Absolute QoS in Synchronous Optical Packet Switched Networks

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Abstract

This paper presents an adaptive service differentiation scheme for a bufferless synchronous Optical Packet Switched (OPS) network. Wavelength allocation is used for service differentiation, where the number of wavelengths reserved for high priority traffic (L) is adjusted according to changes in the system load and the relative share of high priority traffic. The experienced PLR in a node is measured over an interval, and the adjustment of L is made based on measurements in two consecutive intervals. The main issue is when to trigger the change of the parameter L. The absolute change allowed in the system load or relative share of high priority traffic without violating the PLR requirement is also investigated.

1 Introduction

Over the last decade, an increased demand for bandwidth has hastened the introduction of new technologies in the core network. The coaxial cables are being replaced by optical fibers, capable of carrying inconceivable amounts of data simultaneously if only exploited to the utmost. At the same time, real-time applications are gaining a larger audience and services such as video-on-demand, video conferencing and IP-telephony make demand to service differentiation in the network. Important QoS parameters for these applications are delay, delay variations (jitter), packet loss rate (PLR) and bandwidth [13].

Wavelength Division Multiplexing (WDM) became economically viable in the nineties due to the advent of the Erbium Doped Fiber Amplifier (EDFA) which made it possible with long distance WDM transmission [8]. WDM and the improvement, Dense WDM (DWDM) has since then proven to be the most promising technology to satisfy the capacity demand in the core network by multiplexing hundreds of gigabit channels in one fiber. The multiplexing is performed by different lasers which emit light at different wavelengths forming signals which are multiplexed onto a single fiber. A single optical fiber is capable of carrying 10 Terabits per second when DWDM technology is used.

There are three possible switching technologies for (D)WDM [7]. In wavelength routing which is connection oriented, an all-optical path between sender and receiver is established before transmission. Reservation is therefore accomplished as in traditional connection oriented transmission. Wavelength routing thus causes long setup times, but behaves well in networks with constant bit rates and long holding times. With Optical Burst Switching (OBS), packets are assembled into large sized bursts at the network ingress node. No reservation is possible with OBS, which saves setup time. OBS uses out-of-band control information, where the control header is transmitted ahead of the burst on a separate wavelength. The time between sending of the header and sending of the burst can then be used to reserve resources at intermediate switches. Delay is traded for less loss. With Optical Packet Switching (OPS), network layer packets are put into an optical packet payload before transmission. Small packets of equal or varied length are used. The control information is sent together with the payload, which means that the payload must be delayed in Fiber Delay Lines (FDLs) at the switch while setup is performed [7].

OBS and OPS offers a low granularity transmission compared to wavelength routing, and are therefore better suited to the bursty environment of the Internet [7].

Still, high capacities do not solve the QoS issue, and new schemes for supporting QoS in an optical environment are needed. Current proposals for achieving QoS in today's Internet are based on queue management in core switches, e.g. RED which uses electronic RAM [13]. Optical RAM does not exist, which makes buffering in optical networks difficult. Only constant delay could be provided by the use of FDLs. New approaches for achieving service differentiation in optical networks are therefore needed.

Different QoS schemes are needed for OBS and OPS because of the different control plane solutions. For service differentiation in asynchronous OBS networks, Zhang et al. have proposed an early drop scheme [12]. Here, low priority packets are dropped based on the experienced packet loss rate (PLR) for high priority packets. For asynchronous OPS, a service differentiation scheme based on wavelength allocation is proposed in [3] and this scheme is extended to an adaptable scheme by Øverby in [14] to allow for changes in e.g. system load. These ideas are further investigated in this paper for synchronous OPS networks. The scheme developed is absolute, which means that absolute bounds regarding the PLR are given.

The paper is organised as follows. In Section 2 an introduction to OPS networks is given. Section 3 describes the idea behind an adaptive service differentiation scheme, accompanied by an analytical model. In Section 4 some simulation results supporting the scheme are shown while the paper is concluded in Section 5.

2 Optical Packet Switching

With Optical Packet Switching (OPS) a network layer packet is transported in an optical packet payload, with the optical header transported on the same wavelength, called in-band control information. This means that OPS have a different control plane solution compared to OBS, which uses out-of-band control information. OPS provide low delay through the network, since neither setup as in wavelength routing or burst assembly as in OBS are needed. The only delay experienced for an optical packet is propagation delay and delay experienced at the input of a switch since the payload must be sent through FDLs as the header is processed. There may also be buffering delay if a switch with electronic buffers or FDLs are used for contention resolution [7].

A drawback with OPS as well as OBS is the need for either optical-electrical conversion of the header or all-optical technology. Optical-electrical conversions are available today, but will be obsolete in the near future because optical transmission speed will likely outperform the electronics [5]. The all-optical solution is still immature, and the lack of optical buffers means that this option is several years ahead. In this paper a bufferless optical switch with electronic header conversion is used, since this is the most viable solution in years to come.

The OPS network may be synchronous or asynchronous, and the packet size can be fixed or varied. In synchronous OPS networks, packets arrive at the switches at predefined times, and every packet is a fixed or varied multiple of a time slot. In an asynchronous network on the other hand, there are no constraint on the packet length and packets arrive at the switches at random points in time. Synchronous operation have an advantage by being easier to build and operate, while asynchronous operation is more robust and flexible [9]. Synchronous operation with Fixed Length Packets (FLPs) and asynchronous operation with Variable Length Packets (VLPs) are the most attractive modes of operation for OPS networks [7].

Contention Resolution

A nonblocking switch is assumed in this paper, which means that contention is only experienced if two or more packets are destined to the same output wavelength in a fiber in the same timeslot [4]. A possible contention can be resolved in three different dimensions; the wavelength dimension by the use of wavelength converters, the time dimension by the use of optical buffers or the space dimension by the use of deflection routing [9]. One or more of these can be combined in the same switch.

With wavelength conversion, one or more Tuneable Wavelength Converters (TWCs) are used to convert the input wavelength in the case where two or more packets are destined to the same output wavelength in a fiber.

Optical buffering is accomplished by the use of FDLs. A FDL are made of an optical fiber with fixed length and can store a packet for a time given by the speed of light and the length of the fiber [9]. In the case of contention, one of the contending packets will be sent to the proper output port while the rest are sent to a suitable FDL.

With deflection routing, a contended packet is routed to a different fiber to take another, usually longer, way to the destination. The packets which are concerned will thus experience a longer delay through the network, as well as risking that packets arrive out of order at the destination [9].

In this paper contention resolution is accomplished by the use of wavelength converters, which means that contention can only be resolved in the wavelength dimension. In [11], wavelength conversion is proven to be the most effective contention resolution scheme, since neither extra delay nor use of extra network resources is experienced. It is also shown that wavelength conversion is the contention resolution method which causes the network throughput to improve most over a regular network without contention resolution.

3 An Adaptive Service Differentiation Scheme

With absolute QoS requirements in a dynamic OPS network as a goal, an analytical model for a static service differentiation scheme is developed. This model is then enhanced to allow for adaption in important system parameters due to variations in system load and relative share of high priority traffic. The analytical model is developed in the next section while the adaptive scheme is introduced in the succeeding section.

The Access Restricted Service Differentiation Scheme

An absolute service differentiation scheme for synchronous bufferless OPS networks is developed. Since the switching node is bufferless, packets only experience a constant propagation and header processing delay which means that absolute QoS is accomplished by offering absolute bounds on the PLR.

In synchronous OPS networks packets arrive to a node in predefined synchronous time slots. The optical header is extracted at reception and converted to the electronical domain before being processed electronically. The payload is meanwhile delayed in a fixed length FDL. The Binomial process describes traffic in a discrete time environment, and can therefore be used to model the traffic in such a network. In our case we have $n = F \cdot N$ input wavelengths, where F is the number of input fibers and N is the number of wavelengths in a fiber. A specific wavelength in a fiber is considered an input port and a given input port may provide traffic in a timeslot or not. The probability for a packet arrival in a given input port equals the system load, A. The probability for one or more arriving packets to a specific output fiber are then given by the probability for an arriving packet at every input port multiplied by the probability that the packet are destined to output fiber i. The traffic pattern is uniform, which means that the routing probability is given as $1/F$, where F is the number of output fibers, equal to the number of input fibers. The probability that there is a packet at an input port and that this packet is routed to output fiber i is then given as $\alpha = A/F$.

P_k (0$\leq$ P_k $\leq$1) is the probability for k (0$\leq$ k $\leq$ FN) arrivals to output fiber i in a given time slot. This probability is modelled by the Binomial Distribution [6] as:

$$P_k^i(k|F \cdot N) = b\Big(k; FN, \frac{A}{F}\Big) = \binom{F \cdot N}{k} \cdot \Big(\frac{A}{F}\Big)^k \Big(1 - \frac{A}{F}\Big)^{F \cdot N - k}, k = 0, 1, ...F \cdot N \quad (1)$$

The average number of arrivals to fiber i is given as: $E[P_k^i]$=$FN\frac{A}{F}$=$A \cdot N$.

A packet is lost at output fiber i if the number of packets destined to that fiber is greater than the number of wavelengths per fiber, i.e. $P_k^i > N$. The average packet loss rate, PLR_{av} hence becomes:

$$PLR_{av}^i = \frac{1}{A \cdot N} \cdot \sum_{k=N+1}^{F \cdot N} P_k^i \cdot (k - N) \quad (2)$$

Two different traffic classes are used to provide QoS in the network where class 0 has priority over class 1. S_0 and S_1 denotes the relative share of high priority traffic and low priority traffic, respectively. The use of only two priority classes is argued for in [2].

The probability that m out of k packets at output fiber i in a timeslot are high priority packets is also given by a Binomial Distribution:

$$C_{m,k} = \binom{k}{m} \cdot S_0^m \cdot (1 - S_0)^{k-m} \quad (3)$$

The parameter $L (0 \leq L \leq N)$ is then introduced in order to isolate class 0 traffic from class 1 traffic. L is the number of high priority packets per output fiber that is guaranteed to be transmitted in the case of contention. The result is four distinct cases, regarding how many and which packets to drop:

- $k \leq N$

  No packets are lost.

- $k > N, \quad m \leq L$

  $k - N$ class 1 packets are lost.

- $k > N, \quad m > L, \quad k - m \leq N - L$

  $k - N$ class 0 packets are lost.

- $m > L, \quad k - m > N - L$

  $m - L$ class 0 packets are lost and $k - N - (m - L)$ class 1 packets are lost.

Equation 2 and Equation 3 together with the four cases presented above then gives the PLRs for class 0 and class 1 traffic in the Equations 4 and 5.

$$PLR_0 = \frac{1}{ANS_0} \sum_{k=N+1}^{F \cdot N} P_k \left[\sum_{m=L+1}^{min(L+k-N,k)} C_{m,k}(m-L) + \sum_{m=min(L+k-N+1,k+1)}^{k} C_{m,k}(k-N) \right] \quad (4)$$

$$PLR_1 = \frac{1}{ANS_1} \sum_{k=N+1}^{F \cdot N} P_k \left[\sum_{m=0}^{L} C_{m,k}(k-N) + \sum_{m=L+1}^{k-N+L} C_{m,k}(k-N-(m-L)) \right] \quad (5)$$

From these equations it is deduced that a value of $L > \lceil NS_0 \rceil$ is needed in order to guarantee that $PLR_0 < PLR_1$, which is the objective of the service differentiation scheme.

An Adaptive Scheme

In [12], the idea of measuring the experienced PLR after each node is introduced. It is assumed that network nodes operates independently from each other, which means that the maximum PLR through the network may be reduced to maximum PLR in one node. The measured PLR can then be used to adjust system parameters in the next time period, with the objective of keeping the PLR below a certain limit. By combining this method with the Access Restricted Scheme, the parameter L can be changed if the experienced PLR violates the PLR requirement set for the system, thereby being adaptive to a changing environment such as varied system load.

A simulator is realized using the Discrete Event Modelling on Simula (DEMOS) software [1]. The simulator is verified against the analytical results in [10]. The main entity is a packet switch as can be seen in Figure 1.

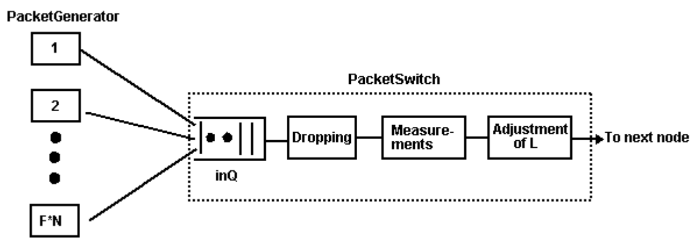


Figure 1: Overview of the simulator

Packets are generated by a packet generator, one per input wavelength, according to a binomial traffic distribution corresponding to Equation 1 and Equation 2. The output fiber is chosen in a uniform manner. The packet switch collects the packets for each output fiber and makes the dropping decisions according to the value of L. After the dropping is performed, the experienced PLR are measured. The measurement method is presented next, while the adjustment of the parameter L is described in the next section.

Measurement Method

A maximum PLR is set for the system, denoted PLR_{req}. The experienced PLR, measured over an interval, should always be kept below this value to achieve absolute bounds on the QoS for high priority traffic. The length of the measurement interval should be long, giving reliable results and short, being able to act fast if the PLR_{req} is violated. These are contradictory requirements and compromises are needed.

The length of the measurement interval is investigated in [10], and a sensitivity analysis is performed, showing that a measurement interval of 10 000 time slots is satisfactory when the PLR_{req} is above a certain limit. A larger measurement interval is however needed if the PLR_{req} is less than 10^{-4}, because more reliable measurements are needed in this case. The adaption to a changed environment will however be slower, since longer time is needed to adjust the parameter L. In this paper the PLR_{req} is 0.0015, and a measurement interval of 10 000 will then suffice.

$lost_n(c)$ and $packets_n(c)$ denotes the number of lost packets for class c until interval number n and the total number of packets for class c until interval number n, respectively.

Hence the PLR for class c in an interval is calculated as:

$$PLR_n(c) = \frac{\sum lost_n(c) - \sum lost_{n-1}(c)}{\sum packets_n(c) - \sum packets_{n-1}(c)} \tag{6}$$

where n is the interval number.

Adjustment of the Parameter L

L should be changed when something in the environment changes, such that the PLR_{req} is violated. L should however be changed before this violation happens, in order to fulfil the absolute QoS bounds at all times. The experienced PLR should therefore be kept inside a tolerated region with a lower bound, k_{min} and an upper bound, k_{max}. L should be adjusted when the PLR_{req} region is violated in two consecutive intervals, this is to avoid adjustment of the parameter L based on packet bursts. When the experienced PLR violates $PLR_{req} \cdot k_{max}$ or $PLR_{req} \cdot k_{min}$ in two consecutive intervals, L should be increased or decreased, respectively.

There are two important issues which needs to be considered when deciding on the values of k_{min} and k_{max}. Foremost, k_{max} should be small enough such that a small increase in system load would be tolerated without violating the PLR_{req}. Second, the distance between k_{min} and k_{max} should be sufficiently large, such that for every system load, a L should be found with expected PLR inside the limits. If this is not fulfilled, the value of L will oscillate causing the experienced PLR to oscillate too. Since L is a discrete parameter, this last condition can be hard to fulfil for all possible system loads and shares of high priority traffic.

In [10] a sensitivity analysis of k_{min} and k_{max} is performed, where k_{min} is varied from $0.2 \cdot PLR_{req}$ to $0.7 \cdot PLR_{req}$ and k_{max} is varied from $0.7 \cdot PLR_{req}$ to $0.95 \cdot PLR_{req}$, where $k_{max} > k_{min}$. The analysis shows that a limit of k_{max} above 0.8 would provide the best result. 0.80, 0.90 and 0.95 gives almost the same results in the simulations, all of them giving a constant value of L when the system load is fixed. As when k_{min} is concerned, 0.2, 0.3, 0.4 and 0.5 gives the same results when k_{max} > 0.80 and the system load is fixed.

k_{max} should be lower than 0.95, based on the fact that a tiny increase in the offered load causes the PLR requirement to be violated. k_{max} is therefore set to 0.85, and later in this paper it is shown that a increase in the system load of 0.01 can now be tolerated.

k_{min} is set to 0.2 based on the requirement that the distance between k_{min} and k_{max} should be large enough. k_{min} must be as low as 0.2 to prevent L from oscillating, possibly leading to violations of the PLR_{req}.

4 Simulation Results

If not otherwise stated, the parameters in Table 1 are used in the simulations. A core network is simulated, hence the capacity between the switching nodes is set to 10 Gbps. The packet length is chosen according to the average packet lengths in Internet. More details about this can be found in [10]. Ten independent simulations are carried out for every scenario, and 95 % confidence intervals is computed using the Student-t distribution with 9 degrees of freedom.

In all of the figures a horizontal line is used to show the current PLR_{req}.

Variable	Description	Value
C	Capacity	10 Gbps
$Size$	Packet Size	600 bytes
A	System Load	0.6
S_0	Relative share of class 0 traffic	0.2
F	Number of input fibers	4
N	Number of wavelengths per fiber	16
T_p	Packet Payload	4.8 μs
T_o	Overhead	0.48 μs
k_{max}	Upper limit for increasing L	0.85
k_{min}	Lower limit for decreasing L	0.2
PLR_{req}	PLR Requirement for Class 0 traffic	0.0015
M	Measurement Interval	10 000

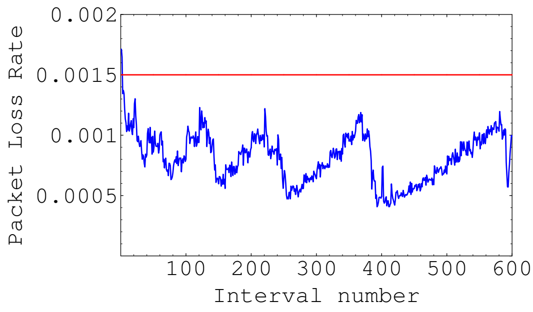
Table 1: Standard Simulation Parameters

Three different simulations are carried out; The system behaviour is investigated with variations in system load, variations in relative share of high priority traffic and variations in both the system load and the relative share of high priority traffic in a random pattern. The parameter L is initially set to 0.

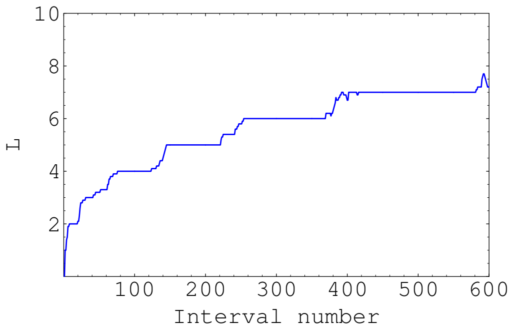
Variation in System Load

The system load is varied from 0.5 to 0.8 with a 0.01 increase every 20th interval. The results from the simulation can be seen in Figure 2, where both the PLR and the variation of the parameter L can be seen.

When comparing the graphs in Figure 2(a) and Figure 2(b) it can be seen that the PLR increase until k_{max} is reached, where L is increased and the PLR drops. This is expected since an increase in L means that more wavelengths are available for class 0 traffic. The figure also shows that the increase in L level off as the system load increases, and the change in PLR from one system load to another is smaller as the system load increases.



(a) PLR



(b) L

Figure 2: Mean values for the PLR and the parameter L with variations in system load.

A system with high load can therefore tolerate larger absolute changes in the system load than a system with low load.

In Figure 3 the 95 % confidence interval for the first 200 intervals is shown.

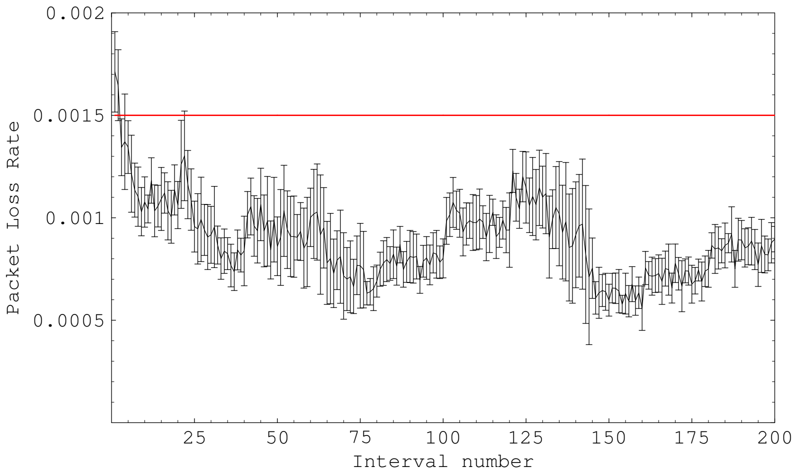
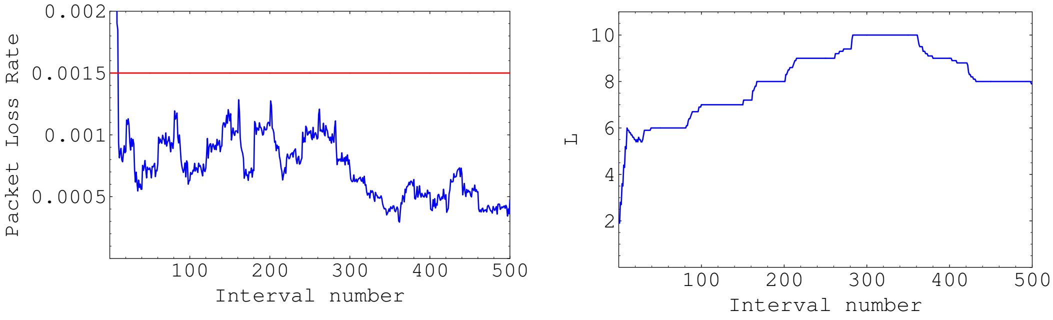


Figure 3: The PLR with variations in system load, 95 % confidence interval.

The confidence interval shows that the experienced PLR is kept below the PLR_{req} for at least 95 % of the time. The system can thus handle changes in system load of 0.01. If a change occurs every 20th interval as in the scenario here, it takes $100 \cdot 20 \cdot 0.0528$ seconds = 105.6 seconds to increase the system load from 0.0 erlang to 1.0 erlang. Faster changes than this will also be possible.

Variations in Relative Share of High Priority Traffic

The system is tested when the relative share of high priority traffic is increased with 0.01 or 0.02 every 20th measurement interval. The relative share is increased until interval number 300, after which the relative share is decreased in an opposite pattern. An increase in relative share of high priority traffic of 0.01 is handled perfectly, and the PLR is kept below the requirement for at least 95 % of the time. The result from the second simulation, where the relative share is increased with 0.02 is shown in Figure 4.



(a) PLR (b) L

Figure 4: Mean values for the PLR and the parameter L with variations in relative share of high priority traffic.

From Figure 4(a) we see that the system is within the upper bound for PLR_{req} as the relative share of traffic is changed with 0.02. The pattern in the graph is the same as for the varied system load scenario. The PLR is increasing until k_{max} is reached, where L is increased and the PLR drops. When the share is decreased after interval number 300, the experienced PLR are kept lower on average. The parameter L is decreased when k_{min} is reached, which causes the PLR to increase. Since k_{min} is relatively low, a decrease in L will still provide a PLR much lower than the PLR_{req}. This means that the PLR for low priority traffic is suffering.

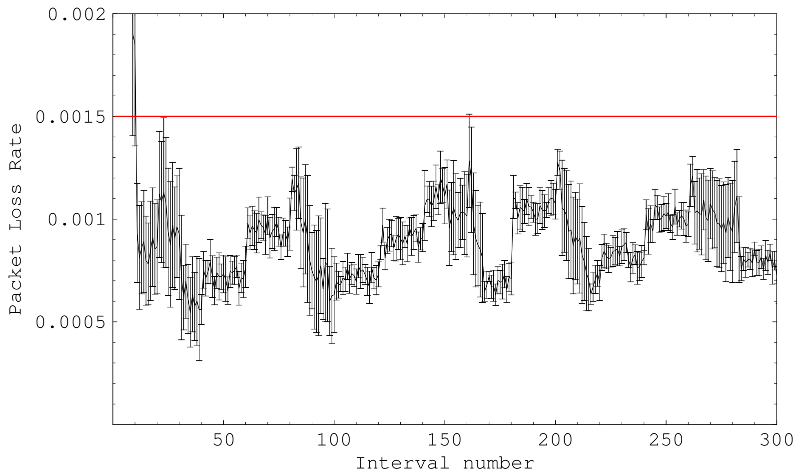


Figure 5: The PLR with varied system load and relative share of high priority traffic, 95 % confidence interval.

Figure 5 shows the 95 % confidence interval for the first 300 measurement intervals when the relative share is changed with 0.02. The PLR requirement is barely violated once, in interval number 160. It is a very small violation, and probably most increases in relative share of 0.02 are tolerated. Still, it can not be absolutely guaranteed that the PLR are kept below the requirement in 95 % of the time.

Random System Load and Share of High Priority Traffic

The system is now simulated with random system load and random share of high priority traffic. The start values are 0.5 and 0.2 for the system load and the relative share respectively. The system load is changed every 20th interval while the relative share is changed every 30th interval. The maximum change allowed is 0.02 for both of them and whether an increase of 0.01 or 0.02 or a decrease of 0.01 or 0.02 occurs is random with probability 0.25 for each of them. The system load and relative share of high priority traffic used for simulations is shown in Table 2.

Interval number	System load
0-20	0.50
20-40	0.51
40-60	0.49
60-80	0.48
80-100	0.50
100-120	0.51
120-140	0.52
140-160	0.54
160-180	0.53
180-200	0.52
200-220	0.53
220-240	0.55
240-260	0.56
260-280	0.57
280-300	0.55

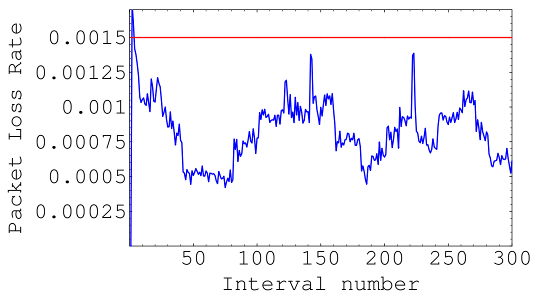
(a) System Load

Interval number	Relative share
0-30	0.20
30-60	0.19
60-90	0.21
90-120	0.22
120-150	0.23
150-180	0.24
180-210	0.22
210-240	0.24
240-270	0.25
270-300	0.23

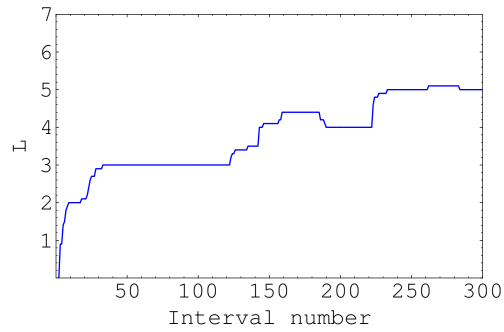
(b) Relative share of HP traffic.

Table 2: Randomly chosen system load and relative share of high priority traffic.

It can be seen from the sample traffic that both increases and decreases of 0.02 occurs, both for system load and relative share of high priority traffic. The results from simulations are shown in Figure 6.



(a) PLR



(b) L

Figure 6: Mean values for the PLR and the parameter L with random system load and relative share of high priority traffic.

The PLR has to drop dramatically before an decrease in L is experienced, in this simulation this only happens in interval number 180, where the system load is decreased with 0.01 and the relative share is decreased with 0.02. Because of the low value of k_{min}, L are seldom decreased. This affects the experienced PLR for low priority traffic.

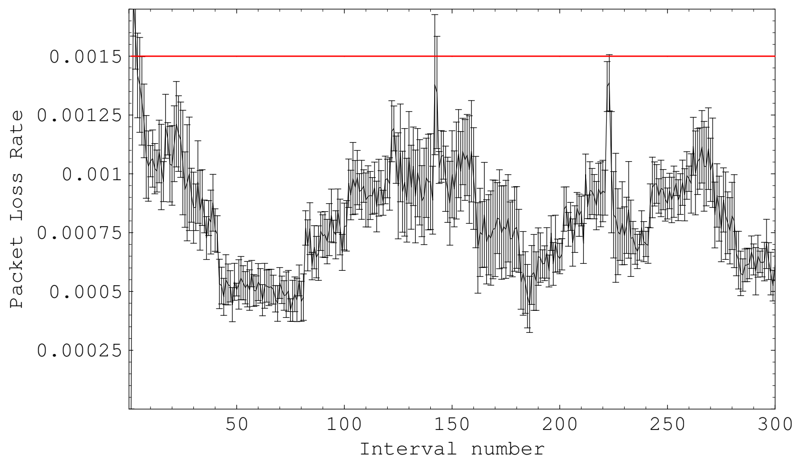


Figure 7: The PLR with varied system load and relative share of high priority traffic in a random pattern, 95 % confidence interval.

As can be seen from the confidence interval in Figure 7, the PLR_{req} is violated two times, both times when an increase in system load of 0.02 occurs. An increase in relative share of high priority traffic of 0.02 is however tolerated in this scenario, which corresponds well to the results found earlier. Increasing the relative share of high priority traffic will not lead to more output contention, a greater increase is therefore tolerated compared to the increase in system load, which increases the output contention.

5 Conclusion

This paper presents a way to achieve QoS in a dynamic network, and absolute QoS can be achieved as long as the changes in system load and relative share of high priority traffic are within acceptable range. The core network experiences a rather constant system load, with few and small changes, making the QoS scheme applicable here.

Simulations show that with the chosen values of k_{min} and k_{max} at 0.2 and 0.85 respectively, an increase in system load of 0.01 and an increase in relative share of high priority traffic of 0.01 is tolerated by the system at the same time. The time between each change must however be larger than two intervals, because two intervals are needed to adjust the parameter L to the correct value. Isolated changes in relative share of high priority traffic of 0.02 can also be tolerated. To allow for greater increases, the k_{max} should be reduced. This will however mean that k_{min} should be reduces too, since the distance between them is important. This will lead to a high PLR for low priority traffic, which may be undesirable.

The measurement interval is chosen to be 10 000 time slots, based on the contradictory desires of having reliable measurements as well as having short measurement intervals and being able to react fast when a change in L is required. The measurement interval must however be longer if the PLR_{req} is low, because more reliable measurements are required in this case. A PLR_{req} of 0.0015 is chosen in this paper, and a measurement interval of 10 000 time slots will then suffice.

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