REAL-TIME SIGNAL TRANSFER OVER IP NETWORKS

Evan Lau
Network Consultant
Advanced Network Services
ISA Technologies
evan@lau-chi.com

Guven Mercankosk
Senior Lecturer
Department of Electrical & Electronic Engineering
University of Western Australia
guven@ee.uwa.edu.au

Abstract Real-time communication over IP networks is becoming increasingly widespread with the advent of real-time applications such as video-conferencing. Integrated Services Guaranteed Service and Differentiated Services Expedited Forwarding are two different architectures that cater for these real-time communications. This paper extends the existing models of the spacer and policer, and describes the relationship between the architectures and these traffic conditioners. From this relationship, this paper will show that Expedited Forwarding represents a more elegant and scalable solution for real-time communications than Guaranteed Service.

Keywords: Real-time communications, IP networks, Integrated Services Guaranteed Service, Differentiated Services Expedited Forwarding, spacing with input queue threshold, Generic Packet Rate Algorithm (GPRA).

1. Introduction

The Internet and other large-scale IP networks are increasingly being used for real-time communications where the time taken for packets generated at a source to reach the destination must be known and bounded. This is known as the principle of delay constancy [Budrikis and Mercankosk, 1996].

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The Guaranteed Service class of Integrated Services is perceived to be the best option for these communications as the network can use idle resources to provide a higher level of service than the guaranteed, or subscribed, service. However, any service above the guaranteed service is not known and cannot be effectively used by these real-time communications. Furthermore, Guaranteed Service must distinguish between each individual communication and arbitrate resource allocation accordingly.

The Expedited Forwarding behaviour of Differentiated Services provides a different solution where communications are classified into aggregates, or classes. Each aggregate contains two or more communications; no distinction is made between packets of different communications. The network is able to implement simple schedulers in the core that simply forward packets to the destination.

With the continual growth in the use of the Internet and large-scale IP networks for real-time communications, it will become important to be able to scale the network core without the need to explicitly facilitate the increasing number of individual communications.

Real-time traffic entering a Guaranteed Service or Expedited Forwarding network must be conditioned to conform to some agreed profile. This paper establishes an equivalence relationship between spacing traffic in Expedited Forwarding and policing traffic in Guaranteed Service by extending existing models of the spacer and policer.

1.1 Integrated Services Guaranteed Service

IntServ Guaranteed uses resource reservation on a per flow basis. This architecture is based on the philosophy that switches or routers in a network must reserve resources to provide the service each individual traffic flow requires, and that this in turn requires flow-specific states in the switches or routers [Braden et al., 1994].

IntServ Guaranteed is intended to be used for communications where traffic characteristics other than the peak rate are known prior to each communication. IntServ Guaranteed is specified by the Peak Rate (PR), the Sustainable Rate (SR), and the Intrinsic Burst Tolerance (IBT).

The PR places a limit on the maximum rate at which packets may enter the network. The SR is the minimum guaranteed rate at which packets are transferred from the source to the destination. The IBT places a limit on the time that packets may enter the network at a rate greater than the SR [Mercankosk, 1995]. No assertions are made that the characteristics of IntServ Guaranteed are the same as the real-time signal generated at the source, which may be policed.

1.2 Differentiated Services Expedited Forwarding

DiffServ EF uses prioritization on a per aggregate basis. This architecture is based on the philosophy that the ingress point classifies traffic according to a finite number of categories; the switches or routers allocate resources to each category and simply forward packets accordingly regardless to which traffic flow they belong [Blake et al., 1998].

DiffServ EF is intended, but not limited, to meet the requirements of Constant Bit Rate (CBR) traffic. DiffServ EF is specified by a single rate, the Peak Rate (R). The R places a limit on the maximum rate at which packtes may enter the network. A Variable Bit Rate (VBR) real-time signal generated at the source may be spaced before being presented to the network.

1.3 Traffic conditioning

We only consider traffic conditioning at the ingress point of a network, so traffic is conditioned before entering the network. Traffic conditioning ensures that traffic from any particular application entering the network does not exceed the ability of the network to provide the subscribed service to that traffic flow.

Traffic conditioners can discard or shape (delay) packets [Blake et al., 1998]in a traffic flow to enforce an agreed traffic profile. Traffic entering an IntServ Guaranteed network is policed to maintain the timing of packets in the flow. On the other hand, traffic entering a DiffServ EF network is shaped to a specified rate; any packet that will experience a delay greater than the specified maximum is discarded.

2. The Spacer

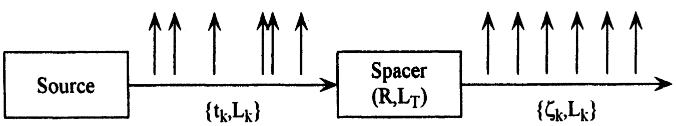

Figure 1. The spacer.

Figure 1 illustrates a general spacer model. Packets are generated at the source according to some general probability distribution and placed into the input queue. The resulting arrival stream at the spacer is represented by the sequence $\{t_k, L_k\}$, where t_k represents the arrival time of packet k and L_k represents the length of packet k. The input queue threshold L_T places a limit on the maximum delay that may be experienced by a packet in the input queue. Packets are spaced in time by the spacer such that the time between successive departures is at least a minimum determined by the rate R and the lengths of preceding packets. This results in the departure sequence $\{\zeta_k, L_k\}$, where ζ_k represents the departure time of packet k.

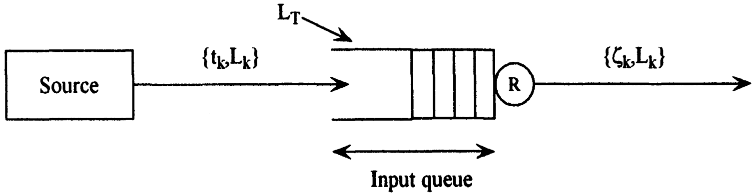

Figure 2. The $G/D/1$ model of the spacer.

We can use a $G/D/1$ system with $FIFO$ service order to model the behaviour of the spacer. Figure 2 illustrates this model. In this model, t_k represents the arrival time of the last bit of packet k and ζ_k represents the emission time of the first bit of packet k. Mercankosk [Mercankosk, 1993]describes an algorithm to calculate these emission times for fixed sized cells. The algorithm has been adapted to determine the emission times for variable length packets. Figure 3 illustrates this modified algorithm. The emission times are described by

$$\zeta_{k+1} = max(t_{k+1}, \zeta_k + \frac{L_k}{R}). \tag{1}$$

The delay experienced by a packet in the input queue is the time between the arrival and the departure of that packet; that is

$$d_k = \zeta_k - t_k. \tag{2}$$

We now draw an analogy between the delay experienced by a packet in the input queue and the work in the system. The work in the system is associated with the packets already in the input queue and the residual work of the most recently emitted packet. From Equations 1 and 2, the delay, or work in the system, is characterised by

$$d_{k+1} = max(0, d_k + \frac{L_k}{R} - (t_{k+1} - t_k)). \tag{3}$$

2.1 Busy periods

A busy period at the spacer is a time interval in which the equivalent $G/D/1$ system is never idle; that is, the input queue is not empty or the delay experienced by packets in the input queue is not zero. The start

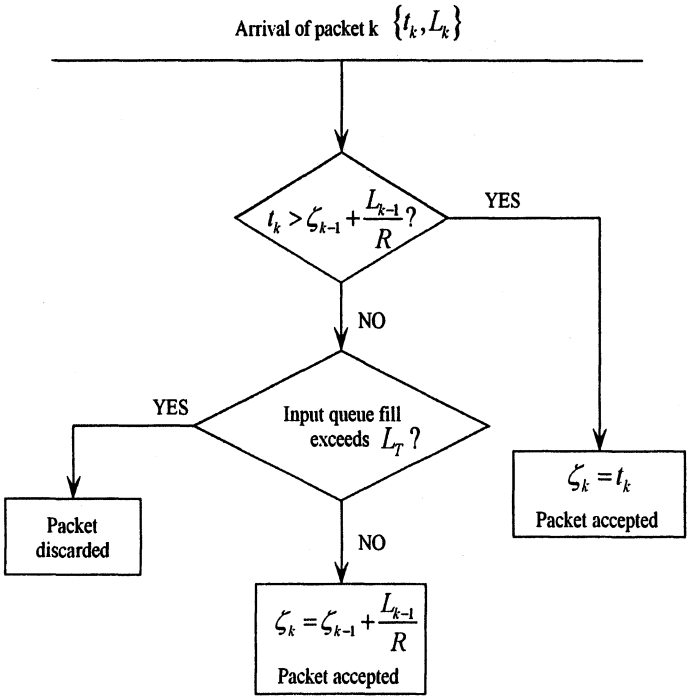

Figure 3. The spacing algorithm for variable length packets.

of a busy period occurs upon the arrival of the very first packet, or when a packet experiences no delay in the input queue before being emitted. The end of a busy period occurs upon the departure of the last bit of the last packet in the input queue. The next packet that arrives after the end of a busy period marks the start of the next busy period.

During a busy period, a packet arrives to find that the input queue is not empty, or that there is residual work associated with the most recently emitted packet. The packet is placed in the input queue if the contents of the input queue are less than the threshold L_T. If the contents are greater than or equal to this threshold, the packet is discarded.

Consider a busy period in the $G/D/1$ system of length B packets and starting at time t_k. Assume that none of the B packets in the busy period are discarded. We have, for the $(j+1)^{th}$ packet,

$$\begin{aligned}
\zeta_k &= t_k && j = 0, \\
t_{k+j} \leq \zeta_{k+j} &= t_k + \frac{1}{R}\sum_{i=0}^{j-1} L_{k+i} && j = 1 \ldots B-1, \\
t_{k+B} = \zeta_{k+B} &> t_k + \frac{1}{R}\sum_{i=0}^{j-1} L_{k+i} && j = B.
\end{aligned} \tag{4}$$

2.2 The input queue threshold

The input queue threshold L_T places a limit on the maximum delay that may be experienced by a packet in the input queue of the spacer. In order to ensure this maximum delay is not exceeded, the threshold must also determine whether a packet that arrives at the spacer is placed in the input queue or discarded. We now derive the relationship between the input queue threshold and the delay experienced by a packet in the input queue.

Consider an arbitrary busy period at the spacer. Let t_0 represent the start of this busy period; that is, the arrival time of the first packet in this busy period. During this busy period, a packet that arrives at the spacer is placed into the input queue if the contents of the input queue are less than the threshold. The contents of the input queue upon arrival of a packet can be related to the arrivals and departures since the start of the current busy period. Hence, a packet k is accepted when

$$\text{Number of Bits Arrived} \quad - \quad \text{Number of Bits Emitted} \quad < \quad L_T,$$

which means

$$(\sum_{i=0}^{k-1} L_i) - \lfloor (t_k - t_0)R \rfloor < L_T, \quad \text{or}$$

$$(\sum_{i=0}^{k-1} L_i) - \lfloor (t_k - t_0)R \rfloor \leq L_T - 1.$$

The above equation assumes that all packets before packet k were accepted. Since $\lfloor x \rfloor \leq x$ for any real x,

$$(t_0 - t_k)R + \sum_{i=0}^{k-1} L_i \leq L_T - 1, \quad \text{or}$$

$$t_0 - t_k + \frac{1}{R}\sum_{i=0}^{k-1} L_i \leq \frac{L_T - 1}{R}. \tag{5}$$

Using Equation 3, we can express Equation 5 in terms of the delay experienced by packet k in the input queue of the spacer.

$$d_k \leq \frac{L_T - 1}{R} \tag{6}$$

During this busy period, a packet that arrives at the spacer is discarded if the contents of the input queue are greater than or equal to the threshold. Hence, a packet is discarded when

$$\text{Number of Bits Arrived} \quad - \quad \text{Number of Bits Emitted} \quad \geq \quad L_T,$$

which means

$$(\sum_{i=0}^{k-1} L_i) - \lfloor (t_k - t_0)R \rfloor \geq L_T.$$

Since $x - 1 < \lfloor x \rfloor$ for any real x,

$$(t_0 - t_k)R + 1 + \sum_{i=0}^{k-1} L_i > L_T, \quad \text{or}$$

$$t_0 - t_k + \frac{1}{R}\sum_{i=0}^{k-1} L_i > \frac{L_T - 1}{R}. \tag{7}$$

Once again, using Equation 3, we can express Equation 7 in terms of the delay experienced by packet k in the input queue of the spacer.

$$d_k > \frac{L_T - 1}{R} \tag{8}$$

From Equations 6 and 8, we can summarise the relationship between the input queue threshold and the delay experienced by a packet in the input queue, along with whether a packet is accepted or discarded.

$$\begin{aligned} d_k &\leq \frac{L_T - 1}{R} && \text{accepted packet} \\ d_k &> \frac{L_T - 1}{R} && \text{discarded packet} \end{aligned} \tag{9}$$

By spacing with input queue threshold, we have demonstrated that a packet is only accepted into the input queue if the delay it will experience in the input queue is less than a specified maximum. The acceptance does not depend on the size of the input queue; however, it is clear that the size of the input queue need only be one maximum packet length greater than the input queue threshold.

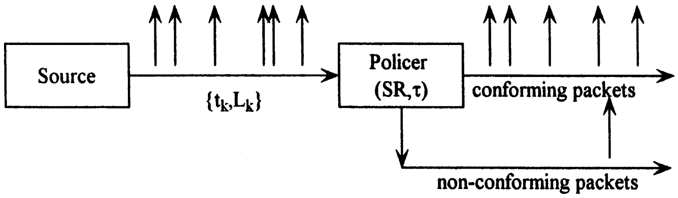

Figure 4. The policer.

3. The Policer

Figure 4 illustrates a policer model. Similar to the discussion about the spacer, packets are generated at the source according to some general probability distribution and arrives at the policer with sequence $\{t_k, L_k\}$. Like the spacer, packets are either accepted or discarded. However, unlike the spacer, accepted packets are not spaced in time but depart immediately upon arrival. Hence, the departure sequence is the same as the arrival sequence, with the absence of any discarded packets.

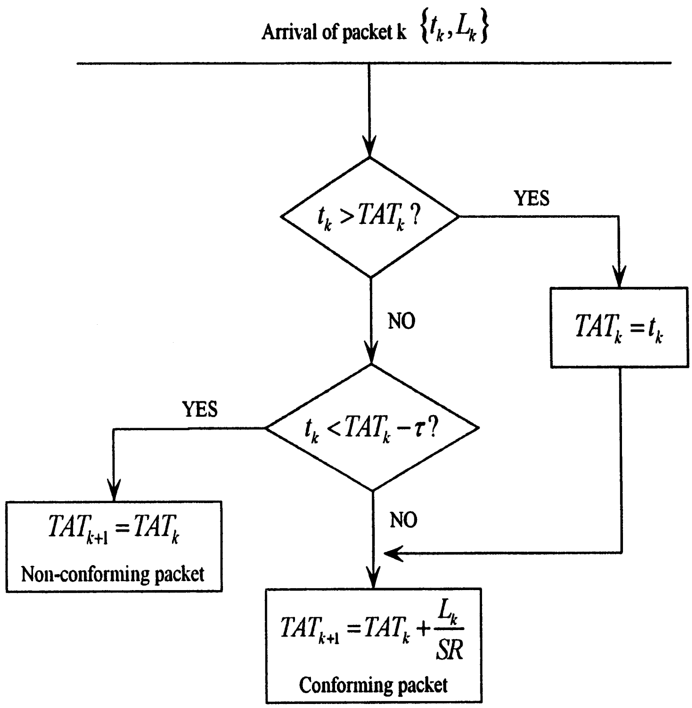

Figure 5. The Generic Packet Rate Algorithm (GPRA).

The ATM Forum [ATM Forum Technical Committee, 1999]describes the Generic Cell Rate Algorithm (GCRA) to determine the conformance of fixed sized cells to an agreed traffic profile. The algorithm has been adapted to form the Generic Packet Rate Algorithm (GPRA), which deals with variable length packets. Figure 5 illustrates this modified algorithm. Packets that arrive too early relative to the Theoretical Arrival Time TAT and the intrinsic burst tolerance τ are marked non-conforming and discarded; otherwise, the packets are conforming and are immediately emitted. The TAT of the next packet is determined by the sustainable rate SR and the lengths of preceding packets.

We can use the same $G/D/1$ system with $FIFO$ service order to model the behaviour of the policer as we used for the spacer. We need only replace all instances of the spacer rate R with the sustainable rate SR and all instances of the spacer emission times ζ with the theoretical emission times TAT. Hence, the emission times are described by

$$TAT_{k+1} = max(t_{k+1}, TAT_k + \frac{L_k}{SR}), \qquad (10)$$

whilst the early arrival of a packet relative to its TAT is given by

$$e_k = TAT_k - t_k. \qquad (11)$$

3.1 Busy periods

A busy period at the policer is a time interval in which the equivalent $G/D/1$ system is continuously busy. The start of a busy period occurs upon the arrival of the very first packet, or when a packet arrives late relative to its TAT. The end of a busy period occurs when a packet does not arrive at, or before, its TAT. During a busy period, each packet arrives at, or before, its TAT. Packets that arrive early within the tolerance τ are conforming; packets that arrive earlier are discarded.

We again replace all instances of R with SR and ζ with TAT in Equation 4. Hence, for a busy period at the policer of length B packets and starting at time t_k, we have, for the $(j+1)^{th}$ packet,

$$\begin{aligned} TAT_k &= t_k & j &= 0, \\ t_{k+j} \le TAT_{k+j} &= t_k + \frac{1}{SR}\sum_{i=0}^{j-1} L_{k+i} & j &= 1 \ldots B-1, \\ t_{k+B} = TAT_{k+B} &> t_k + \frac{1}{SR}\sum_{i=0}^{j-1} L_{k+i} & j &= B. \end{aligned} \qquad (12)$$

Again, we assume that none of the B packets in the busy period are discarded.

3.2 The intrinsic burst tolerance

The tolerance τ places a limit on how early a packet may arrive relative to its TAT. The GPRA describes this relationship, along with whether a packet is conforming or non-conforming. Conforming packets are emitted immediately; non-conforming packets are discarded.

$$\begin{aligned} e_k &\leq \tau \quad && \text{conforming packet} \\ e_k &> \tau \quad && \text{non-conforming packet} \end{aligned} \tag{13}$$

The equation above assumes that all packets before packet k were accepted.

The relationship described by Equation 13 shows that a packet may only arrive early at the policer to its TAT by an amount bounded by the maximum smoothing delay introduced by the bandwidth reduction to SR. Hence, τ is also a bound on the maximum smoothing delay a packet may experience in the network.

4. The Equivalence of Spacing and Policing

We desire to establish the equivalence of spacing and policing a sequence of packets generated by a source. We assume that the same sequence of packets generated by the source passes through a spacer with rate R and policer with rate SR such that

$$R = SR. \tag{14}$$

We will now use R to represent the common rates.

The two departure sequences of the spacer and policer are equivalent if the following two conditions are met:

1 The delay experienced by a packet in the input queue of the spacer is equal to how early the corresponding packet arrives at the policer; and vice versa. This is necessary so that the bandwidth reduction enforced by the spacer is equal to the maximum bandwidth reduction deferred to the network by the policer.

2 The sequences contain the same set of packets. This means that the spacer accepts the same packets that the policer accepts, and discards the same packets that the policer discards; and vice versa.

4.1 Delay at the spacer and early arrival at the policer

Equations 4 and 12 describe the packet emission times during a busy period. Furthermore, the two sets of equations are equivalent under the conditions of Equation 14. Hence,

$$\zeta_k = TAT_k \tag{15}$$

for all k; that is, the emission time for a packet at the spacer is the same as the emission time for the corresponding packet at the policer.

Equation 2 describes the delay experienced by a packet in the input queue of the spacer; Equation 11 describes how early a packet arrives at the policer relative to its TAT. Again, these two equations are equivalent under the conditions of Equation 15.

Hence, the first condition necessary to establish the equivalence of spacing and policing is satisfied.

4.2 Input queue overflow at the spacer and non-conformance at the policer

Without loss of generality, consider an arbitrary busy period starting at time t_0 at the spacer and policer. We will establish the conditions required for the first packet the spacer discards to be the first packet the policer finds non-conforming; and vice versa.

Let packet n be the first packet in a busy period the spacer discards due to input queue overflow. This means that all packets in the busy period that arrived before packet n must have been accepted into the input queue. From Section 1.2, these conditions can be expressed as

$$\begin{aligned} d_k &\leq \frac{L_T - 1}{R} \qquad 0 \leq k \leq n-1, \\ d_n &> \frac{L_T - 1}{R}. \end{aligned} \tag{16}$$

For packet n to be the first packet marked non-conforming by the policer, all packets in the busy period that arrived before packet n must have been marked conforming. From Section 1.3, these conditions are

$$\begin{aligned} e_k &\leq \tau \qquad 0 \leq k \leq n-1, \\ e_n &> \tau. \end{aligned} \tag{17}$$

Since τ can be any real number, there is a unique value of τ that results in the equivalence of Equations 16 and 17, given L_T and R. This unique value is

$$\tau = \frac{L_T - 1}{R}. \tag{18}$$

The behaviour of the spacer and policer is such that discarded packets do not affect the timing of subsequent packets; nor do the discarded packets affect which of these subsequent packets are accepted or discarded.

The first packet the spacer and policer discard is removed from the arrival sequence. The same is done for the resulting sequence after this removal. This process is repeated for the entire arrival sequence.

Hence, we can achieve the equivalent of spacing at rate R with input queue threshold L_T by policing at the same rate R with intrinsic burst tolerance τ; and vice versa.

4.3 The smoothing delay

The smoothing delay in IntServ Guaranteed is associated with the bandwidth reduction in the network as the service rate is reduced below the Peak Rate (PR). This smoothing delay may be as much as when the service rate is limited to the Sustainable Rate (SR).

To satisfy the principle of delay constancy, the transfer delay bound cannot be shorter than the longest expected delay over the lifetime of each communication [Budrikis and Mercankosk, 1996]. Hence, for real-time communications, we must assume that the smoothing delay occurs in full; that is, the service rate is limited to SR. This means that each packet experiences a smoothing delay equal to how early it arrives at the policer relative to its TAT; we must equalize as such at the destination. This also means that the intrinsic burst tolerance τ represents the maximum smoothing delay a packet may experience in the network.

Furthermore, in Section 1.4.1, we established that the delay experienced by a packet in the input queue of the spacer (the smoothing delay) is equal to how early the corresponding packet arrives at the policer. Since we must assume that how early a packet arrives at the policer corresponds to the smoothing delay the packet experiences in the network, this means that the smoothing delay of packets handled by IntServ Guaranteed after being policed is the same as the smoothing delay of packets handled by DiffServ EF after being spaced.

5. Significance of the Equivalence

The transfer delay bound for any communication has three components: propagation delay, smoothing delay, and queueing delay. The propagation and queueing delay components are identical for both architectures under consideration; the network structure and number of competing real-time traffic flows in the network are independent of the chosen architecture.

Since the three components of delay are equal for IntServ Guaranteed and DiffServ EF, the transfer delay bound for real-time communications in both architectures are also equal. This means that we are able to achieve the same level of service for real-time communications in IntServ Guaranteed and DiffServ EF.

5.1 Temporal statistical multiplexing

DiffServ EF requires that the sum of R of each real-time application must be less than the capacity of the pipe. On the other hand, IntServ Guaranteed only requires that the sum of SR of each real-time application be less than this capacity. These arguments have often led to the false conclusion that IntServ Guaranteed facilitates temporal statistical multiplexing as the number of real-time communications IntServ Guaranteed can support in a fixed pipe is greater than the number of these applications DiffServ EF can support in the same pipe.

However, in DiffServ EF, a real-time signal can be smoothed and presented to the network at rate SR instead of PR. This paper has shown the equivalence of spacing in DiffServ EF and policing in IntServ Guaranteed, both at a common rate, in terms of discarded packets and the maximum smoothing delay. So, for *real-time* communications, it is sufficient to smooth real-time traffic to rate SR in DiffServ EF to achieve the same statistical gain as IntServ Guaranteed.

It is also argued that, even if we can present the traffic at SR in DiffServ EF, we introduce a smoothing delay at the input queue of the spacer; this smoothing delay may not occur in IntServ Guaranteed as the network may provide a service greater than SR. However, in fact there is *no* guarantee that this smoothing delay will not occur. Furthermore, the guaranteed service is SR, so it is possible that the maximum smoothing delay associated with the bandwidth reduction to SR in the network may occur.

5.2 Granularity of service

The granularity of service that DiffServ EF provides is not affected by the finite number of service classes within the network, as all real-time communications will be handled by the highest service class. However, in establishing the equivalence of spacing and policing, there is a granularity of the smoothing delay bound introduced by the input queue threshold. We can specify the maximum smoothing delay in IntServ Guaranteed by the intrinsic burst tolerance τ, which can take on any real number. The maximum delay in DiffServ EF is given by Equation 6.

$$d_{max} = \frac{L_T - 1}{R} \tag{19}$$

If we assume that the rate R can take arbitrary value, then the granularity of the smoothing delay bound Δd_{max} depends only on the input queue threshold, which has a granularity ΔL_T of one bit.

$$\Delta d_{max} = \frac{\Delta L_T}{R} < \frac{1}{R}$$

Therefore if we specify an arbitrary intrinsic burst tolerance τ of a VBR real-time signal, we can choose a maximum smoothing delay d_{max} that varies from τ by

$$0 \leq |\tau - d_{max}| \leq \frac{\Delta d_{max}}{2} < \frac{1}{2R}. \tag{20}$$

Since R is in general much larger than one, the difference between the required and actual delay bounds is negligible.

5.3 Relationship between traffic parameters

We observe that we have only one degree of freedom in choosing the traffic parameters of a real-time VBR signal. The PR is a characteristic of the source and we know that we can choose either SR or τ, not both. In this situation, DiffServ EF provides a hard guarantee that the smoothing delay will never exceed τ; thus τ is a *hard* bound. However, the smoothing delay can probabilistically exceed τ such that

$$Pr\{s_k(SR) > \tau\} < \varepsilon, \tag{21}$$

where $s_k(SR)$ represents the actual smoothing delay bound associated with the rate SR and ε is typically within the range 10^{-6} to 10^{-12}. If $\varepsilon \neq 0$, we now have two degrees of freedom in choosing the traffic parameters; once we set any two of SR, τ, or ε, the third parameter is determined immediately. If $\varepsilon = 0$, Equation 21 reduces to the situation where τ represents the hard bound and we again have only one degree of freedom.

6. Conclusion

Real-time communications over IP networks require guaranteed bandwidth with bounded transfer delay. We have discussed two architectures that support real-time communications over the Internet: the Guaranteed Service of Integrated Services; and the Expedited Forwarding behaviour of Differentiated Services.

This paper has explored the behaviour of traffic conditioners and traffic flows in both architectures. It has been shown that policing in IntServ Guaranteed and spacing in DiffServ EF provide the same level of service to *real-time* communications. This paper has also introduced the input queue threshold into the spacer model, along with the development of the Generic Packet Rate Algorithm (GPRA).

This paper also highlights the advantages of DiffServ EF; the most important being the use of aggregate scheduling and the reduction of the amount of flow state information. These advantages translate into a simple network core, which results in a more scalable architecture. These benefits are essential to accommodate the growth of the Internet and other large-scale IP networks in supporting real-time communications.

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