Performance of a Priority-Weighted Round Robin Mechanism for Differentiated Service Networks

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Abstract

Strict priority queueing and weighted round robin are two common scheduling schemes for differentiation of services in telecommunication networks. A combination of these is the Priority Weighted Round Robin (PWRR) scheme, which serves three classes of traffic with distinct quality requirements, namely expedited forwarding (EF), assured forwarding (AF) and best effort forwarding (BF). The response time of the AF class is analysed under a worst case scenario and an expression for its mean value is obtained using a queueing model. Numerical results are validated by simulation and implications on service level agreements are discussed.

1 Introduction

Integration of real-time and multi-media applications into traditional IP networks has attracted considerable attention in recent years. Meeting the quality of service requirement of these applications has become one of the most important tasks for implementing the next generation Internet. For this reason, many new protocols have been proposed. Among them, so-called 'differentiated services' (DiffServ) was proposed as a simple and scalable solution for providing coarse-grained quality of service (QoS) for Internet applications with differing required levels of service. Moreover, DiffServ is relatively easy to integrate into existing IP networks and the related systems, compared with many other schemes. In a DiffServ-supported network, the flows are categorised into different classes according to their QoS requirement. They are commonly threefold and defined as the Expedited Forwarding (EF) class, the Assured Forwarding (AF) class and the Best Effort Forwarding (BF) class, in descending order of priority. A DiffServ edge node marks each class of packets with a Per-Hop Behavior (PHB) identifier, by writing a DiffServ Code Point (DSCP) into each packet's header. Packets of the same class are marked with the same DSCP and experience the same forwarding behaviour in the core nodes.

A DiffServ node can be implemented by incorporating scheduling disciplines into traditional routers. Strict priority queueing is the simplest method for providing service differentiation in an IP network and consists of a set of buffers served with given priorities. Each class of packets enters a separate buffer that is granted a specified priority and the packets in a higher priority buffer are served before those of all lower priorities.

Weighted fair queueing (WFQ) is a widely studied alternative to implementing differentiated services among multiple classes. It can guarantee each class a bandwidth share proportional to its assigned weight but comes at a cost of greatly increased complexity to implement the scheduling discipline. Weighted round robin (WRR) can achieve similar service differentiation to that of WFQ and is a simpler scheme to implement, with similar performance. More importantly, it can be implemented in hardware and therefore can be applied to high-speed infrastructure in both core and edge of the network. WRR is therefore a widespread alternative in the field.

However, neither priority queue nor weighted round robin alone is flexible enough to meet the delay requirements of the three classes EF, AF and BF. We investigate here a DiffServ architecture that combines the priority queue and weighted round robin schemes. This is called Priority-Weighted Round Robin (PWRR) and resembles the Low Latency Queuing (LLQ) and Class Based Weighted Fair Queuing (CBWFQ) used in Cisco routers. Simulation studies on the throughput of this similar architecture appear in [1, 2].

The basic idea of the PWRR scheme is shown in Fig.(1). EF traffic is put into the highest priority queue and has strict priority over the other two classes in a non-preemptive way. This class includes the most time-sensitive traffic, like signalling packets or network management packets, which demand express services without queueing delays or loss. The AF and BF classes share the bandwidth under a work-conserving WRR scheme. In reality, the AF class – typically real-time applications – usually has a quite strict quality of service requirement on delay and should be given a guaranteed amount of bandwidth. Given the fact that there is a large amount of data traffic, or maybe some ill-behaved flow in the network, without differentiation, real time traffic could suffer starvation. Under WRR management, data traffic is prevented from starving other classes and can hurt only itself if it behaves aggressively. For the AF class, the worst case scenario occurs when the traffic volume of the BF class is large and uses its full quota (as much as its weight permits) in each round. The delay in this worst case is actually the upper bound for the AF class.

In this paper, we restrict our attention to the problem of the response time of the AF class under the worst case scenario. We formulate the problem as a queueing model and obtain an expression for the mean response time, the most critical performance metric for the AF class, by a generating function method. As to the BF class, its response time can be evaluated in a similar way but, since BF applications are generally relatively insensitive to delay, such analysis is not necessary. For the EF class, the PWRR scheme appears just as a non-preemptive priority queue, so its delay performance can be evaluated using existing results in the literature on priority queues[3, 4, 5]. It will therefore not be considered here. The rest of the paper is organized as follows. A description of the PWRR scheme is given in section 2 and in section 3 we present our main result for the mean response time of the AF class. Numerical and simulation results are presented in section 4, followed by discussion on the potential impact on service level agreements. Section 5 concludes.

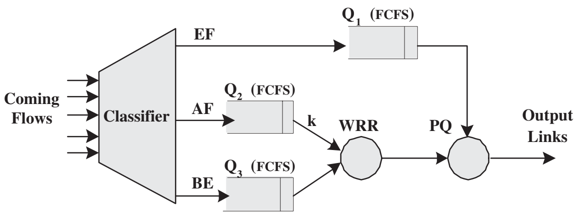

Figure 1: An PWRR architecture at output port of a router in a DiffServ domain [6].

2 System Description

Fig. 1. illustrates a DiffServ router (node) with PWRR scheduling amongst three classes of traffic: EF, AF and BF in descending order of priority. The incoming traffic flows of each class are sent to three separate buffers. Tolerating no delay or loss, EF packets are put into the buffer with the highest priority level, Q_1. The scheduling discipline for EF is the same as for the highest priority class in a non-preemptive priority queue, i.e. a packet in Q_1 will always be served before those in Q_2 and Q_3, but can not interrupt an on-going service of any packet. The AF and BF classes are sent into Q_2 and Q_3, respectively. The server serves these two queues in a round robin fashion, in the order Q_2 then Q_3 in every round, simply to make the scheme easy to implement and maintain. Q_2 and Q_3, are each assigned a weight, which denotes, for each class, the maximum number of packets that can be served in one round. In this scheme, the server can only serve the packets which are already in the queue upon its arrival, up to the maximum number allowed. Any packets that come after the current service visit starts will not be served in this round but will have to wait until a later round. It is therefore possible for the server not to serve its full quota in a round on account of the number of packets in the queue being less than the weight at the time of the server's arrival. No credits are given in later rounds to compensate for this, reducing the possibility of starvation of Q_3. The weight for each queue is fixed in this scheme and, generally speaking, real time traffic, requiring low delay, is put into the AF class and assigned a higher weight. Conversely, the high volume of data traffic in the network, with no specific requirement on delay, can be placed at the lowest priority, the BF class, and assigned a small weight. All packets, after being served, are forwarded to the output links and wait there to be transmitted over the next hop in their paths.

3 Analytical Model Description

In this section, we introduce a queueing model and analyze the mean response time for the AF class under its worst case scenario. We assume that the traffic of each class arrives according to a Poisson process and that buffers Q_1, Q_2 and Q_3 never overflow, i.e. have infinite size. We use the following notation for random variables. For a continuous random variable X, we denote its probability distribution function by $X(t) = Pr(X \leq t)$ and the Laplace-Stieltjes transform of this distribution (the LST) by $X^*(s) = E[e^{-sX}]$, where $E[\cdot]$ and $E[\cdot \mid \cdot]$ denote the expectation and conditional expectation operators. We denote the density function by $x(t) = X'(t)$, the derivative of the distribution function, with Laplace transform $X^*(\theta)$. For a discrete random variable Y, we denote its probability generating function (pgf) by $Y^\sharp(z) = E[z^Y]$.

Let the EF (high priority) and AF packets respectively have arrival rates λ_h, λ and (general) service time random variables B_h, B, with Laplace-Stieltjes transforms $B_h^*(s), B^*(s)$. The service time S of the BF class is also general, with probability distribution $S(t)$ and LST $S^*(s)$. The weight assigned to Q_2 (AF class) is denoted k and, under the worst case scenario, we assume for simplicity that the weight assigned to Q_3 (BF class) is 1.

3.1 Queueing Model

For conciseness, unless stated otherwise, we are referring to the AF class (queue Q_2) when we use terms like 'queue', 'packets' or 'arrivals'. We observe the queueing status of Q_2 at the instant the server arrives at the queue in each round. Let $\{\tau_m : m \geq 0\}$ denote these successive epochs of the rounds beginning at Q_2 and $f_m(n)$ be the probability that the number of packets, F_m, in Q_2 at time τ_m is n. Then $F_m^\sharp(z) = \sum_{n=0}^{\infty} f_m(n) z^n$ is the pgf.

In order to derive the queue length distribution of Q_2 at time τ_{m+1}, we need to know both the number of packets served and the number of new arrivals into Q_2 during one cycle. There are two scenarios we should consider. In the first, the server finds at most k packets in Q_2 at time τ_m. In this case, the server serves all these packets in this round. The other scenario is when the server finds more than k packets in the Q_2 at time τ_m, whereupon it can only serve k packets and leave the remaining ones to later rounds.

To determine how many new AF arrivals come into the system in one round, we first consider the period of a single AF packet's service time, the random variable B. It is well known that the pgf of the number of packets arriving during B is equal to $B^*(\lambda - \lambda z)$ for Poisson traffic input; see Appendix A for a short proof. In the PWRR scheme, the server has to clear Q_1 of the EF packets that enter during B, every time it finishes serving an AF packet. The pgf for the number of EF packets that enter Q_1 during B is $B^*(\lambda_h - \lambda_h z)$, similarly, but more EF packet may arrive while these are being served. The time to clear Q_1 requires a busy period analysis, as in the following lemma and proposition. First we define the random variable V to be the remaining period of the service time of an AF class packet, following the (Poisson) instant of the first EF packet to arrive during that service time. Let B_M denote this extended AF service time, which is one AF packet's service time B plus the sum of the corresponding EF class service times B_h required to empty Q_1 of EF packets (or plus 0 if none arrived in B). Using H to denote a standard busy period in Q_3, we have:

lemma 1 $E[e^{-s(B_M-B)} \mid B] = e^{-\lambda_h(1-H^*(s))B}$

Proof

Suppose N EF class packets arrived in Q_1 during the service time B of an AF class packet in Q_2. Then there are these N present initially when the server begins to serve EF packets immediately after the service of this AF class packet. Therefore, $B_M - B = H_1 + \ldots + H_N$, where $H_1, \ldots, H_N$ and H are independent and identically distributed (i.i.d). This is clear when the queueing discipline is last come first served but we note that busy times are the same for first come first served also (or any other work conserving discipline for that matter). Hence:

$$\begin{aligned} E[e^{-s(B_M-B)} \mid B] &= E[E[e^{-s(H_1+\ldots+H_N)} \mid N, B] \mid B] \\ &= E[E[e^{-sH}]^N \mid B] \\ &= e^{-\lambda_h(1-H^*(s))B} \end{aligned}$$

since the N arrivals are Poisson with rate λ_h. □

Proposition 1 *The time elapsed between the server starting to serve an AF class packet and clearing the EF class queue* Q_1 *has LST*

$$B_M^*(s) = B^*(s + \lambda_h(1 - H^*(s)))$$

Proof

$$\begin{aligned} B_M^*(s) &= E[E[e^{-s(B+B_M-B)} \mid B]] \\ &= E[e^{-sB} E[e^{-s(B_M-B)} \mid B]] \\ &= E[e^{-sB} e^{-\lambda_h(1-H^*(s))B}] \\ &= E[e^{-(s+\lambda_h(1-H^*(s)))B}] \\ &= B^*(s + \lambda_h(1 - H^*(s))) \qquad \square \end{aligned}$$

The required pgf for the number of AF class packets, K_{B_M}, arriving between the server starting to serve an AF class packet and clearing the EF class queue, Q_1, now follows immediately. Similarly, let S_M denote a BF packet's service time plus the corresponding period for emptying Q_1 of EF packets, and let K_{S_M} be the number of AF class packets that arrive during this extended service time S_M.

Proposition 2 *The number of AF class packets arriving during the extended service time of an AF class packet (respectively a BF class packet) has pgf*

$$K^\sharp_{B_M}(z) = B^*_M(\lambda - \lambda z) = B^*(\lambda - \lambda z + \lambda_h(1 - H^*(\lambda - \lambda z)))$$

and

$$K^\sharp_{S_M}(z) = S^*_M(\lambda - \lambda z) = S^*(\lambda - \lambda z + \lambda_h(1 - H^*(\lambda - \lambda z)))$$

We now assume that the system has a steady state and consider the equilibrium pgf of the queue length at Q_2. From the pgf, we can compute the moments of queue length, in particular the mean, by differentiation at $z = 1$. First we define the partial generating function $G^\sharp_m(z) = \sum_{n=0}^{k-1} f_m(n) z^n$, corresponding to those states in the first scenario above. Then the complementary partial generating function $F^\sharp_m(z) - G^\sharp_m(z)$ corresponds to the states in the second scenario. Assuming equilibrium exists, let $F^\sharp_m(z) \to F(z)$ and $G^\sharp_m(z) \to G(z)$ as $m \to \infty$. Then we have the following result.

Proposition 3

$$\begin{aligned} F(z) = \Big[& G\big(B^*(\lambda - \lambda z + \lambda_h(1 - H^*(\lambda - \lambda z)))\big) \\ & + \big(F(z) - G(z)\big) \\ & \cdot \Big(\frac{B^*(\lambda - \lambda z + \lambda_h(1 - H^*(\lambda - \lambda z)))}{z} \Big)^k \Big] \\ & \times S^*(\lambda - \lambda z + \lambda_h(1 - H^*(\lambda - \lambda z))) \end{aligned}$$

Proof

By considering the two scenarios above, the pgf of the length of Q_2 at time τ_{m+1} is:

$$\begin{aligned} F^\sharp_{m+1}(z) &= E[E[z^{F_n + K_{B_M 1} + \ldots + K_{B_M q} + K_{S_M} - q} \mid F_n]] \\ & \quad \text{where } q = \min(F_n, k) \\ & \quad \text{and } K_{B_M}, K_{B_M 1}, \ldots, K_{B_M q} \text{ are i.i.d.} \\ &= E[z^{F_n - q} K^\sharp_{B_M}(z)^q] K^\sharp_{S_M}(z) \\ &= \left[\sum_{n=0}^{k-1} f_m(n) \left(K^\sharp_{B_M}(z) \right)^n \right] \cdot K^\sharp_{S_M}(z) \\ &+ \left[\sum_{n=k}^{\infty} f_m(n) z^n \left(\frac{K^\sharp_{B_M}(z)}{z} \right)^k \right] \cdot K^\sharp_{S_M}(z) \end{aligned} \tag{1}$$

Using proposition 2 in eq.(1), and taking the limit $m \to \infty$, the result follows. □

Finally, we obtain the mean number of packets in Q_2 at an arrival instant of the server by differentiating the pgf $F(z)$ at $z = 1$. To do this, we require the mean number of AF packets served at Q_2 in one cycle, which is given by the following lemma under the appropriate equilibrium conditions.

lemma 2 *The mean number of packets served at* Q_2 *in one cycle at equilibrium is*

$$g_1 = \frac{\lambda \bar{S} + \lambda \lambda_h \bar{S} \bar{H}}{1 - (\lambda \bar{B} + \lambda \lambda_h \bar{B} \bar{H})} \tag{2}$$

where $\bar{B}$, $\bar{S}$ *and* $\bar{H}$ *are the mean values of* B, S *and* H *respectively, under stability conditions that* $\lambda_h \bar{H} + 1 < (\lambda \bar{B})^{-1}$ *and* $\lambda \bar{S} + \lambda \lambda_h \bar{S} \bar{H} < k(1 - (\lambda \bar{B} + \lambda \lambda_h \bar{B} \bar{H})$.

Proof

The required mean value is

$$g_1 = G'(1) + k\sum_{n=k}^{\infty} f(n) \quad (3)$$

Differentiating eq.(1) once with respect to z and setting $z = 1$, gives

$$(\lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H} - 1)k(F(1) - G(1))$$
$$+(\lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H} - 1)G'(1) + (\lambda\bar{S} + \lambda\lambda_h\bar{S}\bar{H})F(1) = 0$$

Since $F(1) = 1$, g_1 follows as required. Since $0 < g_1 < k$, this equation gives the required stability conditions. □

We now define the following terms:

$\rho_S = \lambda\bar{S} + \lambda\lambda_h\bar{S}\bar{H}$;

$\rho_B = \lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H}$;

$V_S = \lambda^2 S^{(2)} + 2\lambda^2\lambda_h\bar{H}S^{(2)} + \lambda^2\lambda_h\bar{S}H^{(2)} + \lambda^2\lambda_h^2\bar{H}^2S^{(2)}$;

$V_B = \lambda^2 B^{(2)} + 2\lambda^2\lambda_h\bar{H}B^{(2)} + \lambda^2\lambda_h\bar{B}H^{(2)} + \lambda^2\lambda_h^2\bar{H}^2B^{(2)}$;

Proposition 4 *The mean queue length at Q_2 at an arrival instant of the server at equilibrium is*

$$\bar{F} = \frac{(V_B + 2\rho_S\rho_B)g_1 + V_S}{2(1-\rho_B)(k-g_1)} - \frac{(1+\rho_B)g_2}{2(k-g_1)} + g_1 \quad (4)$$

where B_2, S_2, H_2 are the second moments of B, S, H respectively and g_2 is the second factorial moment of the number of packets served at Q_2 in one cycle at equilibrium.

Proof

Differentiating eq.(1) twice with respect to z, rearranging terms and evaluating at $z = 1$, we get:

$$(\lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H} - 1)^2k(k-1)(F(1) - G(1))$$
$$+ 2(\lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H} - 1)k(F'(1) - G'(1))$$
$$+ 2(\lambda\bar{S} + \lambda\lambda_h\bar{S}\bar{H})((\lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H} - 1)k(F(1) - G(1))$$
$$+ F'(1) + (\lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H} - 1)G'(1))$$
$$+ (\lambda^2 B^{(2)} + 2\lambda^2\lambda_h\bar{H}B^{(2)} + \lambda^2\lambda_h\bar{B}H^{(2)} + \lambda^2\lambda_h^2\bar{H}^2B^{(2)})$$
$$\cdot G'(1)$$
$$+ k(F(1) - G(1))(2 - 2(\lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H})$$
$$- (\lambda^2 B^{(2)} + 2\lambda^2\lambda_h\bar{H}B^{(2)} + \lambda^2\lambda_h\bar{B}H^{(2)} + \lambda^2\lambda_h^2\bar{H}^2B^{(2)}))$$
$$+ ((\lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H})^2 - 1)G^{(2)}(1) + (\lambda^2 S^{(2)}$$
$$+ 2\lambda^2\lambda_h\bar{H}S^{(2)} + \lambda^2\lambda_h\bar{S}H^{(2)} + \lambda^2\lambda_h^2\bar{H}^2S^{(2)}) = 0$$

Substituting $g_2 = G^{(2)}(1) + k(k-1)\sum_{n=k}^{\infty} f(n)$ and the above defined terms into eq.(5), the result follows. □

Again as expected, we find that the value of $\bar{F}$ depends on the first two moments of the number of packets served in a cycle. In fact, this result is in the same format as, but an extension of, eq.(3.2) of [7].

3.2 Waiting Time

The sojourn or waiting time of a packet is the sum of its queueing time Q and its own service time B, i.e., $W = Q + B$. By standard M/G/1 queueing theory, the pgf of the number of AF packets that arrive during a packet's sojourn time is given by:

$$K_W^{\sharp}(z) = W^*(\lambda - \lambda z) = Q^*(\lambda - \lambda z)B^*(\lambda - \lambda z) \quad (5)$$

Since the AF class packets in the queue are served in FIFO order, the above expression is equal to the queue length seen by a departing packet. In [7], it is shown that the mean queue length seen by any departure is equal to the average queue length seen by all the departures from the queue in that round, i.e.

$$Q^*(\lambda - \lambda z)B^*(\lambda - \lambda z)$$
$$= \frac{\sum_{i=1}^{k} B^*(\lambda - \lambda z)\left(\frac{F(z) - \sum_{j=0}^{i-1} f(j)z^j}{z^i}\right)}{g_1} \quad (6)$$

Differentiating with respect to z, rearranging terms, and setting $z = 1$, we obtain:

$$\bar{Q}(k) = \frac{1}{\lambda g_1}\left(k(\bar{F} - g_1) + \frac{1 + \lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H}}{2}g_2\right) \quad (7)$$

Substituting eq.(4) into eq.(7), an expression for $\bar{W} = \bar{Q} + \bar{B}$ follows as:

$$\bar{W}(k) = \frac{k}{\lambda g_1}\left(\frac{(V_B + 2\rho_S\rho_B)g_1 + V_S}{2(1-\rho_B)(k-g_1)} - \frac{(1+\rho_B)g_2}{2(k-g_1)}\cdot\frac{g_1}{k}\right) + \bar{B} \quad (8)$$

3.3 Approximation

We know $g_2 = 0$ when $k = 1$, so the accurate value of $\bar{W}$ can be computed at weight $k = 1$. We now evaluate the second moment of the number of packets served at Q_2 in one cycle as k goes to infinity. The physical meaning of $k = \infty$ is that in each round, the server will serve all the packets in the queue, which are already there at the time the cycle starts. Therefore, as $k \to \infty$, $g_1 \to \bar{F}$ and g_2 can be derived from eq.(4) as

$$g_2 = \frac{V_B g_1 + 2\rho_S\rho_B g_1 + V_S}{1 - \rho_B^2} \quad (9)$$

The exact value of the mean delay of an AF packet at $k = \infty$ can then be computed as:

$$\bar{W}(\infty) = \frac{1 + \lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H}}{2\lambda g_1}\cdot g_2(\infty) + \bar{B} \quad (10)$$

Although a closed form expression for g_2 is not available at other values of k, [7] gives a good algorithm for approximating g_2 from $g_2(\infty)$, by estimating the number of packets served in one cycle as a negative binomial distribution. The algorithm is attached in Appendix B for completeness. This algorithm works well for our PWRR scheme and by adopting it, the mean waiting time for the AF class of packets with any pre-assigned weight k can be computed easily. $\bar{W}(k)$ is therefore estimated as:

$$\bar{W}(k) = \frac{1}{1 - g_1/k}\left(\bar{W}(\infty) - \frac{1 + \lambda\bar{B} + \lambda\lambda_h\bar{B}\bar{H}}{2}\frac{g_2}{\lambda k}\right) \quad (11)$$

4 Analytical and Simulation Results

In this section, we present some numerical results and discuss how the parameters impact on the delay performance of the AF class in the PWRR DiffServ architecture. The numerical results are validated by computer simulation. As we are interested only in the delay performance of the AF class under heavy BF traffic load, the so-called worst case scenario, the arrive rate for the BF class is set to a high value, 0.9, for all the simulations, unless stated otherwise.

Fig.(2) illustrates the impact of packet size of the EF class (B_h) on the mean waiting time of the AF class ($W(k)$). The service times of all three classes are assumed to be exponential random variables and $\bar{B} = \bar{B}_h = \bar{S} = 1$. The pre-assigned weights are 3 and 1 for AF class and BF class, respectively. The waiting time $W(3)$ is evaluated at $\lambda = 0.1, 0.3$. We can see from the figure that as B_h increases, $W(3)$ increases accordingly for both cases, as expected. This is because AF class packets arrive and accumulate in the queue during the time when the server serves EF packets in Q_1, so inducing a longer waiting time for an AF packet. These results suggest that excessive EF traffic will possibly consume nearly all the bandwidth of the system and lead to the starvation of the AF and BF classes. Therefore, it is very important in the real implementation that traffic policing should be provided at the ingress router of the DiffServ domain, making sure that the EF class does not exceed its quota, which can be chosen appropriately in the service level agreement using an analysis such as ours.

In Fig.(3), we investigate how the BF packets affect the AF class's delay performance, even though it is regarded as a lesser class to the AF class. It is found that, at fixed weights for the two classes, a larger BF packet's size will induce a longer waiting time for the AF packets in both the cases that AF loads are $\lambda = 0.1, 0.3$. This result suggests that the weights of the classes under the WRR scheme need to be adjusted when mean service times change in order to meet their delay requirement.

In Fig (4), we investigate the mean waiting time $W(k)$ of the AF class at different values of k. The weight assigned to the BF class is always 1. In both the cases that the AF traffic loads are medium (λ=0.3) and high (λ=0.6), as k increases, $W(k)$ will eventually converge to the limit $W(\infty)$. Comparing the two curves, we found it relatively more important to assign an appropriate weight to the AF class when its traffic load is high. Lack of bandwidth in this case will induce severe delay.

5 Conclusion

In this paper, a DiffServ architecture, PWRR, for serving three classes of traffic with distinct quality of service requirements, namely EF, AF and BF, was studied. A queueing model was used to solve for the mean waiting, or response, time of the AF class under a worst case scenario, where there is always a BF packet ready to be processed. The model is also applicable to the BS class if its delay performance is of interest. By using the generating function approach, an approximate expression for the upper bound of the AF class' waiting time was computed using Everitt's algorithm. The accuracy of these numerical results was assessed by computer simulations, which indicated good agreement at low loads and the same trends at increasing loads, although with less absolute precision. The impact of various different parameters was also evaluated quantitatively. The numerical results reveal insight into this DiffServ architecture and indicate the impact from the EF and BF classes. Our work will help to decide the service level agreements on, for example, the values of the weights and the maximum amount of traffic allowed, especially for the EF class in this architecture, in order to fulfil and enhance quality of service requirements in IP networks. The assumption of Poisson arrivals in our model is preliminary. As commonly noted for other models, it is often realistic, for example when traffic is a superposition of independent, relatively sparse streams that are well approximated by renewal processes. We plan to extend our work by considering real network traffic in the near future.

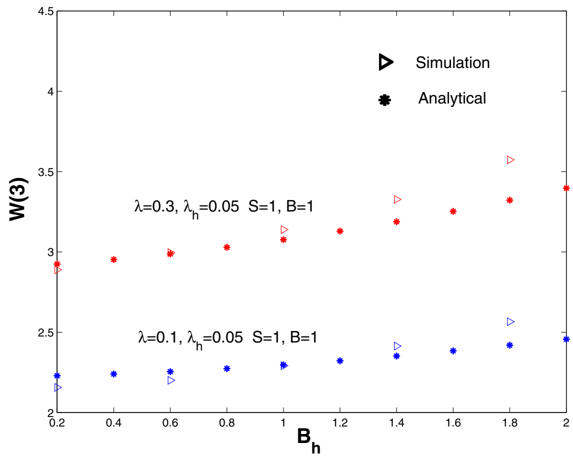

Figure 2: Mean delay ($\bar{W}(k)$) versus the mean packet size of EF class (B_h): k=3.

Appendix A: Review of Poisson arrivals in a random interval and busy periods

For Poisson traffic with arrival rate λ, the pgf of the number of arrivals in time $(0, t)$ is $e^{-(\lambda-\lambda z)t}$. In one service time B, The pgf of the number of AF packets, A, arriving in the system is:

$$\begin{aligned} K_B^{\sharp}(z) &= E[z^A] = E[E[z^A \mid B] \\ &= E[e^{-(\lambda-\lambda z)B}] \\ &= B^*(\lambda - \lambda z) \end{aligned} \quad (A.1)$$

Now let H denote the busy period of EF class packets, i.e. the time elapsed between an arrival to an empty queue and the

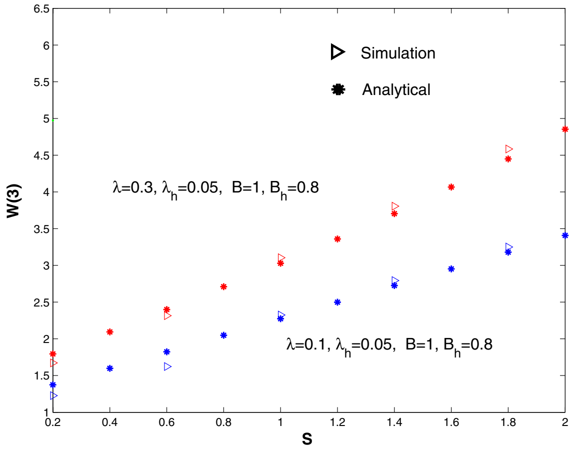

Figure 3: Mean Delay ($\bar{W}(k)$) versus the mean packet size of BF class (S): k=3.

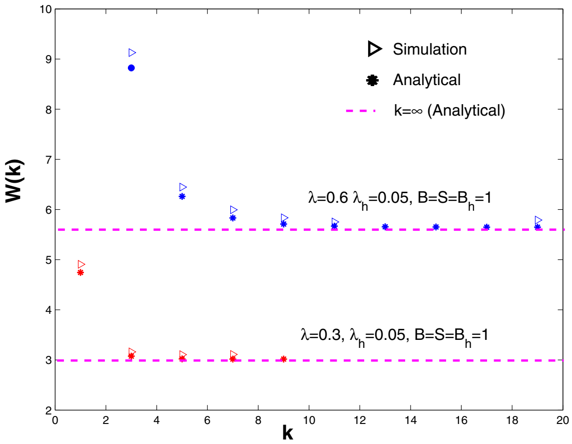

Figure 4: Mean delay ($\bar{W}(k)$) versus the weight k.

instant at which the queue next becomes empty. Let Z be the number of arrivals during a service time B_h. Then

$$\begin{aligned} H^*(s) &= E[E[e^{-sH} \mid B_h]] \\ &= E[E[E[e^{-s(B_h+H_1+\ldots+H_Z} \mid Z, B_h] \mid B_h]] \\ &= E[E[e^{-sB_h} E[e^{-sH}]^Z \mid B_h]] \\ &= E[e^{-sB_h} e^{-\lambda_h(1-H^*(s))B_h}] \\ &= E[e^{-(s+\lambda_h(1-H^*(s)))B_h}] \\ &= B_h^*(s+\lambda_h(1-H^*(s))) \end{aligned} \quad \text{(A.2)}$$

where the random variables $H, H_1, \ldots, H_Z$ are i.i.d.

Appendix B: The algorithm in [7]

The distribution of the number of AF packets served in one round can be approximated by a negative binomial distribution, i.e. by

$$P\{X = j\} = \binom{r+j-1}{j} p^r (1-p)^j \quad \text{(B.1)}$$

which has mean g_1 and variance $g_2 + g_1(1-g_1)$ (or, equavaliently, the second factorial moment is g_2). Thus we have

$$p = \frac{1}{1 - g_1 + g_2/\bar{g}} \quad \text{(B.2)}$$

and

$$r = \frac{1}{g_2/{g_1}^2 - 1} \quad \text{(B.3)}$$

For limited k, we approximate this rndom variable X by X', which has probability function:

$$P\{X' = j\} = \begin{cases} \delta \cdot \binom{r+j-1}{j} p^r (1-p)^j, \\ \qquad 0 \le j \le k-1 \\ 1 - \delta \sum_{j=0}^{k-1} \binom{r+j-1}{j} p^r (1-p)^j, \\ \qquad j = k-1 \end{cases}$$

where δ is chosen so that the mean value of this distribution remains g_1. Then, g_2 is approximated as the second factorial moment of this distribution.

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