scenarios is the assessment of the algorithm behavior in cases of abrupt change of the transmission rate of flows sharing the same link (multiplexing). As in the case of the first set, two phases (estimation/assessment) are also implemented. During the second phase, the percentage of violations and the deviation from the actual flow rate are measured determining the effectiveness of the algorithm, while the queuing delay demonstrates the impact of the algorithm during large traffic load fluctuations.

Each scenario (of both sets) has a duration of 1050 sec (50 sec for network initialisation and 1000 sec of network operation) during which 100 iterations of the algorithm under consideration are performed. The duration of both estimation phase and assessment phase was 10 sec. In the case of the Gaussian approximation and Courcoubetis approximation algorithm, for each phase (10 sec) 100 network measurements are collected. In the case of LB and RLB algorithms, a measurement is collected on each packet arrival.

In case of the single flow scenarios, the simulations results regarding the estimation of the effective bandwidth are illustrated in Fig. 5. From the results of Fig. 5 it is apparent that the Gaussian algorithm performs an overestimation of the effective bandwidth (approximately 26.3 Mb/s on average compared with the actual flow of 25 Mb/s) while the Courcoubetis algorithm and the LB algorithm for k = 0 underestimate the equivalent bandwidth (in many cases the actual flow is greater than the estimate). The RLB algorithm and the LB algorithm for k = 1 and k = 0.5 estimate a closer approximation.

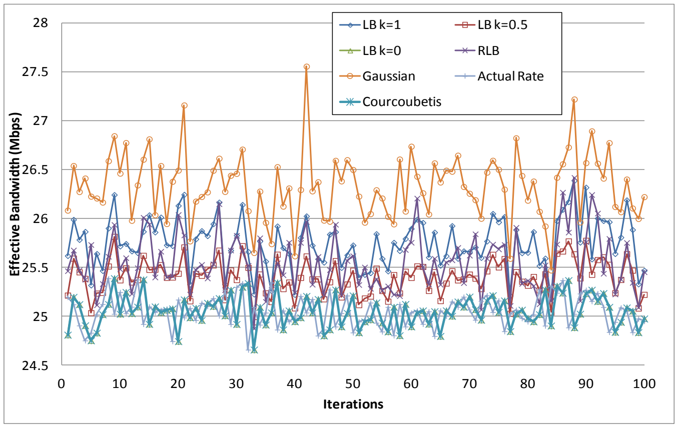

Fig. 5: Effective Bandwidth Estimation

One very interesting figure is the probability of the effective bandwidth estimation to be close or far from the actual rate. Fig. 6 illustrates the Probability Density Function (PDF) of absolute difference between the estimated effective bandwidth and the actual rate. From the results of Fig. 4 it becomes clear that the Courcoubetis algorithm and the LB algorithm for k = 0 have the closest approximation. Fig. 6 illustrates that approximately 75% of effective bandwidth estimation results are very close to the actual rate (less than 300 Kbps). The Gaussian algorithm performs an overestimation of the effective bandwidth with large deviations from the actual rate, having a pick value at around 1.4 Mbps. The RLB algorithm and the LB algorithm for k = 1 and k = 0.5 estimate a close approximation with values of absolute difference between 0 and 1.5 Mbps.

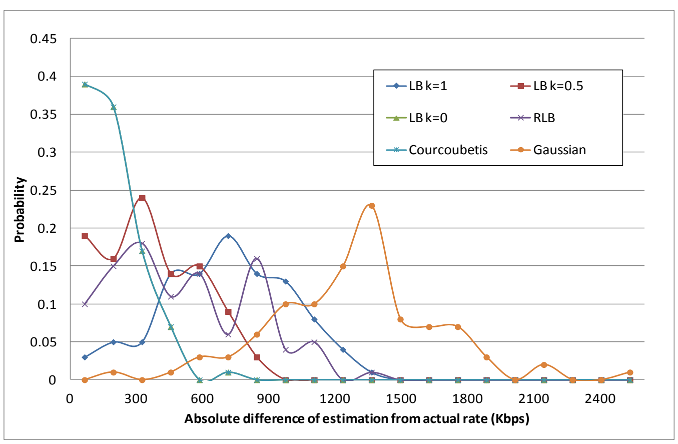

Fig. 6: PDF of Absolute Difference of Effective Bandwidth Estimation from Actual Rate

The practical importance of effective bandwidth estimation is translated into a commitment of resources on the optical network. Overestimating the value of effective bandwidth means that the network must commit greater amount of bandwidth to satisfy the flow than is actually required, resulting in large percentage of bandwidth remaining unused while at the same time increases the likelihood of new flows to be rejected by the admission control mechanism because of lack of bandwidth.

The success in estimating the effective bandwidth can only be studied when considering the impact that this selection has for the packets that compose the flow. Therefore the performance assessment should take into consideration the number of violations (red packets) as well. As mentioned in the previous paragraph in the assessment phase a policing mechanism is applied in order to examine the effects of the estimation. Fig. 7 illustrates the percentage of violations detected by the policer. From this figure it becomes clear that the (conservative) algorithms, which tend to overestimate the effective bandwidth (Gaussian) show nearly zero violations, while the algorithms with low estimations (Courcoubetis and LB with k = 0) have large, often prohibitive rates of violations (e.g. greater than 0.5%). The algorithms with average estimations (RLB, LB with k=0.5 or k =1) tend to have a limited percentage of violations.

In addition, another important metric that should be taken into consideration during the performance assessment is the delay that is experienced by the packets. Fig. 8 illustrates the packet delay throughout the simulation time. From the results of Fig. 8 it is apparent that the LB algorithm with k = 0 produces high, unacceptable values of delay (greater than 20ms), while Courcoubetis, RLB and LB with k=0.5 produce medium values (between 8 and 20 ms). The Gaussian algorithm has the best performance regarding delay but on the expense of high bandwidth estimation, while LB with k=1 produce low delay values below 10ms.

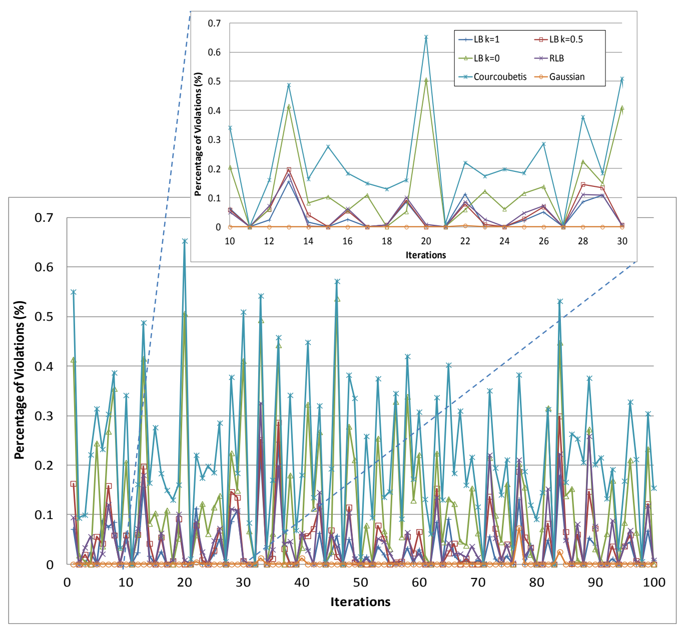

Fig. 7: Percentage of Violations

Therefore, the choice of the appropriate estimation algorithm depends on the importance of the flow for the system and the type of traffic carried by the flow. For example, flows of high priority customers (Gold users) or applications sensitive to losses and delay must be protected from loss and high delays and therefore algorithms of low estimations are not suitable for such cases. In addition, algorithms with medium or low losses and medium delay values can be used in the case of low priority flows (Bronze users) which according to the SLA is tolerant to losses and delays.

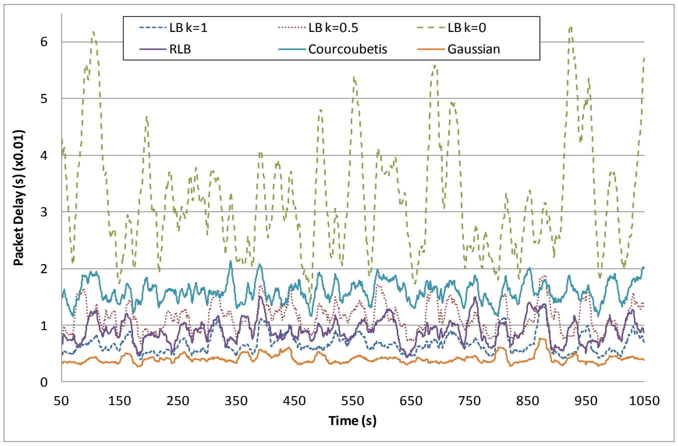

Fig. 8: Packet Delay

As already mentioned in previous section, all LB algorithms estimates a new bucket size b during each algorithm iteration, while Gaussian, Courcoubetis and RLB algorithms operates given a predefined bucket size. Fig. 9 illustrates the bucket size for all algorithm iterations. In all simulation scenarios the bucket size of Gaussian, Courcoubetis and RLB algorithms is set to 100 Kbytes, while LB algorithms are left to estimate their desirable bucket size. From the results of Fig. 9 it become obvious that LB algorithms present large fluctuations of bucket size, which in some cases can be multiple of previous values (e.g. LB algorithm with k = 0 at 5th iteration, estimates a bucket size of 120 Kbytes, while at 87th iteration estimates a bucket size of 360Kbytes, a multiple of three from the previous value). This approach of a variable size of bucket in some times can exceed the physical boundaries of the buffer, while in other times will underutilize the available buffer capacity.

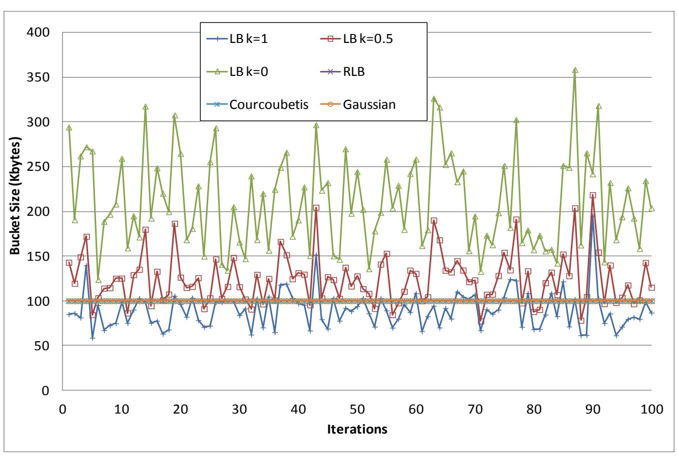

Fig. 9: Bucket Size

In all scenarios of the second set, we assume that a second flow starts to generate packets at a rate of 5Mb/s at time t = 250s and stops at time t = 750s. Fig. 10 illustrates the effective bandwidth estimation during the whole simulation duration.

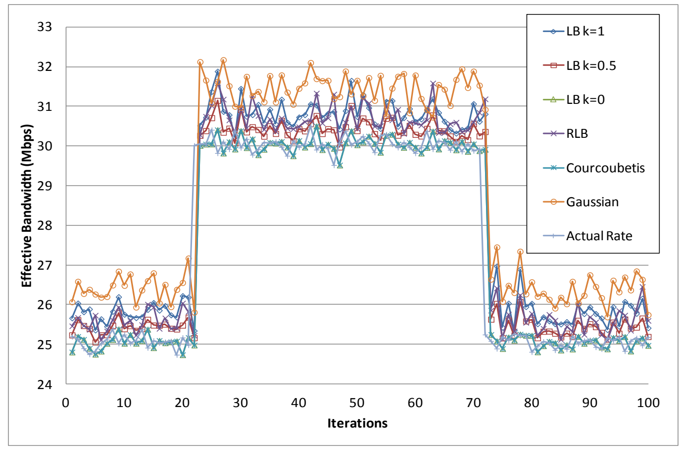

Fig. 10: Effective Bandwidth Estimation

From the results of Fig. 10 it is clear that the Gaussian algorithm performs an overestimation of the effective bandwidth, while the Courcoubetis algorithm and the LB algorithm for k = 0 are very close to the actual rate both in the periods of one and two flows. The RLB algorithm and the LB algorithm for k = 1 and k = 0.5 succeed in calculating an effective bandwidth close to actual rate.

In addition, Fig. 11 illustrates the PDF of absolute difference between the estimated effective bandwidth and the actual rate. Fig. 11 illustrates that the Gaussian algorithm produces large deviations from the actual rate, with the largest probability at around 1.8 Mbps. Courcoubetis algorithm and the LB algorithm for k = 0 produce the closest approximation with 75% of effective bandwidth estimation results very close to the actual rate, while the RLB algorithm and the LB algorithm for k = 1 and k = 0.5 produce estimation with probabilities between Gaussian and Courcoubetis highest values.

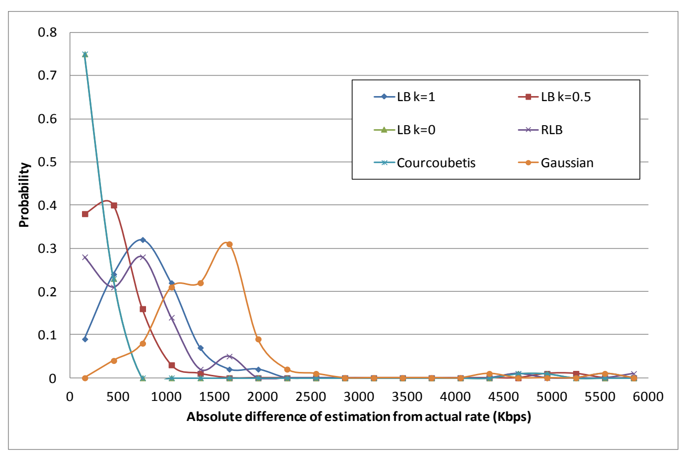

Fig. 11: PDF of Absolute Difference of Effective Bandwidth Estimation from Actual Rate

All algorithms cannot react directly and one iteration of the algorithm is required for closer approximation. This become obvious in Fig. 12, which illustrates the percentage of violations around the time that the new flow enters the network (t = 250s). At this time a high pick of violations is observed for all algorithms. In detail, the Gaussian algorithm produces the minimum percentage of violation (4.8%) while all other algorithms produce violations spanning from 5.3% to 5.8%. In the next algorithm iteration all algorithms adapt to the new flow requirements and therefore all algorithms converge to low packet violations.

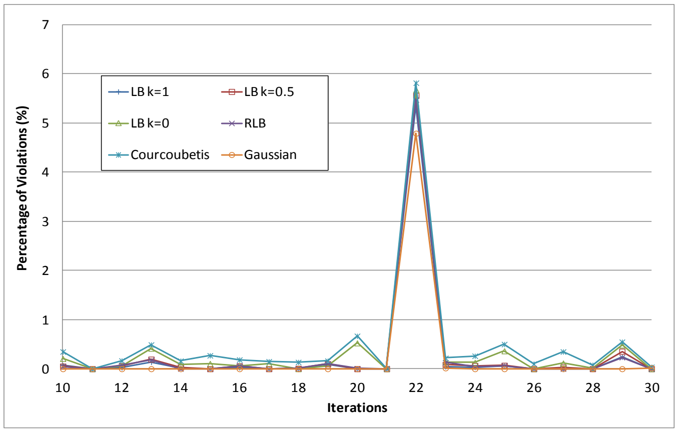

Fig. 12: Percentage of Violations

Regarding the packet delay (Fig. 13) on bitrate change (t = 250s), all algorithms except LB (k = 0) converge within 10 sec (one iteration of the algorithm) after a transition state with average delay (30ms). Unlike, in the case of the LB algorithm (k = 0) the accumulated packets in the queue create a longer delay (70ms) which is normalized after 12s.

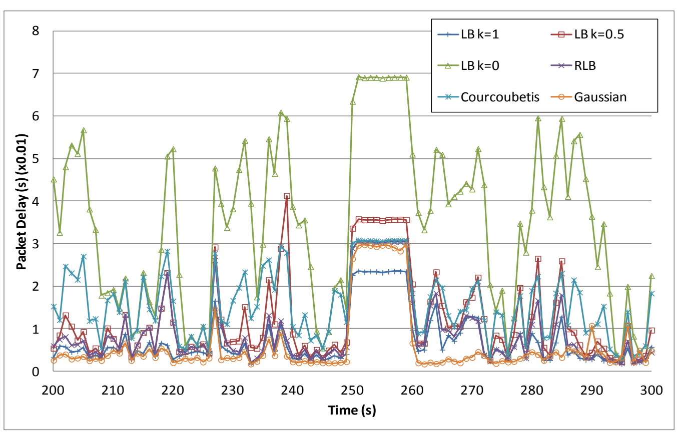

Fig. 13: Packet Delay

A number of observations can be obtained from the performance assessment of the algorithms under both single and multi flow environments. The Gaussian algorithm performs an overestimation of the effective bandwidth resulting in available bandwidth underutilization. Although it has almost zero violations, however due to the large percentage of unused bandwidth cannot be recommended for optimal resource allocation. The Courcoubetis and LB algorithm for k = 0 produce an underestimation of the effective bandwidth and although their optimal bandwidth utilization, high rates of violations are presented. Because of the high percentages of violations these algorithms are inappropriate for sensitive traffic like traffic coming for mobile BSs. The LB algorithm for k = 1 and k=0.5 make intermediate estimations of effective bandwidth and achieve both satisfactory bandwidth utilisation and low number of violations. However the main drawback is their requirements for a variable size of bucket size, which in some cases can be multiple or can exceed the physical boundaries of the buffer. In addition, in some environments, the rapid change of buffer size in small timescales becomes impractical. The proposed RLB algorithm exhibits similar results with LB algorithms for k = 1 and k = 0.5, while in parallel takes as input the bucket size. However the main advantage of RLB, which make it highly practical (in comparison to LB) is the fact that leaves to the administrator the selection of bucket size which can be directly mapped from network dimensioning, while disengage from the administrator the difficult task of k parameter selection.

V. Conclusions

The widespread deployment of PON systems for fixed communications comes at a time that mobile backhaul systems are stressed by the spreading of smart phones and the concomitant fast rise in data rates due to the introduction of next generation access network technologies. Thus, the use of PON for mobile traffic backhauling provides an opportunity that cannot be missed as it offers a smooth migration path both in technical as well as financial terms for both operators. To take advantage of the PON utilization potential without QoS degradation, novel functionality is required in the area of traffic monitoring and estimation. A framework for supporting this functionality providing autonomic network operation and SL management was presented in this work. The framework is based on an algorithm highly fine tuned to the technological constrains of PON and with noticeable performance in terms of utilisation, percentage of violations and practical feasibility.

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