# JITTER IN PACKET NETWORKS –

# A SIMULATION BASED STUDY

By

HEE JUN KIM

Bachelor of Science

Hong-Ik University

Seoul, Korea

1992

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
December, 2001

# JITTER IN PACKET NETWORKS –

# A SIMULATION BASED STUDY

Thesis Approved:

George Scheets

Thesis Adviser

Dean of the Graduate College

# ACKNOWLEDGMENTS

This study was funded by Williams Communications Group (WCG) of Tulsa, Oklahoma. I appreciate their support. And I also appreciate the guidance and support from my advisor Dr. George Scheets.

I appreciate the guidance and wisdom of my committee members Dr. Rao Yarlagadda and Dr. Jong-Moon Chung.

Especially, I would like to thank my wife Yun-Gyoung and my son Jin-Ho as well as my parents for their patience, love and understanding during this research.

TABLE OF CONTENTS

Chapter Page

## LIST OF TABLES

## LIST OF FIGURES

Number Page

# I. INTRODUCTION

## *Importance of Quality of Service*

The Internet infrastructure was originally developed to move data traffic, such as File Transfer Protocol or E-mail, that had little or no requirements for high levels of Quality of Service (QoS). Hence a best-effort network was acceptable. The success of the World Wide Web and a drive by many towards convergence, the merging of data, voice, and video onto a single network, has led the characteristics of Internet traffic to change. Multimedia traffic is becoming more common. Real-time interactive video conferencing and IP telephony, non-interactive traffic such as video and audio on demand, real time streaming of data such as stock quotes, and other new and developing uses have placed demands on the Internet that the system was not originally designed to meet. Successful implementation of all these services will likely require modifications to the original Internet protocols in order to enable different levels of QoS. The major goal of this research is to investigate one of the key parameters which affects QoS, jitter.

## *Quality of Service Overview*

*Quality of Service* refers to the capability of a network to provide better service to selected network traffic over various technologies, including Frame Relay, Asynchronous Transfer Mode (ATM), Ethernet, SONET, and IP-routed networks that may use any or all of these underlying technologies. The primary goal of QoS is to provide guarantees including dedicated bandwidth, controlled latency and jitter, and improved loss characteristics.

The term bandwidth refers to the data-clocking rate of the system, typically expressed in bits per second (bps). Dedicating bandwidth allows some of the clock rate to be reserved for certain traffic.

Latency is a measurement of time, specifically, the period of time it takes a data packet to traverse from one point in the network to another.

Jitter is the variation of delay over a period of time. Among the delay components are fixed delay components and variable delay components. Jitter results from the variable delay components, specifically changes in queuing delays at network switches due to variations in the short term network load.

Loss is an attribute of packet networks indicating the probability that an individual packet will be discarded by the network.

Of these QoS attributes, controlling jitter is among the least studied and least understood.

### *Motivation for This Research*

Jitter control is critical to certain types of Internet traffic, such as many of the voice and video coders, that require fixed rate delivery to the information source. For example, ITU G.729, a voice coder, requires that one frame of compressed voice be delivered to the voice decoder every 10 ms. Since jitter on packet networks can never be completely eliminated, information streams that have fixed rate delivery requirements must have a receiver dejitter buffer to smooth out the delay variability. In effect, a dejitter buffer reduces or eliminates delay variation by converting it to constant delay. The larger the end-to-end jitter, the larger the size of the dejitter buffer required to fully compensate. Jitter is an important QoS parameter in fixed rate traffic because it can limit the minimum size of the dejitter buffer required to compensate it, which in turn can increase the end-to-end delay seen by the traffic.

There is a maximum end-to-end delay requirement for many types of real-time interactive traffic. According to ITU recommendations for voice, 150 ms of end-to-end delay is the maximum acceptable subject to current voice quality [1]. Even though packets may be delivered by the network with a delay below this value, if the network has excessive amounts of jitter, the size of the dejitter buffer at the receiver required to compensate may make it impossible to guarantee delivery of the voice signal end-to-end under this time limit.

Jitter can be viewed as an important QoS parameter for fixed rate traffic, and especially for real-time interactive traffic.

The objective of this simulation based study is to investigate and better understand some of the characteristics of jitter, in order to gain insight that will enable fixed rate services to be better carried by Packet Switched networks.

***Overview of this Research***

In the next chapter, previous studies regarding jitter are surveyed. The purpose of this survey was to become familiar with previous investigations regarding jitter in packet networks, and ideally find an equation claiming to predict jitter that could be verified as correct via simulations. We found a reasonable amount of previous work about jitter in general, but little research about jitter in packet networks under the assumption that the background traffic is self-similar in nature, a key shortcoming given that recent studies have identified real-world Internet traffic as having self-similar characteristics.

To accurately model actual traffic characteristics, this study uses self-similar traffic generators provided in OPNET to generate the background traffic in the jitter simulations. Chapter 3 presents an overview of Self-Similar traffic.

Chapter 4 presents an overview of Differential Services (DiffServ), a technique for adding priorities to Internet traffic. While a large portion of this study examines jitter on a best effort Internet, the affects of assigning fixed rate traffic high DiffServ priorities were also investigated.

This study seeks to understand the relationship between traffic load, router hops, packet service times, and jitter. These relationships were analyzed via extensive OPNET simulations in Chapter 5.

Finally, conclusions are presented in Chapter 6 along with some suggestions for future research.

## II. LITERATURE SURVEY

This chapter provides a review of past research regarding jitter in general and the relationship between jitter and trunk loads in packet and ATM networks.

The main objective of this investigation is to better understand jitter in *packet* networks, that is, networks in which a variable sized entity is transported. ATM networks with their fixed size cells can be viewed as a subset of packet networks and are included in this literature survey. Knowing that jitter and trunk loads have a very close relationship, a key goal of this literature search was to find studies which claimed to have found an analytical relationship between jitter and trunk load.

This review found that early articles (1991) tended to focus on packet networks. This was followed by an emphasis on jitter in ATM networks for several years while ATM was a hot topic, and finally a recent surge in IP articles when the Internet moved to the forefront.

### *ATM Networks*

For ATM engineers, jitter was of interest because, among its many characteristics, ATM was designed to provide fixed rate services, which in the old legacy circuit switched TDM networks had no jitter (other than that due to clock instability) once the circuit had been established. Hence an understanding of jitter in statistically multiplexed ATM networks was vital in terms of predicting ATM's ability to mimic a fixed rate connection.

ATM literature can be grouped into two general categories. The first category focuses on jitter in general while the second examines the affects of cell scheduling on jitter. Articles from the first category are discussed first.

Privalov et al. [2] provided simple results for the computation of the bound on the jitter variance for mix of CBR streams. They showed that combined streams with a low rate (large period) experience little jitter variance, while the jitter variance for the high-rate combined streams could be quite substantial.

Fulton et al. explains the individual effects of various system and traffic parameters on the jitter statistics of aggregated CBR streams modeled as an (MMPP)/M/1/K process [3][4]. They also derived an analytic approximation for the first-order statistics of the delay jitter experienced by a stationary traffic stream multiplexed at a major communication node. This approximation applies when the node can be modeled as a finite Quasi-Birth-Death (QBD) process and the inter-arrival time probability density function for the tagged stream is obtainable. They have another paper that derives an expression for the delay jitter correlation of a aggregated CBR stationary traffic stream in an MMPP (Markov modulated Poisson process)/M/1/K system with First In, First Out (FIFO) service disciplines [5].

Matragi et al. have a paper that provides simple techniques for estimating the end-to-end jitter incurred by periodic traffic in an ATM network [6]. They also have a paper that explains the impact of various traffic parameters (e.g., the background traffic load and burstiness, the inter-arrival time of the renewal stream, etc.) on the jitter of the tagged stream [7]. They have other papers about jitter in general [8-9].

Landry et al. [10] studied the modification of a tagged traffic stream due to statistical multiplexing by presenting a numerical approach for the calculation of the tagged delay jitter and inter-departure processes.

A second category of ATM papers is about packet scheduling schemes. Iatrou et al. established the substantially better throughput and jitter characteristics of a dynamic-R&S (regulation and scheduling) scheme. The dynamic-R&S scheme can provide substantially better jitter control and achieve higher statistical multiplexing gain than the static-R&S scheme [11-12].

There are also other papers about various packet scheduling schemes [13-19] in ATM networks.

***Packet Networks***

ATM was designed to support both traditional TCP and UDP traffic, as well as real-time traffic. In the late 1980's and early 1990's, the rise in the amount of data traffic, combined with the already large amounts of voice traffic, appeared to point towards ATM as the best one-network solution to haul this traffic mix. By the mid-1990's, data traffic was growing at rates far faster than initially visualized, and it became apparent that data would shortly be the dominant form. Thus, recently there has been strong interest in the jitter characteristics of a TCP/IP based network supporting a variety of traffic, possibly with different QoS requirements.

One of the early works is by Verma et al. [20] in 1991. This paper studies the feasibility of bounding delay jitter for real time channels in a packet-switched store-and-forward wide-area network with general topology. One advantage of the variance control schemes presented in this paper is that the amount of buffer space required for real-time channels in order to prevent packet losses in routers or switches is significantly reduced.

Zhang [21] presented a tutorial about various packet service disciplines at the switching nodes to minimize the delay jitter. A general framework for studying and comparing these disciplines is presented.

Internet Request For Comments (RFC) 2598 concerns jitter and Differential Services (DiffServ) [22]. This Internet Standard defines the target relationship between Expedited Forwarding Per Hop Behavior (EF PHB) and jitter.

Bennett *et al.* [23] considered the definition of EF PHB as given in RFC 2598, and its impact on worst case end-to-end delay jitter. They gave some analytical deterministic bounds on jitter as a function of trunk loads.

There are other articles about controlling jitter in packet networks [24-27]. There is also an article about measuring jitter in packet networks [28].

While there are many articles discussing jitter in general, and there is some literature that derives an analytical relationship between jitter and trunk loads in ATM networks, there is very little literature that has an analytical relationship between jitter and trunk loads in *real world* packet networks.

Specifically one article was found that has an analytical relationship between jitter and trunk loads in packet networks, other than FIFO M/M/1 systems. This article [23] did not address the self-similar behavior of Internet traffic found in many other studies. This survey failed to turn up any analytical expressions useful for predicting jitter in a packet network carrying self-similar traffic.

## III. SELF-SIMILAR TRAFFIC

### *Self-Similarity*

As was mentioned previously, a number of studies on traffic measurement from a variety of working packet networks have demonstrated that actual network traffic is *self-similar* in nature (i.e., bursty over a wide range of time scales).

A key paper by Willinger *et al.* [29] compared actual measurements and a synthetic Poisson model and concluded that the Poisson model lacks the burstiness over large time scales which is present in actual traffic measurements.

Figure III-1 clearly shows this phenomenon [29]. The first column shows actual traffic measurements over different time scales. The second column shows computer generated traffic based on classical queuing theory and the Poisson model. Note that plots in the second column do not show the burstiness of real world traffic on the larger time scales. The third column shows the synthetic traffic based on a self-similar model that better matches actual measurements more accurately over all time scales.

The following discussion is based largely on Stallings [30], who probably has one of the better tutorial explanations of self-similarity.

For a stationary time series $\mathrm{x}$, we define the *m*-aggregated time series $\mathrm{x}^{(m)} = \{\mathrm{x}_k^{(m)}, k = 0,1,2,\ldots\}$ by summing the original time series over non-overlapping, adjacent blocks of size *m*. This may be expressed as

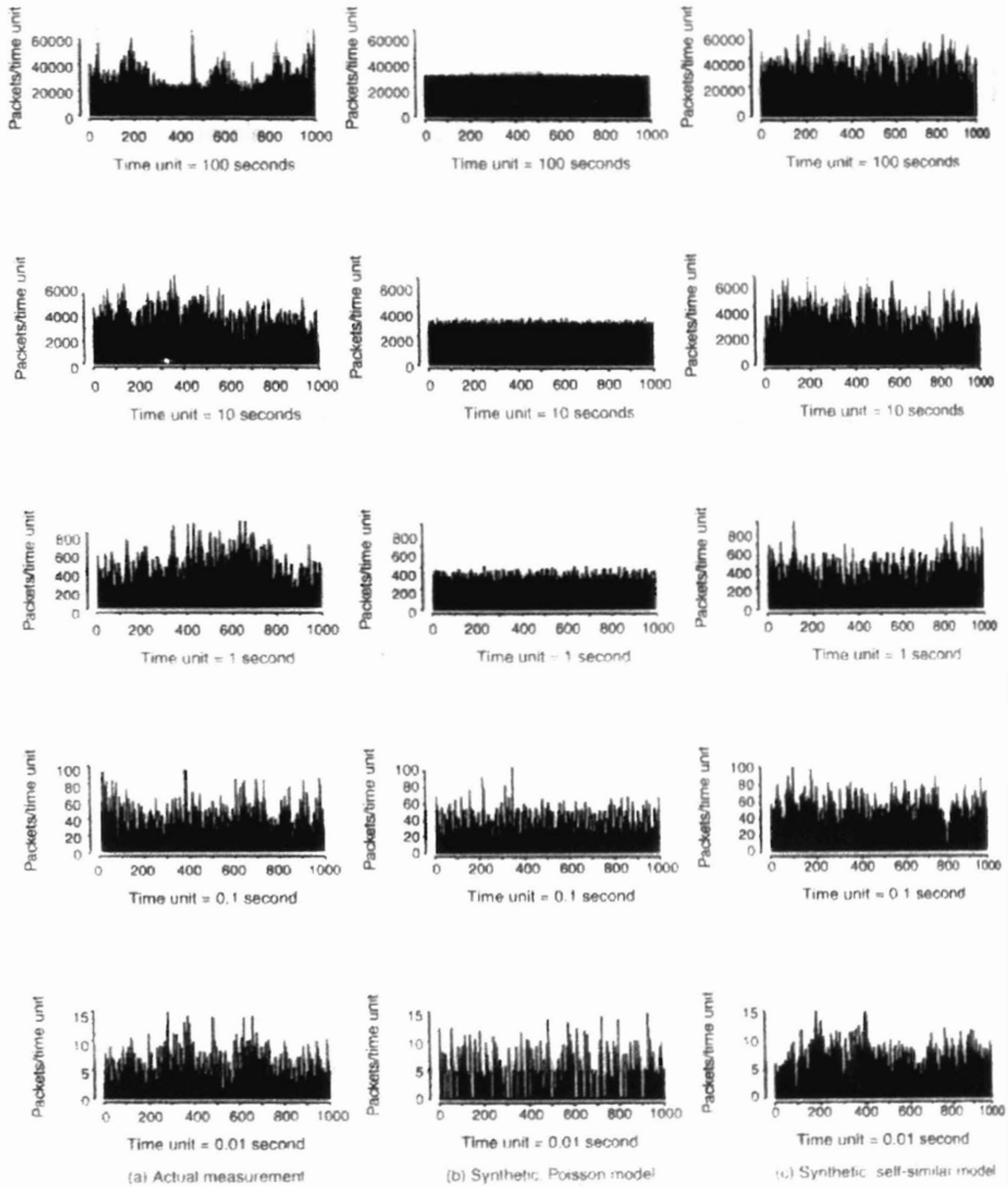


**Fig. III-1. Comparison of actual and synthetic Ethernet traffic**

$$x_k^{(m)} = \frac{1}{m} \sum_{i=km-(m-1)}^{km} x_i \qquad \text{(Eq. III-1)}$$

For example, $x^{(3)}$ is defined as

$$x_k^{(3)} = \frac{x_{3k-2} + x_{3k-1} + x_{3k}}{3}$$

A process x is said to be **exactly self-similar** with parameter $\beta$ $(0 < \beta < 1)$ if for all $m = 1,2,...$ we have

$$\mathrm{Var}(x^{(m)}) = \frac{\mathrm{Var}(x)}{m^{\beta}} \quad \text{Variance} \qquad \text{(Eq. III-2)}$$

$$R_{x^{(m)}}(k) = R_x(k) \quad \text{Autocorrelation} \qquad \text{(Eq. III-3)}$$

The parameter $\beta$ can be shown to be related to the Hurst parameter, defined as $H = 1-(\beta/2)$. For a stationary, ergodic process, $\beta = 1$ and the variance of the time average decays to zero at the rate of $1/m$. For a Self-Similar process, the variance of time average decays more slowly. For a perfectly self-similar process, $\beta = 0$ and the variance of the time average does not decay at all.

The next simple example clearly shows that fact. We considered the case when $m = 10$, the individual variance $\mathrm{Var}(x) = 1$, and $\beta = 0.4$. The figure shows the theoretical decays in the aggregated variance $\mathrm{Var}(x^{(m)})$ as $m$ increases from 1 to 10.

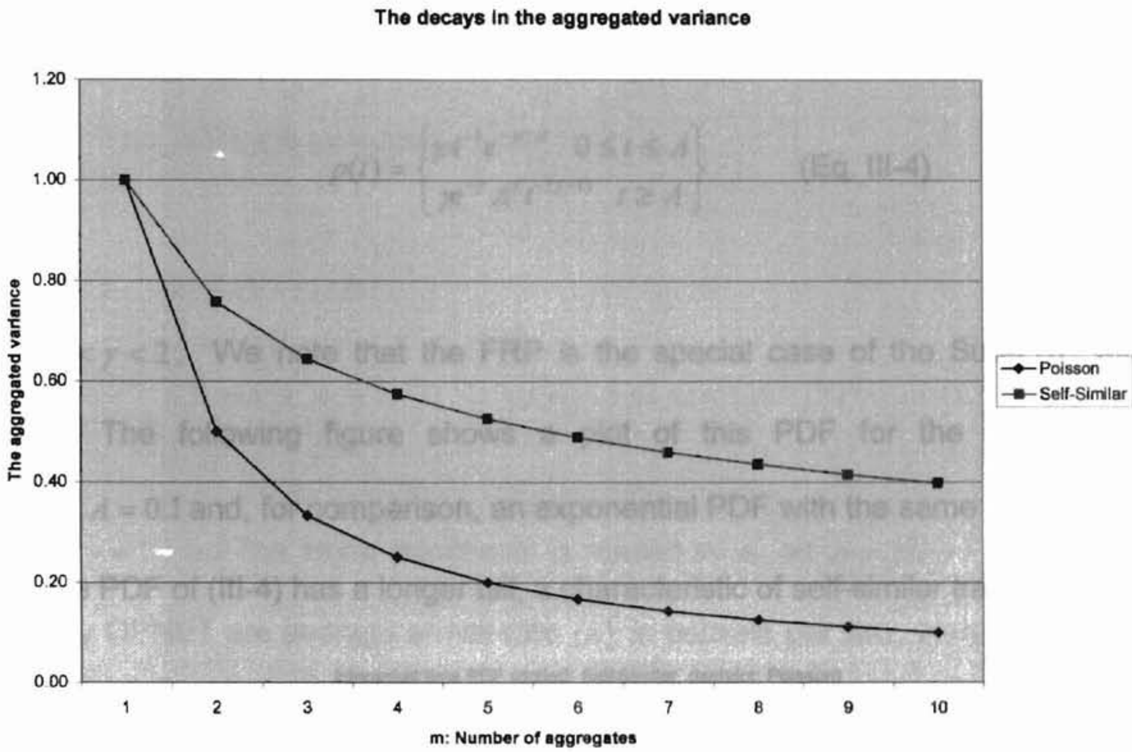


**Fig. III-2. The theoretical decays in the aggregated variance**

From the practical point of view, the above results show that for self-similar traffic, considerably more data points are required, compared to classical Poisson traffic, in order to get equivalently accurate experimental results

***Modeling of Self-Similar Traffic for Simulation***

According to Ryu *et al.* [31], OPNET uses what's called a Sup-FRP model as a default self-similar traffic generator. Sup-FRP (Superposition of the Fractal

Renewal Process) is one of the Fractal Point Processes (FPP's). The Sup-FRP model is constructed as the superposition of $M$ i.i.d. FRPs where each FRP is completely characterized by the following power-law Probability Density Function (PDF) for inter-arrival times:

$$p(t) = \begin{Bmatrix} \gamma A^{-1} e^{-\gamma t/A} & 0 \le t \le A \\ \gamma e^{-\gamma} A^{\gamma} t^{-(\gamma+1)} & t \ge A \end{Bmatrix} \qquad \text{(Eq. III-4)}$$

with $1 < \gamma < 2$. We note that the FRP is the special case of the Sup-FRP with $M = 1$. The following figure shows a plot of this PDF for the case when $\gamma = 1.5, A = 0.1$ and, for comparison, an exponential PDF with the same mean. Note that the PDF of (III-4) has a longer tail, a characteristic of self-similar traffic.

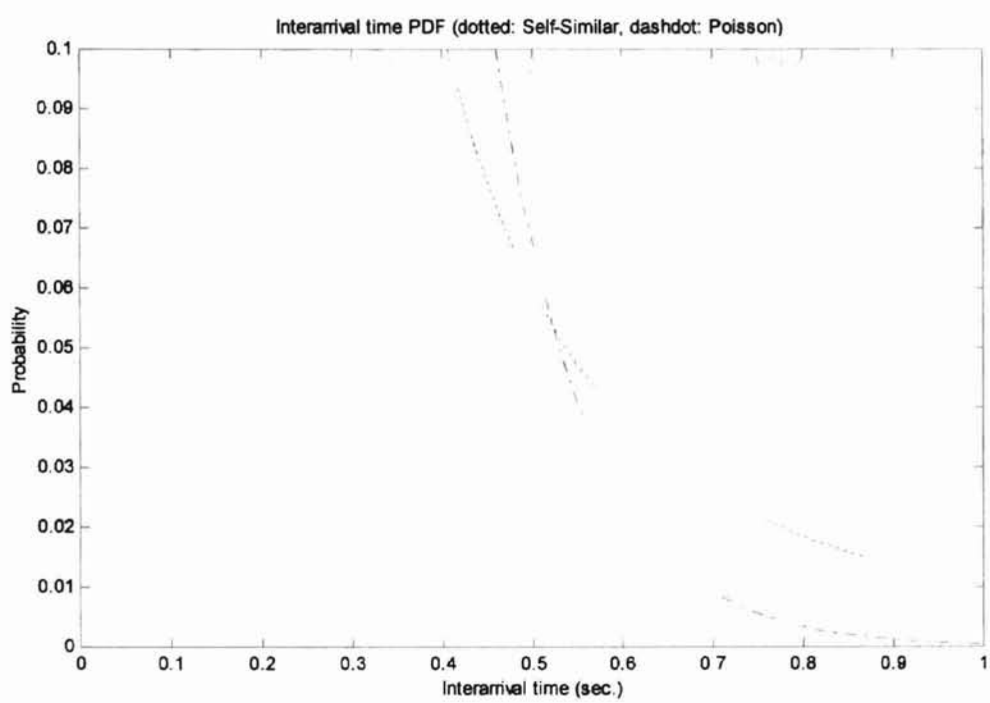


**Fig. III-3. Inter-arrival Time PDF for Self-Similar and Poisson Traffic**

The Sup-FRP has three parameters $(\gamma, A, M)$. $\gamma$ is a fractal exponent, $A$ is a cutoff parameter, and $M$ is the number of FRPs superposed. These are mapped into Three Fundamental Parameters (TRPs), that are the parameters that can be changed in OPNET.

The TFPs are as follows:

$$
\begin{aligned}
H &= (3-\gamma)/2 \\
\lambda &= M\gamma[1+(\gamma-1)^{-1}e^{-\gamma}]^{-1}A^{-1}, \\
T^{\alpha} &= 2^{-1}\gamma^{-2}e^{-\gamma}(\gamma-1)^{-1}(2-\gamma)(3-\gamma)[1+(\gamma-1)e^{\gamma}]^{2}A^{\alpha}
\end{aligned}
\qquad \text{(Eq. III-5)}
$$

where $\gamma = 2-\alpha$. The Hurst parameter is related to $\alpha$ as $\alpha = 2H-1$. The TFP's used by OPNET are average arrival rate $(\lambda)$ in packets per sec., Hurst parameter $(H)$, and Fractal Onset Time Scale $(T)$ in sec. Fractal Onset Time Scale $(T)$ is the parameter that marks the lower time limit from which the scaling behavior begins to appear. We used $T=1$ sec. in our simulations, which is OPNET's default setting.

Crovella et al. [32] reports that from their measurement data of Web traffic, they estimated the Hurst parameter to be around 0.8, which is the value chosen for the simulations in this study.

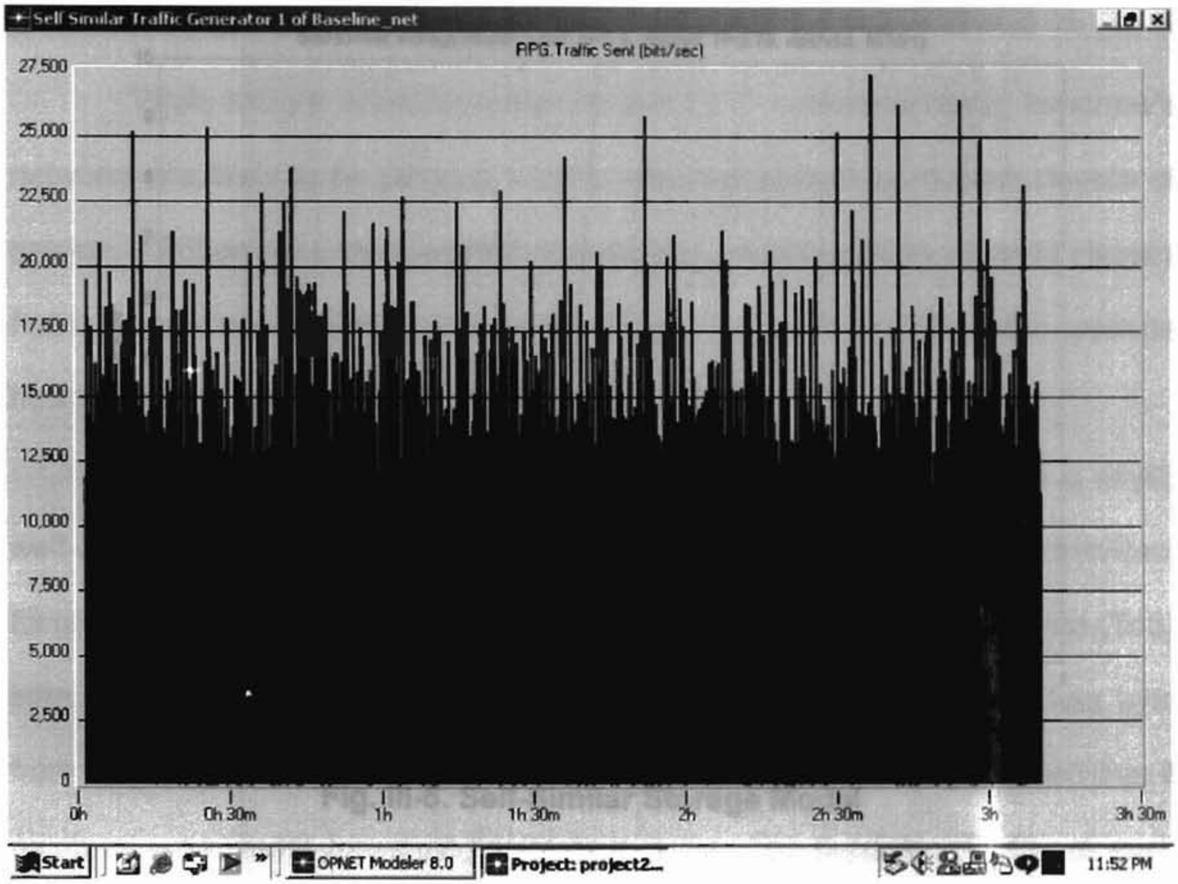


**Fig. III-4. Self-Similar Traffic (H=0.8, T=1)**

Figure III-4 shows an example of the self-similar traffic generated in OPNET. It has an H parameter of 0.8 and T=1. This traffic is considerably burstier than that generated by an M/M/1 traffic generator. See the second row of Figure III-1 for a comparison.

One consequence of this additional burstiness is that average queue sizes of switches forced to deal with this type of traffic explode at much lower average loads than is predicted by classical queuing theory. Figure III-5 shows an example of the average queue sizes as predicted by theory [30].

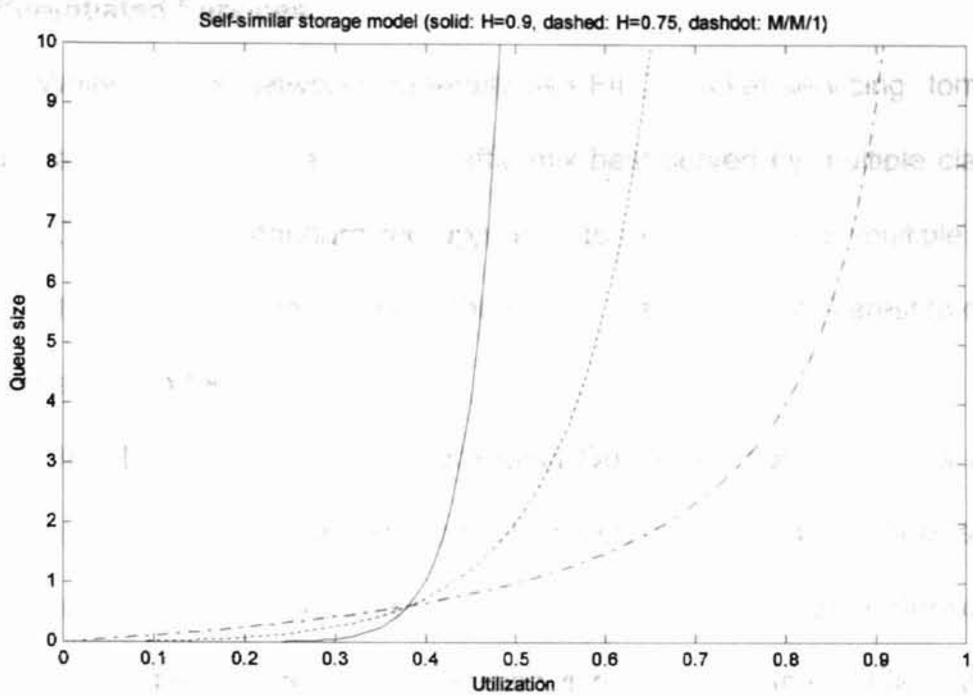


**Fig. III-5. Self-Similar Storage Model**

## IV. Differentiated Services

While today's networks generally use FIFO packet servicing, tomorrow's networks are likely to be carrying a traffic mix best served by multiple classes of service. DiffServ is a standardized approach to providing these multiple classes that is likely to see widespread use in the future. Hence, it is of interest to examine how DiffServ will affect jitter.

The DiffServ approach to providing QoS in networks employs a small, well-defined set of building blocks from which you can build a variety of services. Its aim is to define the Differentiated Services (DS) byte, the Type of Service (ToS) byte from the Internet Protocol (IP) version 4 header and the Traffic Class byte from IP version 6, and mark the standardized DS byte of the packet such that it receives a particular forwarding treatment or per-hop behavior (PHB), at each network node.

Differentiated services [33] enhancements to the Internet protocol are intended to enable scalable service discrimination in the Internet without the need for per-flow state and signaling at every hop. There is a base set of packet forwarding treatments, or per-hop behaviors.

### *Expedited Forwarding*

Among these PHBs (Per-Hop Behaviors), you can use EF PHB (Expedited Forwarding Per-Hop Behavior) [22] to build a low-loss, low-latency, low-jitter, assured bandwidth, end-to-end service through multiple domains. EF PHB targets applications such as Voice over IP (VoIP) and video conferencing, and services such as virtual leased lines. EF PHB is the highest available in DiffServ, and is best suited for premium services.

EF PHB is defined in RFC 2598 [22] as 'a forwarding treatment for a particular aggregate where the departure rate of the aggregate's packets from any node must equal or exceed a configurable rate'.

***Implementation of EF PHB***

A number of mechanisms might be used to implement the EF PHB. The simplest of these is a priority queue (PQ) where the arrival rate of the queue is strictly less than its service rate.

As jitter comes from the random queuing delays along the path, a feature of this implementation is that EF-marked flows will see reduced jitter at their subscribed rate since packets spend little time in queues.

***Priority Queueing***

PQ (Priority Queueing) allows you to define how traffic is prioritized in the network. A series of filters based on packet characteristics could be defined to cause the router to place traffic into these queues; the queue with the highest priority is serviced first until it is empty, then the lower queues are serviced in sequence. The next figure shows an example of this PQ (Priority Queuing) [36].

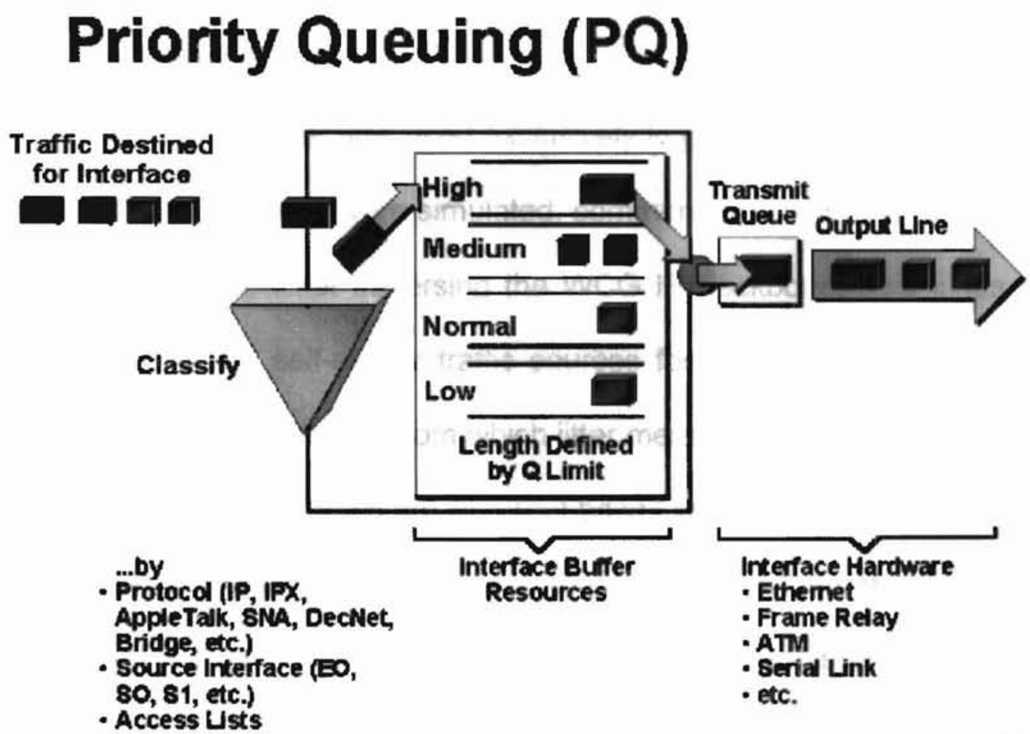


**Figure IV-1. Priority Queuing**

During transmission, PQ gives priority queues absolute preferential treatment over low priority queues. Important traffic, given the highest priority, always takes precedence over less important traffic. Packets are classified based on user-specified criteria and placed into one of the multiple output queues based on the assigned priority. Packets that are not classified by priority fall into the normal queue. In the next chapter, we will present the PQ simulation results as well as FIFO.

## V. Simulations Study

### *Simulations Model*

OPNET Modeler was used exclusively in generating all results [34]. One, two, and four router hops were simulated, commensurate with the number of hops faced by a typical packet traversing the WCG IP backbone. Two kinds of traffic sources were used, self-similar traffic sources for generating background traffic, and a fixed-rate traffic source from which jitter measurements were determined. In OPNET, these traffic sources are Ethernet based work stations. The default router configuration available in OPNET only contained two Ethernet Ports, allowing a maximum of two traffic sources/sinks per router. While this default configuration can undoubtedly be changed, to maintain maximum flexibility, a decision was made early on in this study to use multi-port Ethernet Switches at the main source and sink destinations, in the event other traffic sources or sinks were required. These switches complicate the block diagrams somewhat. *It is best to think of the switch and attached router as one unit.* Link speeds of T-1 and OC-48 were used between routers. Figure V-1 shows the two hop (3 router) case.

For simulation, a worst-case model was chosen in order to investigate the maximum bounds of the jitter. To generate the worst possible jitter, a self-similar traffic source and sink pair is allocated to each router-to-router hop. The self-similar background traffic is statistically multiplexed with fixed-rate traffic in one router, then completely off-loaded at the next router and replaced by other traffic

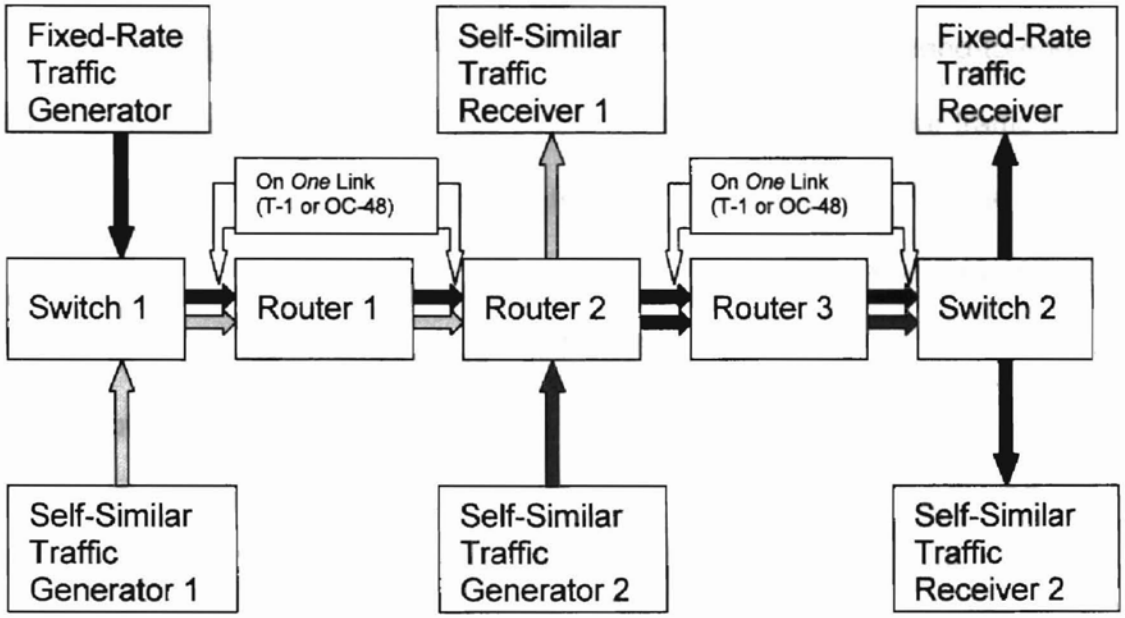


**Figure V-1. Traffic Flows on OPNET sample project**

generated by a new self-similar source. Hence, the fixed rate traffic gets multiplexed with *entirely* new background traffic over every router hop. This configuration will yield the worst possible end-to-end jitter because the jitter mainly arises from the contention between *different* traffic sources for network resources. For example, in Figure V-1 jitter largely arises from Switch 1 and Router 2. In theory, Router 1 and Router 3, where all traffic enters on one link and exits on another, add no jitter if the input/output trunks are the same speed, though in practice a small amount of jitter may occur depending upon how the internal switching is accomplished. Switch 2 also adds negligible jitter, as the fixed rate traffic to the information sink, from which the jitter measurements occur, is not multiplexed with any other source.

The fixed rate traffic was limited to be 1% of the composite traffic flow. This choice was also made in order to simulate the worst case end-to-end jitter. Jitter mainly comes from the burstiness of the traffic and self-similar traffic has that burstiness, especially when compared to fixed rate traffic. To generate the worst possible jitter, the portion of the self-similar traffic should be maximized. Hence, we chose the mixed traffic to be composed of 99% of self-similar background traffic and 1% of fixed-rate traffic.

As mentioned previously, a Hurst parameter of .8 was used for the generated self-similar background traffic. Based on statistics collected from MCI's Internet backbone in 1997, the background traffic had a mean packet size of 300 bytes, and a packet size that was exponentially distributed [35].

For the fixed rate traffic source, we simulated jitter resulting from minimum and maximum service times wide enough apart to bound the results seen by most any sized legal Ethernet-based packet on any corporate or carrier backbone link. The maximum service time was generated by moving 1500 byte fixed-rate traffic on a T-1 link, and the minimum service time was generated by moving 100 byte fixed-rate traffic on an OC-48 link.

Trunk loads were varied over values of 10%, 50%, and 70%, representing light, medium, and heavy traffic.

Router processing speeds were set at 5,000,000 packets/second in order that IP I/O processing not be a limiting factor for these simulations.

Router-to-Router hops were set at 0.01 Km. Router-to-Switch hops at 0.01 Km. Note that these values, while important in the calculations of end-to-end delay, do not affect the jitter.

In total, 18 different cases were simulated using FIFO servicing, according to different service times, number of routers, and trunk loads as shown in the following table.

| Packet Service Times | | 0.0003ms | | | 7.7720ms | | |
|---|---|---|---|---|---|---|---|
| Trunk Loads | | 10% | 50% | 70% | 10% | 50% | 70% |
| Number of Routers | 2 routers | *1* | *2* | *3* | *4* | *5* | *6* |
| | 3 routers | *7* | *8* | *9* | *10* | *11* | *12* |
| | 5 routers | *13* | *14* | *15* | *16* | *17* | *18* |

**Table V-1. Simulation Cases**

These 18 different cases were again simulated to examine the affect of a QoS enabled Internet using DiffServ. The DSCP (Differentiated Services Code Point) bit of fixed-rate traffic was set to EF, which is the highest priority, and the DSCP bit of self-similar background traffic was set to be Best-Effort, which is the lowest priority.

On the figures to follow, each plotted point represents 5,000 simulated fixed-rate packet transmissions. It was noted in Chapter III, equation III-2, that one characteristic of self-similar traffic is that the variance of the m-aggregated time series decays much more slowly than that of traffic which is not self-similar. From the practical point of view this means that for self-similar traffic, considerably more data points are required, compared to classical Poisson traffic, in order to get equivalently accurate experimental results.

After some OPNET experimentation, involving fixing a sample size and trunk load, repeating experiments with different random number seeds, and then examining the variation in the results, we settled on experiment run sizes of 5,000 fixed rate packets as satisfactory.

***Jitter Results***

Table V-2 illustrates the jitter results. Jitter here is defined as the variance of the end-to-end delay of the fixed rate traffic. Figure V-2 through V-5 show plots of the above results. Figure V-2 shows a non-log plot of the end-to-end delay variance for fixed rate packets with the minimum service time as the number of routers and queuing mechanism is varied. Figure V-3 shows a log plot of the same. Figure V-4 and V-5 show the results for fixed rate packets with the maximum service time.

As expected, PQ always has less jitter than FIFO. As you can see from Figure V-2 and V-4, for identical loads, approximately the same amount of jitter reduction occurs regardless of the number of router hops when implementing PQ as opposed to FIFO. The log plots of Figure V-3 and V-5 emphasize that, percent wise, the effectiveness of PQ decreases as the number of router hops increases.

| Queuing | No. of Routers | Trunk Loads<br>Minimum Service Time | | | Maximum Service Time | | |
|---|---|---|---|---|---|---|---|
| | | 10% | 50% | 70% | 10% | 50% | 70% |
| FIFO | 2 | 4.283E-13 | 3.180E-12 | 7.276E-12 | 2.993E-07 | 3.247E-06 | 1.096E-05 |
| | 3 | 5.900E-13 | 5.073E-12 | 1.246E-11 | 6.558E-07 | 7.290E-06 | 2.025E-05 |
| | 5 | 9.315E-13 | 8.275E-12 | 2.461E-11 | 1.209E-06 | 1.583E-05 | 4.176E-05 |
| PQ | 2 | 4.047E-13 | 1.658E-12 | 1.839E-12 | 1.434E-07 | 9.958E-07 | 1.463E-06 |
| | 3 | 5.394E-13 | 3.220E-12 | 7.173E-12 | 4.316E-07 | 5.031E-06 | 1.156E-05 |
| | 5 | 8.636E-13 | 7.137E-12 | 1.815E-11 | 1.207E-06 | 1.258E-05 | 3.458E-05 |

**Table V-2. Experimental Jitter Results.**

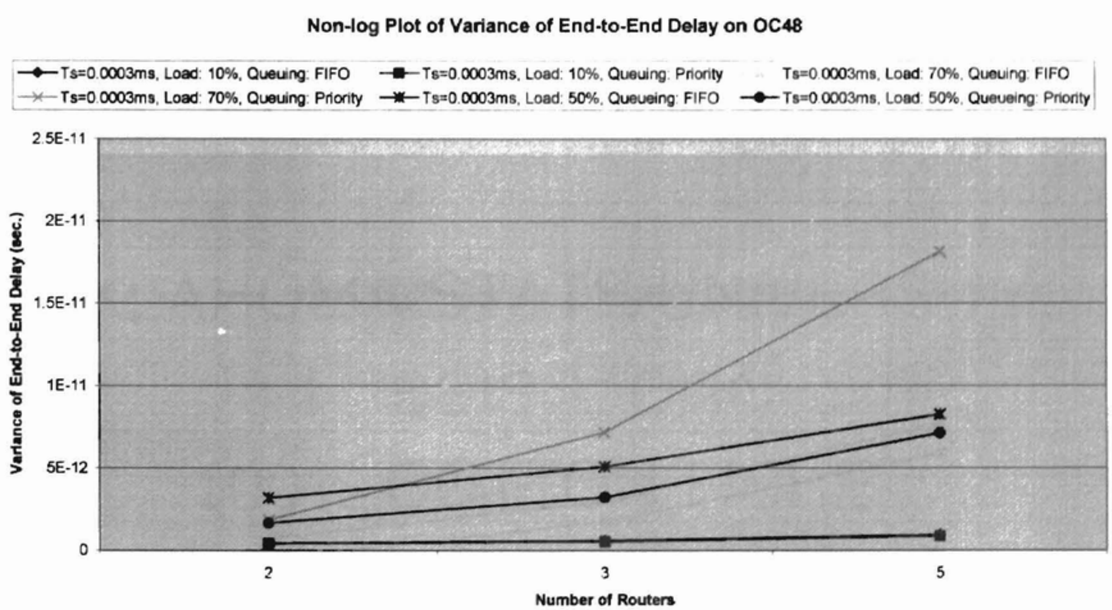


**Figure V-2. Non-log plot of variance of end-to-end delay, Ts = .0003 ms**

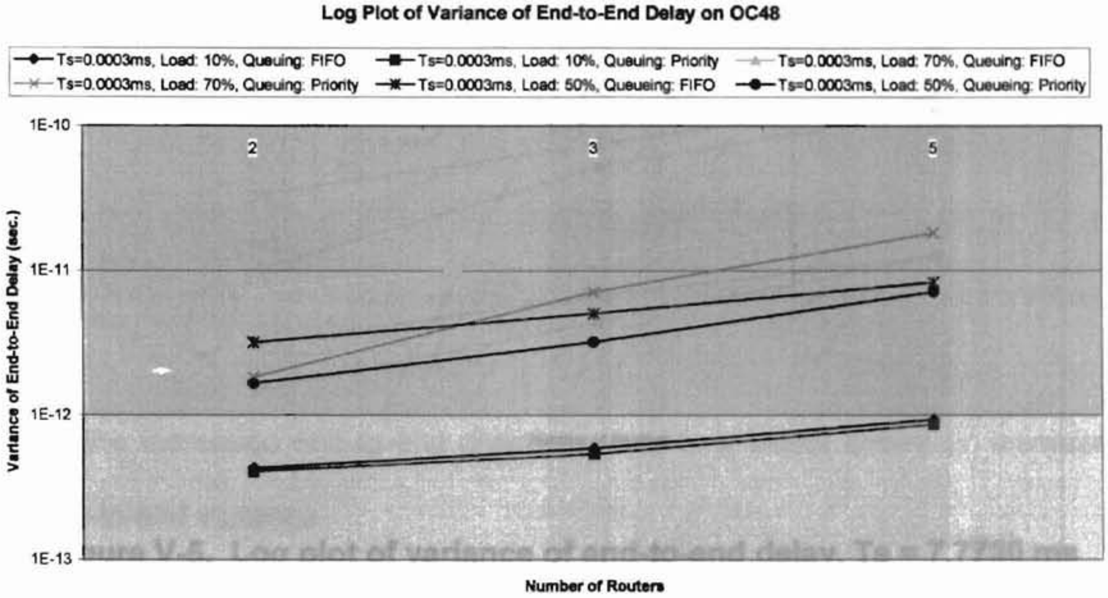


**Figure V-3. Log plot of variance of end-to-end delay, Ts = .0003**

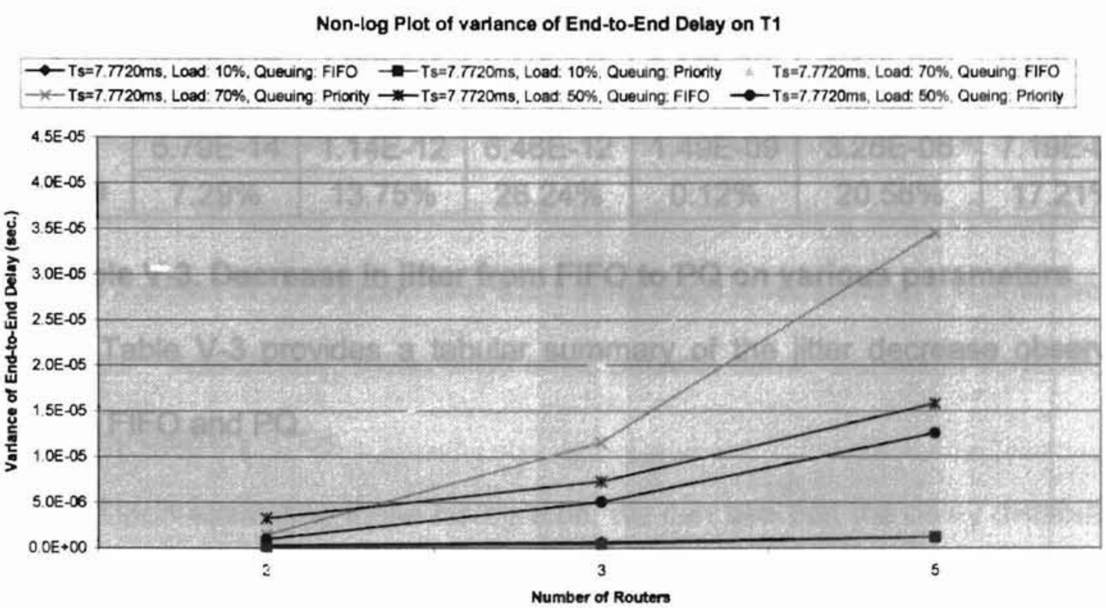


**Figure V-4. Non-log plot of variance of end-to-end delay, Ts = 7.7720 ms**

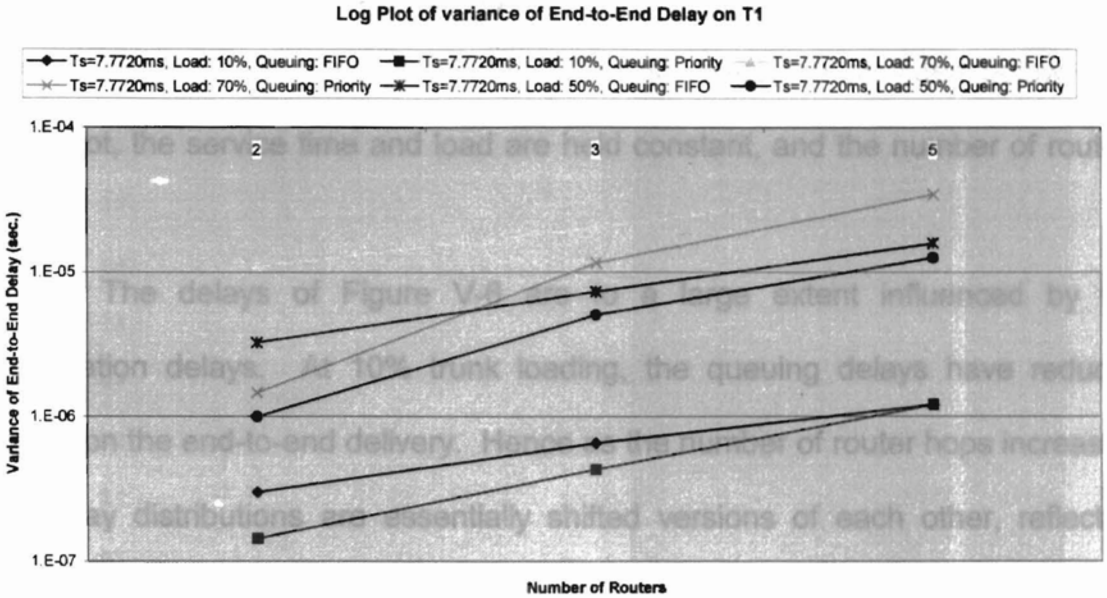


**Figure V-5. Log plot of variance of end-to-end delay, Ts = 7.7720 ms**

| | Small Ts 10% | Small Ts 50% | Small Ts 70% | Large Ts 10% | Large Ts 50% | Large Ts 70% |
|---|---|---|---|---|---|---|
| 2 routers | 2.36E-14 | 1.52E-12 | 5.44E-12 | 1.56E-07 | 2.25E-06 | 9.50E-06 |
| | 5.50% | 47.87% | 74.72% | 52.11% | 69.33% | 86.65% |
| 3 routers | 5.06E-14 | 1.85E-12 | 5.28E-12 | 2.24E-07 | 2.26E-06 | 8.69E-06 |
| | 8.57% | 36.52% | 42.42% | 34.19% | 30.98% | 42.93% |
| 5 routers | 6.79E-14 | 1.14E-12 | 6.46E-12 | 1.49E-09 | 3.26E-06 | 7.19E-06 |
| | 7.29% | 13.75% | 26.24% | 0.12% | 20.56% | 17.21% |

**Table V-3. Decrease in jitter from FIFO to PQ on various parameters**

Table V-3 provides a tabular summary of the jitter decrease observed between FIFO and PQ.

***Delay Distributions. FIFO Queuing.***

Delay distributions for all 18 FIFO test cases are provided below. On each plot, the service time and load are held constant, and the number of routers varied.

The delays of Figure V-6 are to a large extent influenced by the propagation delays. At 10% trunk loading, the queuing delays have reduced impact on the end-to-end delivery. Hence as the number of router hops increases, the delay distributions are essentially shifted versions of each other, reflecting mostly the increased end-to-end distances, and to a lesser extent an increase in the end-to-end variance.

As the load increases, queuing delays increase and become a more dominating factor. Figure V-7 and V-8 reflect this in terms of an increased spread in the end-to-end delay distribution, and a change in the distribution shape.

Figure V-9 through V-11 show a second set of delay distributions reflecting a service time of 7.7720 ms for the fixed rate traffic. The graphs here have similar characteristics of Figures V-6 through V-8, except that the end-to-end delivery times, which are measured from the time the leading edge of a fixed rate packet is injected in the system until the trailing edge is received at the destination, are greater. Additionally, these large sized packets cause increased variability in end-to-end delivery times.

Upon examining these histograms, we can see that the delay distribution cannot be modeled as Gaussian, though the distribution does begin to assume Gaussian-like characteristics in Figure V-8 and V-11.

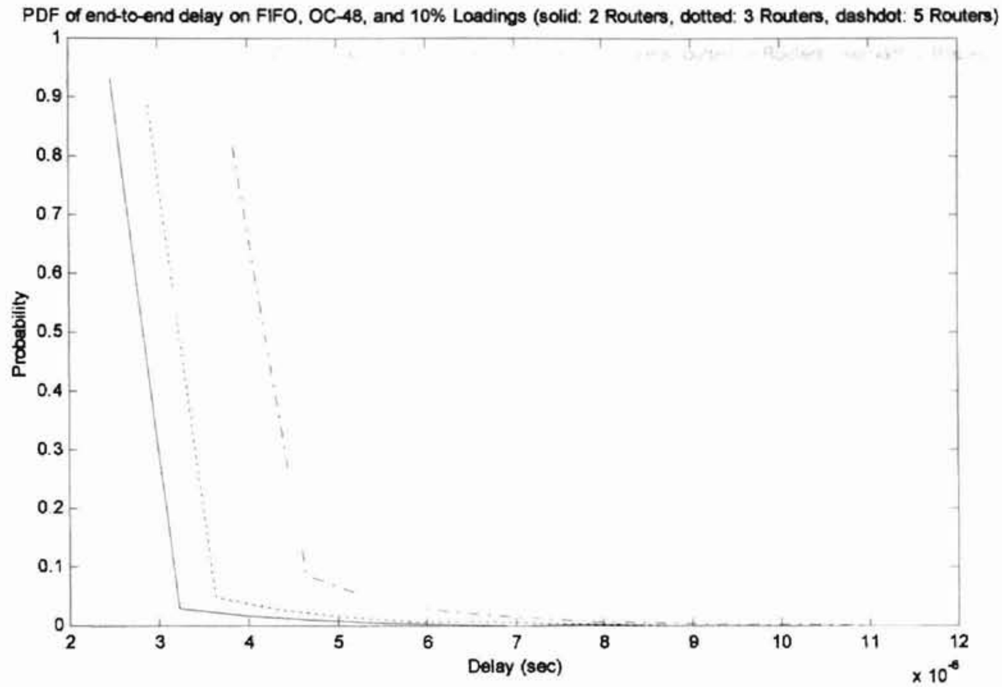


**Figure V-6. Histogram of end-to-end delay on FIFO, Ts = .0003 ms, and 10% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

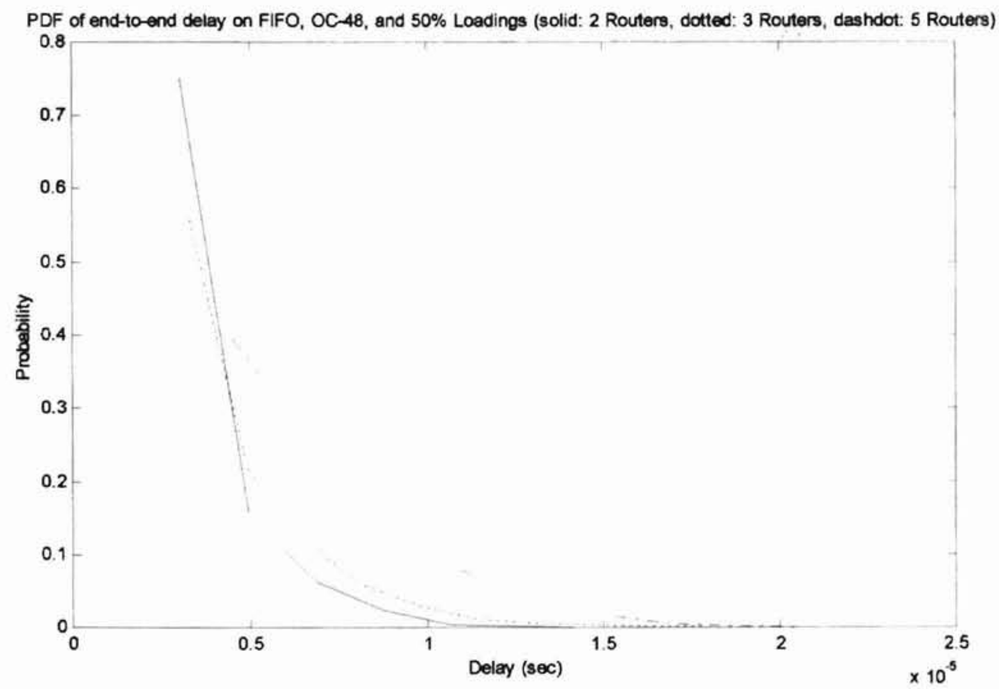


**Figure V-7. Histogram of end-to-end delay on FIFO, Ts = .0003 ms, and 50% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

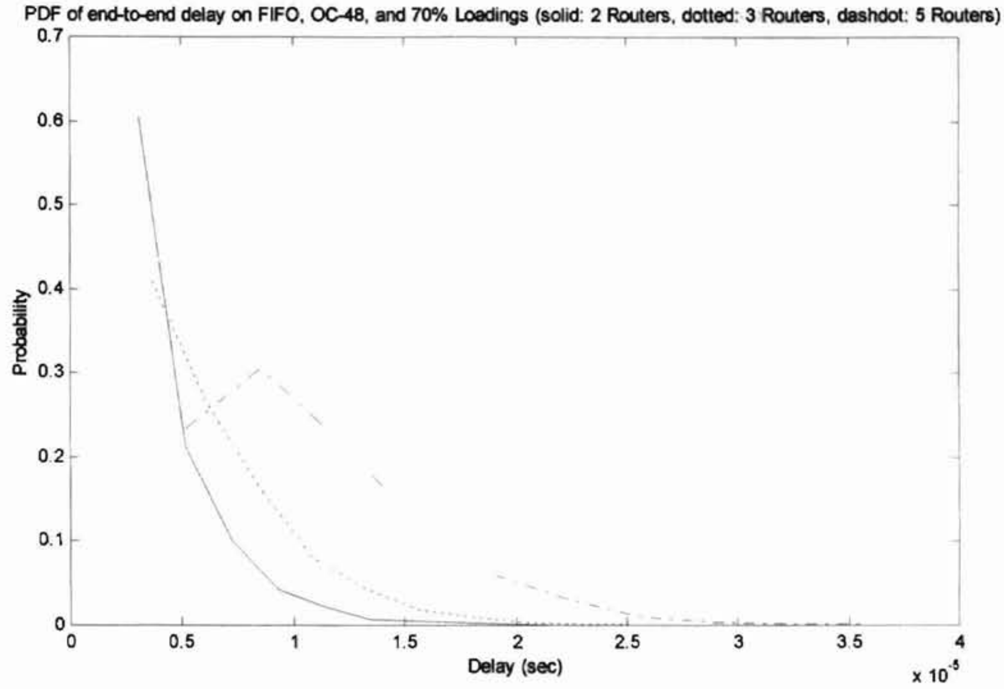


**Figure V-8. Histogram of end-to-end delay on FIFO, Ts = .0003 ms, and 70% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

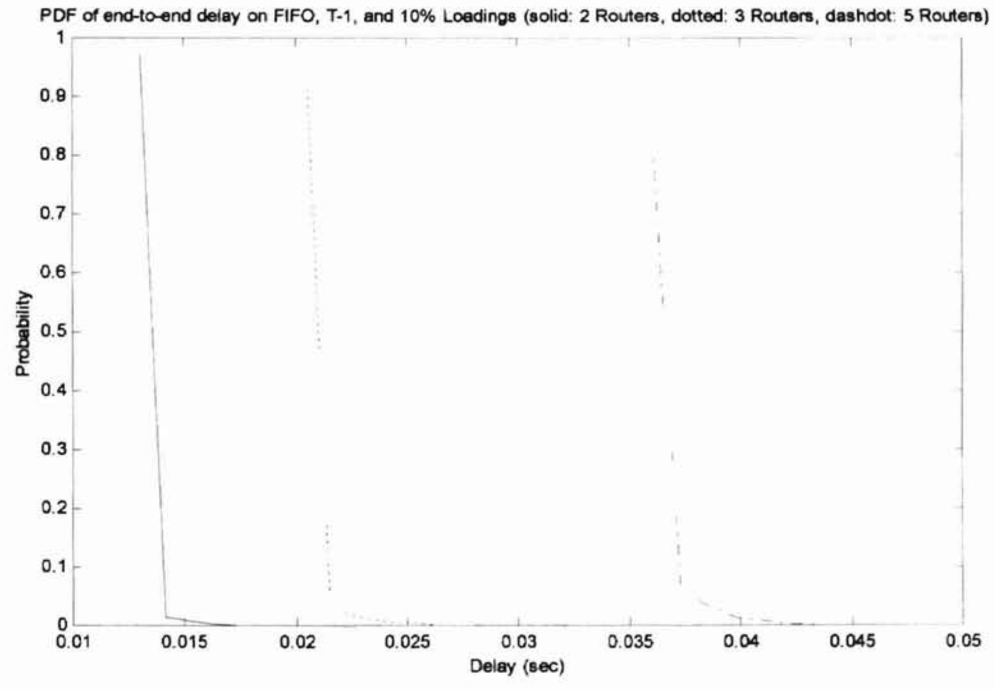


**Figure V-9. Histogram of end-to-end delay on FIFO, Ts = 7.7720 ms, and 10% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

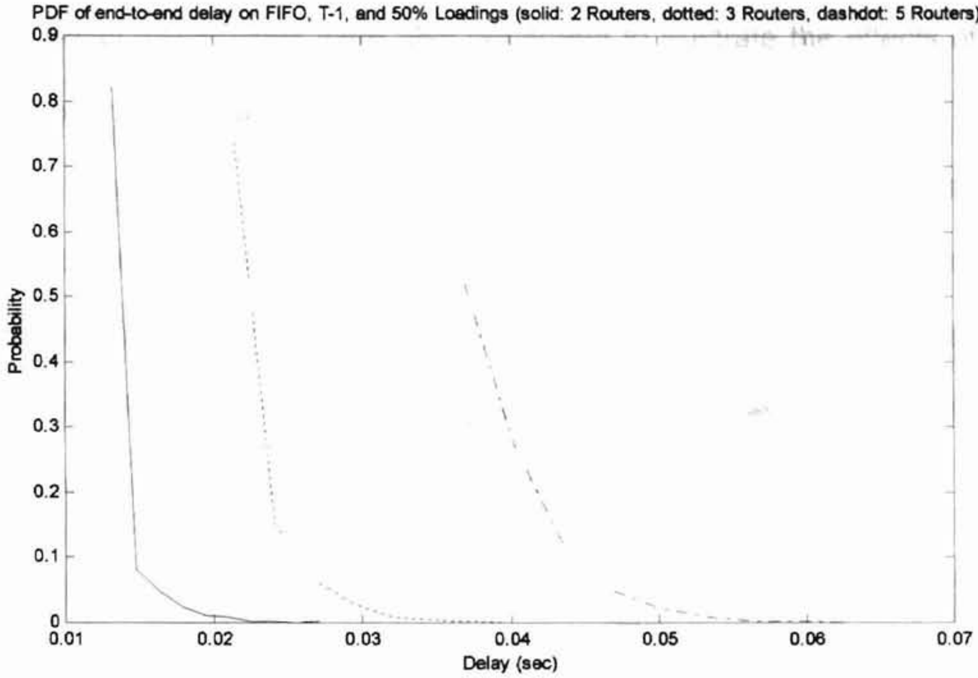


**Figure V-10. Histogram of end-to-end delay on FIFO, Ts = 7.7720 ms, and 50% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

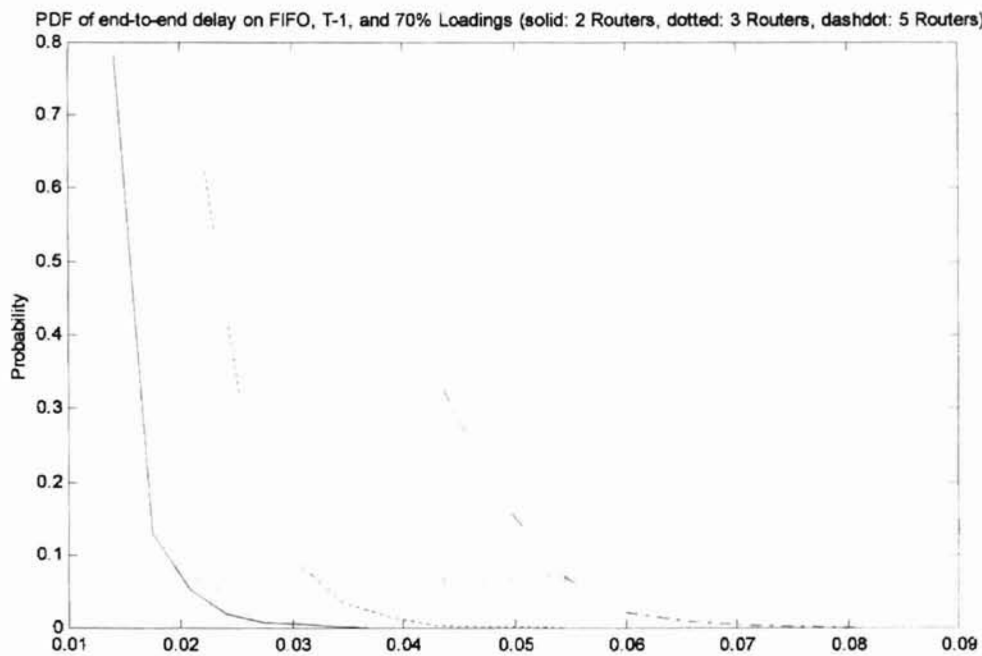


**Figure V-11. Histogram of end-to-end delay on FIFO, Ts = 7.7720 ms, and 70% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

***Effect of Priority Queuing***

Delay distributions were also generated to illustrate the effects of Priority Queuing on the fixed rate traffic jitter.

As expected, the priority queuing reduced the end-to-end delay for the high priority fixed rate traffic, as well as its variance. There is more of a decrease in the end-to-end delay and its variance as the trunk load increases and the queuing delays, and PQ's affect on reducing this parameter, begin to dominate. The decrease is greater with large packet service times than with the smaller.

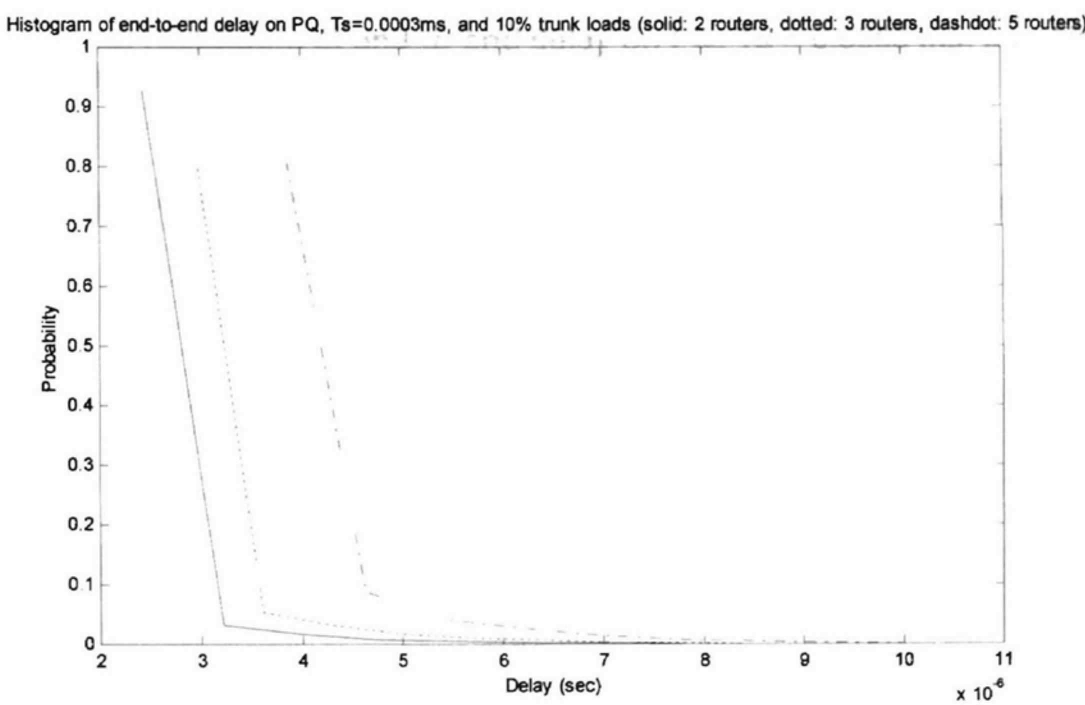


**Figure V-12. Histogram of end-to-end delay on PQ, Ts = 0.0003 ms, and 10% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

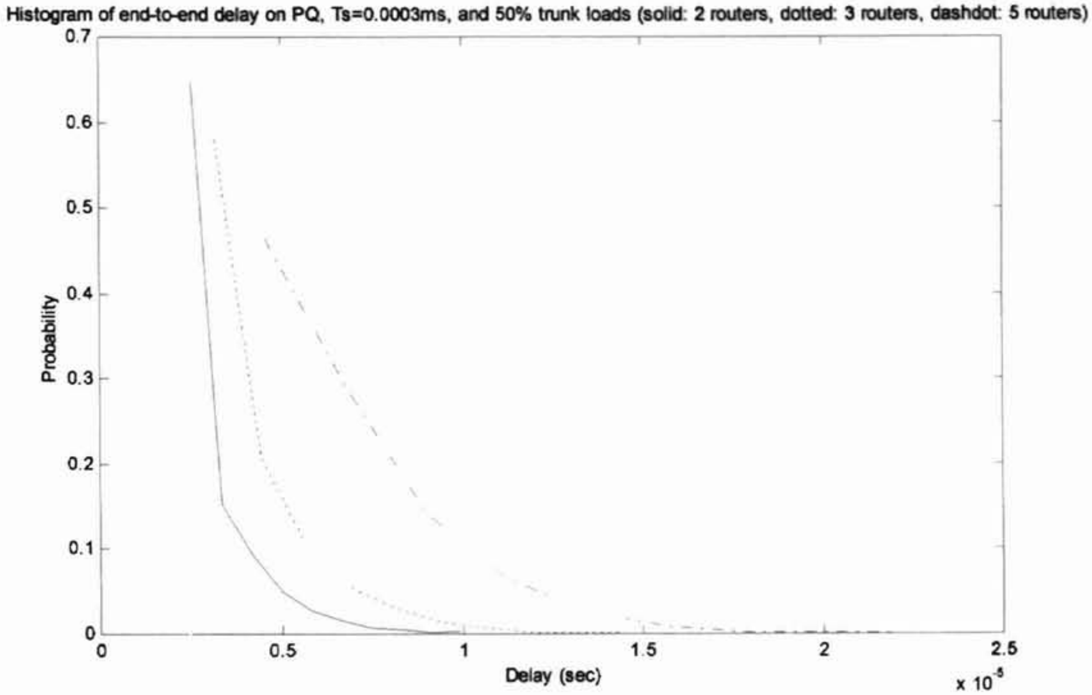


**Figure V-13. Histogram of end-to-end delay on PQ, Ts = 0.0003 ms, and 50% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

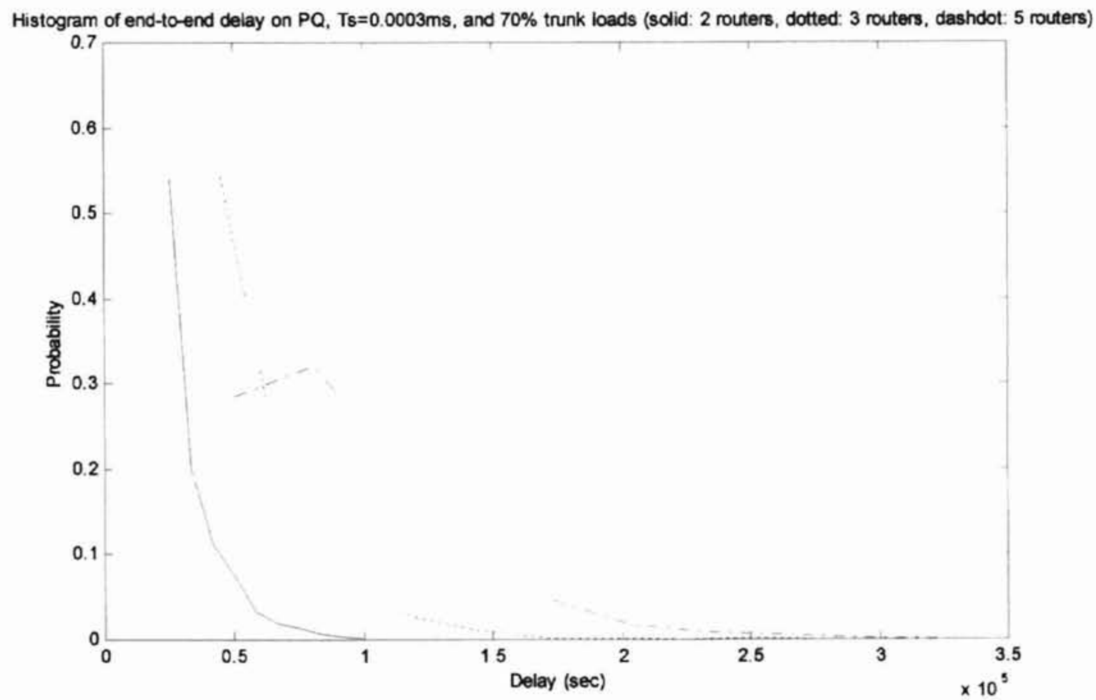


**Figure V-14. Histogram of end-to-end delay on PQ, Ts = 0.0003 ms, and 70% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

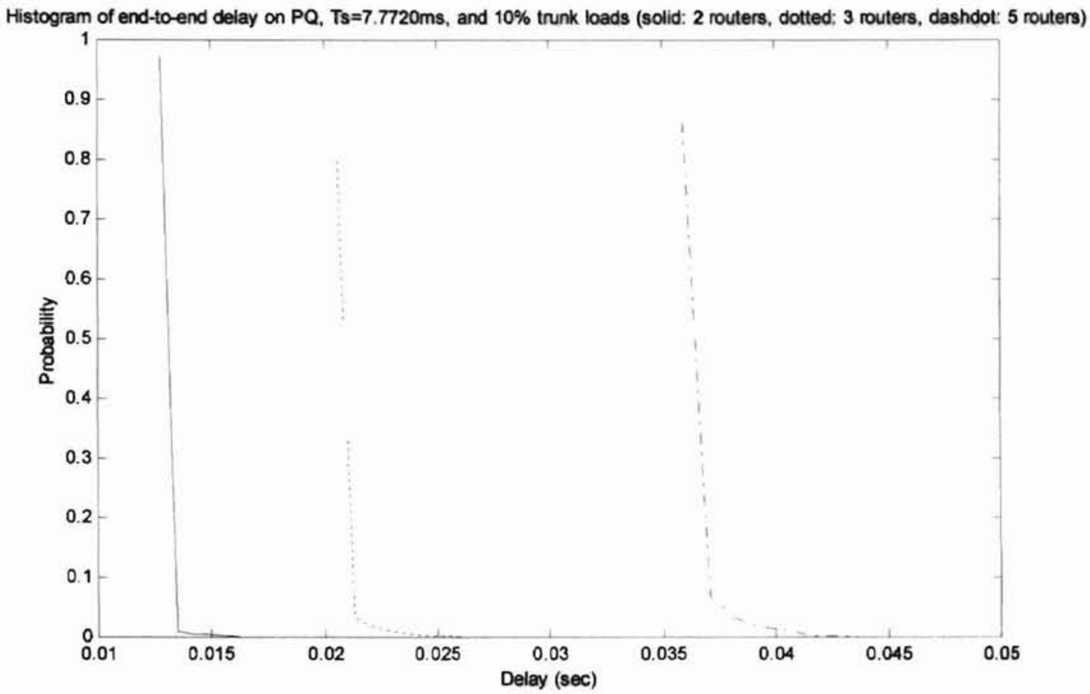


**Figure V-15. Histogram of end-to-end delay on PQ, Ts = 7.7720 ms, and 10% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

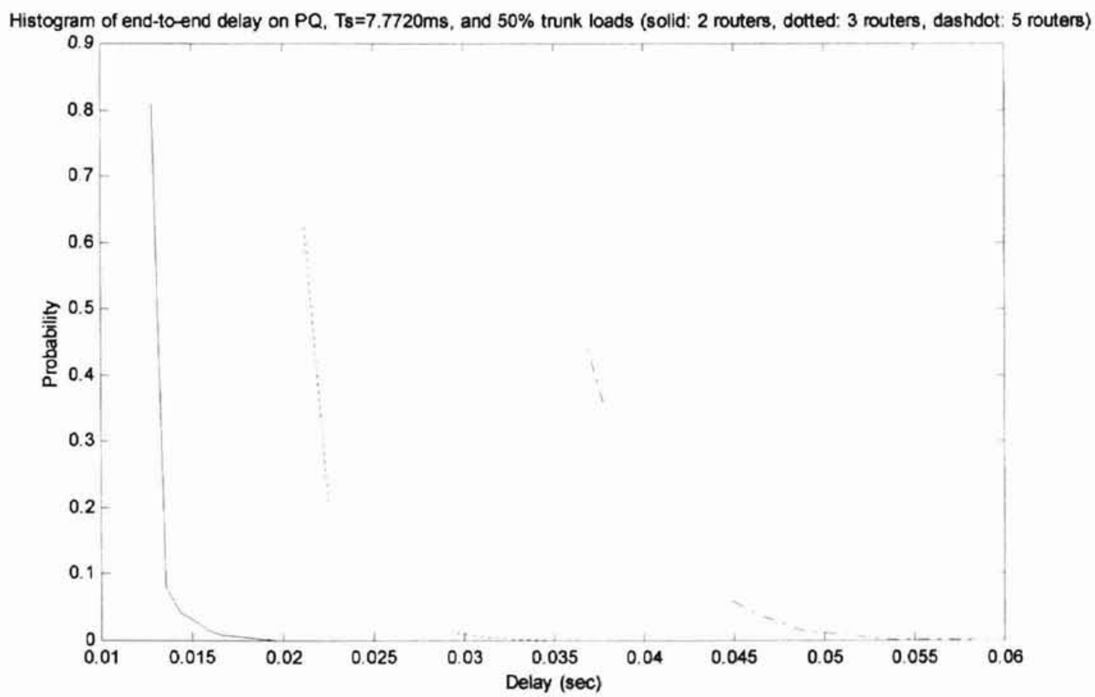


**Figure V-16. Histogram of end-to-end delay on PQ, Ts = 7.7720 ms, and 50% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

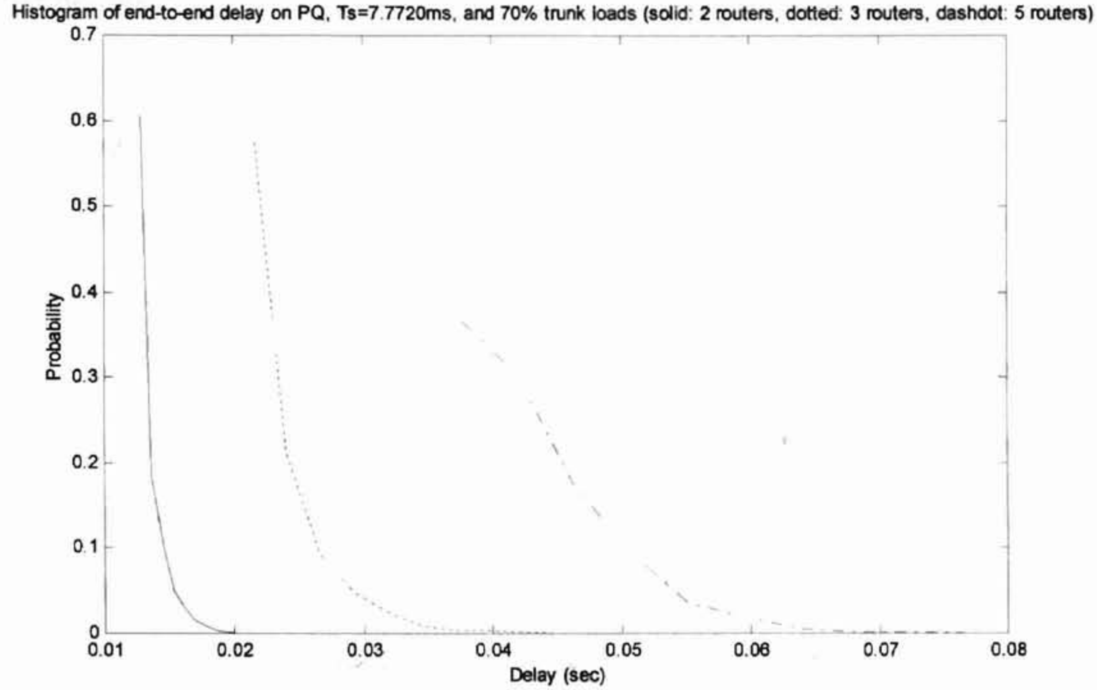


**Figure V-17. Histogram of end-to-end delay on PQ, Ts = 7.7720 ms, and 70% loads (solid: 2 routers, dotted: 3 routers, dashdot: 5 routers)**

## VI. Conclusion

### *Work Done*

Investigating jitter is important because it is very critical to quality of service for fixed rate traffic, be it real-time multimedia, broadcast multimedia, or leased line emulation. OPNET simulations were used to provide estimates of the expected jitter for several different Internet parameter sets, including the current best effort Internet as well as for the future Internet that will likely use DiffServ priorities. These simulations used self-similar traffic as background traffic to most closely approximate real-world Internet background traffic. We provided estimates of the jitter associated with today's best effort Internet, and of the jitter reduction that could occur with the use of Priority Queuing. These results are provided in graphical and tabular manner in a form which it is hoped will be useful for network engineers who have a need to estimate the impact on jitter of their network design choices.

From table V-3, and elsewhere, it was noted that as the trunk loads increase, the benefits of priority queuing increases. But as the number of router hops increases, the effect of priority queuing does not always increase. Priority queuing is seen to be an effective tool for reducing jitter at high trunk loads, but its relative effectiveness decreases as the end-to-end router count increases.

From table V-3, and elsewhere, we can see that lower trunk loads, or a combination of faster link speed and smaller packet size, is an alternative technique to achieve a lower jitter. The choice of controlling jitter by using priorities or deploying trunk bandwidth at a rate that will keep loads low is an economic one that is beyond the scope of this study.

### *Future Research*

This was a simulations based study of jitter in packet networks. To better validate these results, a comparison against up-to-date real world carrier core Internet traffic statistics is in order. To better understand the theoretical causes and effects of jitter in a network carrying traffic with Self-similar characteristics, a mathematical analysis that accurately describes the relationship between jitter and traffic parameters such as H Parameter, trunk load, and packet size distribution is also in order. Future research into these areas is strongly suggested.

## Appendix I – Numerical Values of the Histograms in Chapter V

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 1.0e-005 * | | 1.0e-005 * | | 1.0e-004 * | |
| 0.2476 | 0.9316 | 0.2892 | 0.8887 | 0.0384 | 0.8181 |
| 0.3235 | 0.0288 | 0.3634 | 0.0479 | 0.0464 | 0.0843 |
| 0.3995 | 0.0167 | 0.4376 | 0.0264 | 0.0545 | 0.0447 |
| 0.4754 | 0.0097 | 0.5118 | 0.0153 | 0.0625 | 0.0233 |
| 0.5514 | 0.0058 | 0.586 | 0.0076 | 0.0706 | 0.0135 |
| 0.6273 | 0.003 | 0.6602 | 0.0072 | 0.0786 | 0.0076 |
| 0.7033 | 0.0012 | 0.7344 | 0.0038 | 0.0866 | 0.0044 |
| 0.7792 | 0.0014 | 0.8086 | 0.002 | 0.0947 | 0.0018 |
| 0.8552 | 0.001 | 0.8828 | 0.0006 | 0.1027 | 0.0014 |
| 0.9311 | 0.0008 | 0.9571 | 0.0004 | 0.1107 | 0.0008 |

**Table A-1. Numerical Values of Figure V-6.**

| solid | | dotted | | Dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 1.0e-004 * | | 1.0e-004 * | | 1.0e-004 * | |
| 0.0305 | 0.7538 | 0.0333 | 0.5572 | 0.0446 | 0.3961 |
| 0.0495 | 0.1527 | 0.0494 | 0.2165 | 0.0651 | 0.2694 |
| 0.0686 | 0.0619 | 0.0655 | 0.1167 | 0.0856 | 0.1764 |
| 0.0876 | 0.0241 | 0.0816 | 0.0582 | 0.1061 | 0.0862 |
| 0.1067 | 0.0047 | 0.0977 | 0.0294 | 0.1266 | 0.0418 |
| 0.1257 | 0.0015 | 0.1138 | 0.0117 | 0.1471 | 0.0203 |
| 0.1448 | 0.0004 | 0.1299 | 0.0049 | 0.1676 | 0.0066 |
| 0.1638 | 0.0004 | 0.1459 | 0.0032 | 0.1881 | 0.0023 |
| 0.1829 | 0.0002 | 0.162 | 0.0011 | 0.2086 | 0.0006 |
| 0.2019 | 0.0002 | 0.1781 | 0.0011 | 0.2291 | 0.0002 |

**Table A-2. Numerical Values of Figure V-7.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 1.0e-004 * | | 1.0e-004 * | | 1.0e-004 * | |
| 0.0313 | 0.6044 | 0.0371 | 0.4098 | 0.0514 | 0.2339 |
| 0.0518 | 0.2118 | 0.0608 | 0.267 | 0.0855 | 0.305 |
| 0.0724 | 0.1014 | 0.0846 | 0.1644 | 0.1195 | 0.2215 |
| 0.093 | 0.043 | 0.1083 | 0.081 | 0.1536 | 0.1279 |
| 0.1136 | 0.0225 | 0.132 | 0.0437 | 0.1876 | 0.0639 |
| 0.1342 | 0.0076 | 0.1558 | 0.0184 | 0.2217 | 0.032 |
| 0.1548 | 0.0044 | 0.1795 | 0.0094 | 0.2558 | 0.0094 |
| 0.1754 | 0.003 | 0.2033 | 0.0028 | 0.2898 | 0.0039 |
| 0.196 | 0.0011 | 0.227 | 0.0023 | 0.3239 | 0.0014 |
| 0.2166 | 0.0007 | 0.2507 | 0.0011 | 0.3579 | 0.0011 |

**Table A-3. Numerical Values of Figure V-8.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 0.013 | 0.9724 | 0.0206 | 0.9259 | 0.036 | 0.88 |
| 0.0142 | 0.014 | 0.0215 | 0.0355 | 0.0373 | 0.0642 |
| 0.0153 | 0.0075 | 0.0225 | 0.0171 | 0.0386 | 0.0319 |
| 0.0164 | 0.0024 | 0.0235 | 0.0089 | 0.0398 | 0.0132 |
| 0.0175 | 0.001 | 0.0244 | 0.0047 | 0.0411 | 0.0063 |
| 0.0186 | 0.001 | 0.0254 | 0.0047 | 0.0424 | 0.002 |
| 0.0197 | 0.0008 | 0.0264 | 0.0006 | 0.0437 | 0.0008 |
| 0.0208 | 0.0004 | 0.0273 | 0.0012 | 0.045 | 0.0012 |
| 0.022 | 0 | 0.0283 | 0.0006 | 0.0462 | 0.0002 |
| 0.0231 | 0.0004 | 0.0292 | 0.0008 | 0.0475 | 0.0002 |

**Table A-4. Numerical Values of Figure V-9.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 0.0132 | 0.8215 | 0.0214 | 0.7386 | 0.037 | 0.5193 |
| 0.0147 | 0.0811 | 0.0241 | 0.1531 | 0.0402 | 0.2748 |
| 0.0163 | 0.0484 | 0.0267 | 0.0669 | 0.0435 | 0.1206 |
| 0.0178 | 0.0233 | 0.0294 | 0.0276 | 0.0468 | 0.05 |
| 0.0194 | 0.0113 | 0.032 | 0.0078 | 0.05 | 0.0216 |
| 0.0209 | 0.008 | 0.0347 | 0.0039 | 0.0533 | 0.0089 |
| 0.0224 | 0.0025 | 0.0373 | 0.0012 | 0.0566 | 0.0019 |
| 0.024 | 0.0014 | 0.04 | 0.0002 | 0.0598 | 0.0014 |
| 0.0255 | 0.001 | 0.0426 | 0.0004 | 0.0631 | 0.001 |
| 0.027 | 0.0014 | 0.0453 | 0.0002 | 0.0663 | 0.0004 |

**Table A-5. Numerical Values of Figure V-10.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 0.0141 | 0.7828 | 0.0221 | 0.6332 | 0.0381 | 0.3959 |
| 0.0175 | 0.1292 | 0.0263 | 0.2183 | 0.0436 | 0.3251 |
| 0.0208 | 0.0533 | 0.0304 | 0.09 | 0.049 | 0.1706 |
| 0.0241 | 0.0196 | 0.0345 | 0.0357 | 0.0545 | 0.0711 |
| 0.0275 | 0.0079 | 0.0387 | 0.016 | 0.06 | 0.0216 |
| 0.0308 | 0.005 | 0.0428 | 0.004 | 0.0655 | 0.0105 |
| 0.0341 | 0.0012 | 0.0469 | 0.0014 | 0.0709 | 0.0034 |
| 0.0374 | 0.0004 | 0.051 | 0.001 | 0.0764 | 0.0014 |
| 0.0408 | 0 | 0.0552 | 0.0002 | 0.0819 | 0.0002 |
| 0.0441 | 0.0006 | 0.0593 | 0.0002 | 0.0874 | 0.0002 |

**Table A-6. Numerical Values of Figure V-11.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 1.0e-005 * | | 1.0e-005 * | | 1.0e-004 * | |
| 0.2433 | 0.9304 | 0.2909 | 0.8764 | 0.0386 | 0.8122 |
| 0.3215 | 0.0316 | 0.3608 | 0.0535 | 0.0464 | 0.089 |
| 0.3997 | 0.0175 | 0.4307 | 0.031 | 0.0542 | 0.0419 |
| 0.4779 | 0.0085 | 0.5005 | 0.0179 | 0.0619 | 0.0276 |
| 0.5561 | 0.0052 | 0.5704 | 0.0087 | 0.0697 | 0.0137 |
| 0.6343 | 0.0028 | 0.6403 | 0.0062 | 0.0775 | 0.0068 |
| 0.7125 | 0.002 | 0.7102 | 0.0026 | 0.0853 | 0.005 |
| 0.7907 | 0.001 | 0.78 | 0.0024 | 0.093 | 0.0024 |
| 0.8689 | 0.0006 | 0.8499 | 0.0006 | 0.1008 | 0.001 |
| 0.9472 | 0 0004 | 0.9198 | 0.0006 | 0.1086 | 0.0004 |

**Table A-7. Numerical Values of Figure V-12.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 1.0e-005 * | | 1.0e-004 * | | 1.0e-004 * | |
| 0.254 | 0.648 | 0.0318 | 0.58 | 0.0458 | 0.4648 |
| 0.3364 | 0.1515 | 0.0443 | 0.2067 | 0.068 | 0.2897 |
| 0.4187 | 0.0917 | 0.0569 | 0.103 | 0.0902 | 0.1412 |
| 0.501 | 0.0488 | 0.0694 | 0.0538 | 0.1124 | 0.0657 |
| 0.5833 | 0.0271 | 0.0819 | 0.0299 | 0.1346 | 0.0265 |
| 0.6656 | 0.0156 | 0.0944 | 0.0141 | 0.1568 | 0.0083 |
| 0.7479 | 0.007 | 0.1069 | 0.0073 | 0.179 | 0.0026 |
| 0.8302 | 0.0055 | 0.1194 | 0.0026 | 0.2012 | 0.0011 |
| 0.9125 | 0.0019 | 0.1319 | 0.0017 | 0.2234 | 0 |
| 0.9949 | 0.0028 | 0.1444 | 0.0011 | 0.2455 | 0.0002 |

**Table A-8. Numerical Values of Figure V-13.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 1.0e-005 * | | 1.0e-004 * | | 1.0e-004 * | |
| 0.254 | 0.5416 | 0.0389 | 0.6357 | 0.0501 | 0.2847 |
| 0.3363 | 0.1992 | 0.0654 | 0.2307 | 0.0808 | 0.3206 |
| 0.4186 | 0.1102 | 0.0919 | 0.0892 | 0.1115 | 0.21 |
| 0.5009 | 0.0738 | 0.1184 | 0.0281 | 0.1423 | 0.1065 |
| 0.5831 | 0.0317 | 0.145 | 0.0106 | 0.173 | 0.0455 |
| 0.6654 | 0.0186 | 0.1715 | 0.0025 | 0.2037 | 0.0172 |
| 0.7477 | 0.0131 | 0.198 | 0.0018 | 0.2345 | 0.0085 |
| 0.83 | 0.0067 | 0.2246 | 0.0002 | 0.2652 | 0.0048 |
| 0.9123 | 0.0037 | 0.2511 | 0.0009 | 0.2959 | 0.0018 |
| 0.9945 | 0.0014 | 0.2776 | 0.0002 | 0.3267 | 0.0002 |

**Table A-9. Numerical Values of Figure V-14.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 0.0128 | 0.9742 | 0.0205 | 0.9291 | 0.0359 | 0.8641 |
| 0.0135 | 0.0104 | 0.0213 | 0.0327 | 0.037 | 0.0689 |
| 0.0142 | 0.0057 | 0.0222 | 0.0177 | 0.0382 | 0.0309 |
| 0.0149 | 0.0043 | 0.023 | 0.0095 | 0.0393 | 0.0173 |
| 0.0156 | 0.003 | 0.0238 | 0.0051 | 0.0404 | 0.0114 |
| 0.0164 | 0.001 | 0.0246 | 0.002 | 0.0415 | 0.0035 |
| 0.0171 | 0.0004 | 0.0255 | 0.002 | 0.0427 | 0.003 |
| 0.0178 | 0.0006 | 0.0263 | 0.0008 | 0.0438 | 0.0008 |
| 0.0185 | 0.0002 | 0.0271 | 0.0008 | 0.0449 | 0 |
| 0.0192 | 0.0002 | 0.028 | 0.0002 | 0.0461 | 0.0002 |

**Table A-10. Numerical Values of Figure V-15.**

| solid | | dotted | | dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 0.0128 | 0.8092 | 0.021 | 0.6943 | 0.0366 | 0.4699 |
| 0.0136 | 0.0819 | 0.0227 | 0.1575 | 0.039 | 0.2382 |
| 0.0143 | 0.0426 | 0.0245 | 0.0725 | 0.0414 | 0.1499 |
| 0.0151 | 0.0301 | 0.0262 | 0.0387 | 0.0438 | 0.0737 |
| 0.0159 | 0.0159 | 0.028 | 0.0183 | 0.0463 | 0.0385 |
| 0.0166 | 0.0082 | 0.0297 | 0.0105 | 0.0487 | 0.0159 |
| 0.0174 | 0.0056 | 0.0315 | 0.0049 | 0.0511 | 0.008 |
| 0.0182 | 0.0037 | 0.0332 | 0.0025 | 0.0536 | 0.0031 |
| 0.0189 | 0.0019 | 0.035 | 0.0006 | 0.056 | 0.0016 |
| 0.0197 | 0.001 | 0.0367 | 0.0002 | 0.0584 | 0.0012 |

**Table A-11. Numerical Values of Figure V-16.**

| solid | | dotted | | Dashdot | |
|---|---|---|---|---|---|
| X | Y | X | Y | X | Y |
| 0.0129 | 0.6053 | 0.0214 | 0.6117 | 0.0376 | 0.3664 |
| 0.0137 | 0.1831 | 0.024 | 0.2092 | 0.042 | 0.3028 |
| 0.0145 | 0.1016 | 0.0266 | 0.0915 | 0.0464 | 0.1744 |
| 0.0153 | 0.0491 | 0.0293 | 0.047 | 0.0508 | 0.0937 |
| 0.0161 | 0.0307 | 0.0319 | 0.0236 | 0.0552 | 0.0363 |
| 0.0169 | 0.0159 | 0.0345 | 0.0085 | 0.0596 | 0.0184 |
| 0.0178 | 0.0087 | 0.0371 | 0.004 | 0.064 | 0.0046 |
| 0.0186 | 0.003 | 0.0398 | 0.0026 | 0.0684 | 0.0024 |
| 0.0194 | 0.002 | 0.0424 | 0.0012 | 0.0728 | 0.001 |
| 0.0202 | 0.0006 | 0.045 | 0.0008 | 0.0772 | 0.0002 |

**Table A-12. Numerical Values of Figure V-17.**

## References:


[1] International Telecommunication Union (ITU)., "General recommendation on the transmission quality for an entire international telephone connection; one-way transmission time, Transmission systems and media, Recommendation G.114", Telecommunication Standardization Sector of ITU, Geneva, Switzerland, March 1993.

[2] Privalov, A.; Sohraby, E., "Per-stream jitter analysis in CBR ATM multiplexors", INFOCOM '98, Volume: 3, Page(s): 1325-1332, vol.3.

[3] Fulton, C.A.; San-Qi Li, "Delay jitter first-order and second-order statistical functions of general traffic on high-speed multimedia networks", IEEE/ACM Transactions on Networking, Volume: 6, Issue: 2, April 1998.

[4] Fulton, C.; San-Qi Li, "Delay jitter first-order statistical function in high-speed multimedia networks", ICC '96, Page(s): 1722-1729, vol.3.

[5] Fulton, C.; San-Qi Li, "Delay jitter correlation analysis for traffic transmission on high speed networks," INFOCOM '95, Page(s): 717-727, vol.2.

[6] Matragi, W.; Sohraby, K.; Bisdikian, C., "Jitter calculus in ATM networks: multiple nodes", IEEE/ACM Transactions on Networking, Volume: 5, Issue: 1, Feb. 1997, Page(s): 122-133.

[7] Matragi, W.; Bisdikian, C.; Sohraby, K., "Jitter calculus in ATM networks: single node case," INFOCOM '94, Page(s): 232-241, vol.1.

[8] Matragi, W.; Bisdikian, C.; Sohraby, K., "On the jitter and delay analysis in ATM multiplexer", ICC '94, Page(s): 738-744, vol.2.

[9] Sohraby, K.; Privalov, A., "End-to-end jitter analysis in networks of periodic flows", IEEE INFOCOM '99, Volume: 2, Page(s): 575 -583 vol.2.

[10] Landry, R.; Stavrakakis, I., "Study of delay jitter with and without peak rate enforcement", IEEE/ACM Transactions on Networking, Volume: 5 Issue: 4, Aug. 1997 Page(s): 543 -553.

[11] Iatrou, S.; Stavrakakis, I., "A dynamic regulation and scheduling scheme for real-time traffic management", IEEE/ACM Transactions on Networking, Volume: 8, Issue: 1, Feb. 2000, Page(s): 60-70.

[12] Iatrou, S.; Stavrakakis, I., "An integrated regulation and scheduling scheme for real-time traffic management", GLOBECOM '97, Volume: 3.

[13] Ting-Chao Hou; Chien-Chang Chen, "Jitter-EDD implementation for transporting MPEG-2 video streams on ATM networks", ICOIN-12, 1998, Page(s): 155 -160.

[14] Le Pocher, H.; Leung, V.C.M.; Gillies, D.W., "An efficient ATM voice service with flexible jitter and delay guarantees", IEEE Journal on Selected Areas in Communications, Volume: 17, Issue: 1, Jan. 1999, Page(s): 51-62.

[15] Rosado-Sosa, C.; Rubin, I., "Jitter compensation scheduling schemes for the support of real-time communications", ICC 98, Volume: 2, Page(s): 885 -890, vol.2.

[16] Kamiyama, N.; Ohta, C.; Tode, H.; Yamamoto, M.; Okada, H., "Quasi-STM transmission method based on ATM network", GLOBECOM '94. Volume: 3, 1994, Page(s): 1808-1814, vol.3.

[17] Jou, Y.F.; Fengmin Gong; Winkelstein, D.; Hillery, N., "A method of delay and jitter measurement in an ATM network", ICC '96, Volume: 1, Page(s): 328-332, vol.1.

[18] Mansour, Y.; Patt-Shamir, B., "Jitter control in QoS networks", IEEE/ACM Transactions on Networking, Volume: 9 Issue: 4, Aug. 2001, Page(s): 492-502.

[19] Guillemin, F.; Roberts. J.W., "Jitter and bandwidth enforcement", GLOBECOM '91, Page(s): 261-265, vol.1.

[20] Verma, D.C.; Zhang, H.; Ferrari, D., "Delay jitter control for real-time communication in a packet switching network", TRICOMM '91, Page(s): 35 -43.

[21] Hui Zhang, "Service disciplines for guaranteed performance service in packet-switching networks", Proceedings of the IEEE, Volume: 83 Issue: 10, Oct. 1995 Page(s): 374-1396.

[22] Jacobson, V., Nichols, K., Poduri, K., "An Expedited Forwarding PHB", RFC 2598, June 1999.

[23] Bennett, J.C.R.; Benson, K.; Charny, A.; Courtney, W.F.; LeBoudec, J.-Y., "Delay jitter bounds and packet scale rate guarantee for expedited forwarding", IEEE INFOCOM, Volume: 3, 2001.

[24] Wang, P.Y.; Yemini, Y.; Florissi, D.; Zinky, J.; Florissi, P., "Experimental QoS performances of multimedia applications", IEEE INFOCOM, Volume: 2, 2000.

[25] Yletyinen, T.; Kantola, R., "Voice packet interarrival jitter over IP switching", ITS '98, Page(s): 16 -21, vol.1.

[26] Bonald, T.; May, M.; Bolot, J.-C., "Analytic evaluation of RED performance", INFOCOM 2000, Page(s): 1415-1424 vol.3.

[27] Ye Ge; Hou, J.C.; Hung-Ying Tyan, "A packet eligible time calculation mechanism for providing temporal QoS for multicast routing", ICC '99, Page(s): 721-726 vol.2.

[28] Hofmann, U.; Pfeiffenberger, T.; Hechenleitner, B., "One-way-delay measurements with CM toolset", IPCCC '00, Page(s): 41-47.

[29] Willinger, W.; Taqqu, M.S.; Sherman, R.; Wilson, D.V., "Self-similarity through high-variability: statistical analysis of Ethernet LAN traffic at the source level", IEEE/ACM Transactions on Networking, Volume: 5, Issue: 1, Feb. 1997.

[30] William Stallings, High Speed Networks TCP/IP and ATM Design Principles, Prentice-Hall Inc., Englewood Cliffs, New Jersey, 1998.

[31] Bo Ryu; Lowen, S., "Fractal traffic models for Internet simulation", ISCC 2000.

[32] Crovella, M., and Bestavros, A., "Self-similarity in World Wide Web traffic: Evidence and Possible Causes", ACM SIGMETRICS, 1996, Pages 160-169.

[33] Blake, S., Black, D., Carlson, M., Davies, E., Wang, Z., Weiss, W., "An Architecture for Differentiated Services", RFC 2475, December 1998.

[34] OPNET Modeler Documentation 8.0.C, OPNET Technologies, Inc., Bethesda, Maryland, July 2001.

[35] Thompson, K., et al, 'Wide Area Internet Traffic Patterns and Characteristics', IEEE NETWORK, November/December 1997, p. 10-22.

[36] Cisco systems white paper , "Quality of service (QoS) networking ", Available at http://www.cisco.com/univercd/cc/td/doc/cisintwk/ito_doc/qos.pdf

VITA

Hee Jun Kim

Candidate for the Degree of

Master of Science

Thesis: JITTER IN PACKET NETWORKS – A SIMULATION BASED STUDY

Major Field: Electrical Engineering

Biographical:

Personal Data: Born in Seoul, Korea, On March 19, 1968, the son of Eung-Soo Kim and Soon-Ja Kwak.

Education: Graduated from Yo-I High School, Seoul, Korea in February 1986; received Bachelor of Science in Mechanical Engineering from Hong-Ik University, Seoul, Korea in February of 1992. Completed the requirements for the Master of Science Degree with a major in Electrical Engineering at Oklahoma State University in December 2001.

Experience: Served as project engineer for KIA Motors Company, Seoul, Korea, 1992 to 1995; project engineer at Monarch Machine Tool Company, Cortland, New York, 1999; research assistant at Oklahoma State University 2000 to 2001.