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TITLE: IP Network Impairment Model

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1 Introduction

In order to accurately assess the performance of networked real-time applications it is essential to model the underlying behavior of the network such that realistic impairments are present. Many real-time systems have dynamic elements (for example jitter buffers) that have a complex response to impairments, therefore it is important to generate impairments that are representative of network behavior in time as well as in terms of statistical properties.

The model presented in this contribution is the result of several years of analysis of IP network traces, development of VoIP network/service models using NS2 and a two year study of jitter buffer behavior. Initial studies focused on conventional models for packet loss and jitter.

A 4-state Markov model representation of packet loss distribution was developed and has been in use for network monitoring since mid-2001 with considerable success. A simpler Gilbert-Elliott form of the model was made available to one of the network emulator software vendors and has been used since early 2001. Feedback from users has been that the technology "represents the way that their network behaves".

A new jitter model was developed in late 2002, which resulted from time series analysis of jitter. This was combined with the earlier Markov/ Gilbert-Elliott model for packet loss to give a combined impairment model.

Two companion contributions describe in detail typical packet loss/ discard and jitter distributions. These show clearly the effects described above and the basis for the models described in this document.

2 Packet Loss Model

It is well known that packet loss in IP networks is bursty in nature. It is intuitively obvious but less well known that the distribution of packet discard due to jitter is also bursty – as jitter is a congestion related phenomena and hence depends on time varying traffic levels.

It is therefore reasonable to assume that either:-

(i) A burst model for packet loss can be used in conjunction with a jitter model or
(ii) A burst model for loss and discard can be used without a jitter model

Within the context of this contribution the definition of "burst" is a period of time bounded by lost packets during which packet loss is "high" (say over 6%). This is distinguished from a "consecutive loss period", which is a period of time bounded by lost packets during which <u>all</u> packets are lost.

A Gilbert-Elliott model is able to represent a two state channel with low and high loss rates, and is hence suitable for our needs. A 4-state Markov model, described in one of the companion contributions, provides a computationally efficient means for measuring the characteristics of a packet stream and determining both the Gilbert-Elliott model parameters and the consecutive loss period properties of the stream.

Gilbert-Elliott model with states 1 and 2:

```
if rand() < loss_probability[state]
        loss = TRUE
else
        loss = FALSE
if rand() < transition_probability[state]
        state = 3 - state
```

There is also some small probability of a long consecutive loss period due to a link or equipment failure. This is most conveniently modeled as a separate process.

3 A Time Series Model for Jitter

Time series models are used to represent the characteristics of sequences that have some properties that vary in time. They typically comprise one or more filter functions driven by a combination of noise and some underlying signal or periodic element.
The "spiky" nature of delay traces suggested that jitter could be modeled using an impulse noise sequence. The delay encountered by a packet at some specific stage in the network should be a function of the serialization delay of interfering traffic and the volume of traffic. The height of the impulses should therefore be a function of serialization delay and the frequency a function of congestion level.
LAN congestion tends to occur in short bursts – with Ethernet's CSMA/CD algorithm one packet may be delayed however the next may gain access to the LAN immediately; this suggests a short filter response time. Access link congestion tends to be associated with short term delay variations due to the queue in the edge router filling; this suggests a longer filter response time.

Core IP networks may be either low capacity (e.g. T1 interconnections) or high capacity (e.g. 2.4 Gbits/s interconnections) and the level of jitter resulting from congestion can be modeled as above. In both cases there is some probability of route changes, which if periodic are termed *route flapping*, and link failures.

A typical connection may comprise a LAN segment, access link, core IP network, access link and LAN segment. Packet order would be preserved through LAN and access link paths however reordering may occur

The jitter model therefore comprises a series of stages, each of which comprises a filter function and source of impulses. The result of each stage is an incremental delay for each packet passing through the stage. This delay may be extended by the requirement in some stages for the preservation of packet order.

Jitter stage k:

```
at time T
if rand() < impulse_probability(k)
        i = impulse_height(k)
else
        i = 0
d(k) = (d(k) * (f(k) –1) + i) / f(k)
```

4 Impairment Model

Packet loss is often due to buffer overflow, *random early detection* (RED) or some similar congestion related effect, although sometimes to other effects such as occasional routing table updates. This means that packet loss is often correlated with jitter level.

The combined impairment model therefore comprises a series of stages, corresponding to LAN segments, access links and core IP network. Each stage can switch independently between congested and uncongested states. In a congested state there is a higher probability of packet loss and an increase in impulse frequency.

Example Impairment model:

Order preserving stages (e.g. LAN, Access Link):

```
d = 0
for k = 0 to N
	/* jitter model */
	if rand() < impulse_probability(k)
		i = impulse_height(k)
	else
		i = 0
	d(k) = (d(k) * (f(k) –1) + i) / f(k)
	d = d + d(k)
	/* loss model */
	if rand() < loss_probability(k, state)
		d = LOST
	/* state transition model */
	if rand() < transition_probability(k, state)
		transition_probability(k, state) = 3 - transition_probability(k, state)
next k
/* modify delay to preserve order */
if d < lastd
	d = lastd
lastd = d
```

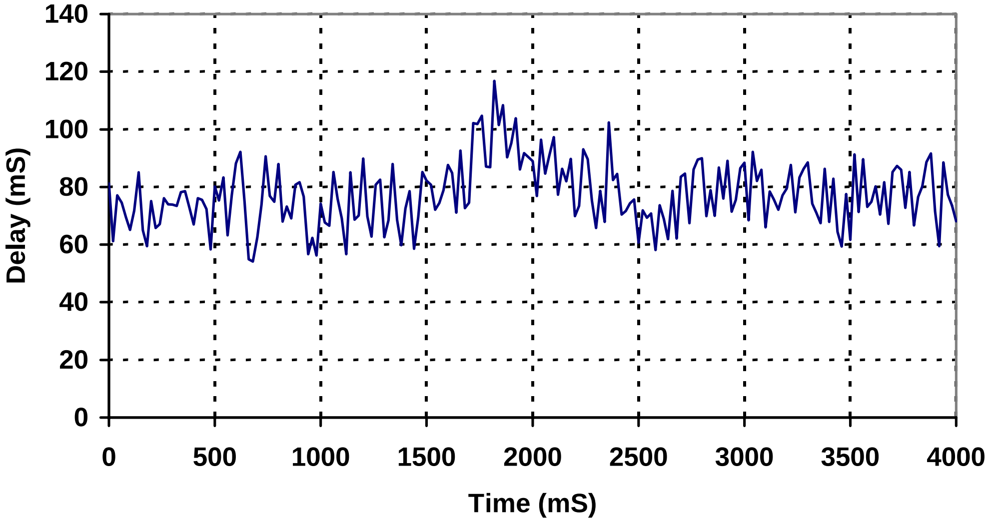
Non-order preserving stages:

```
for k = N+1 to M
	/* jitter model */
	if rand() < impulse_probability(k)
		i = impulse_height(k)
	else
		i = 0
	d(k) = (d(k) * (f(k) –1) + i) / f(k)
	d = d + d(k)
	/* loss model */
	if rand() < loss_probability(k, state)
		d = LOST
	/* state transition model */
	if rand() < transition_probability(k, state)
		transition_probability(k, state) = 3 - transition_probability(k, state)
next k
```

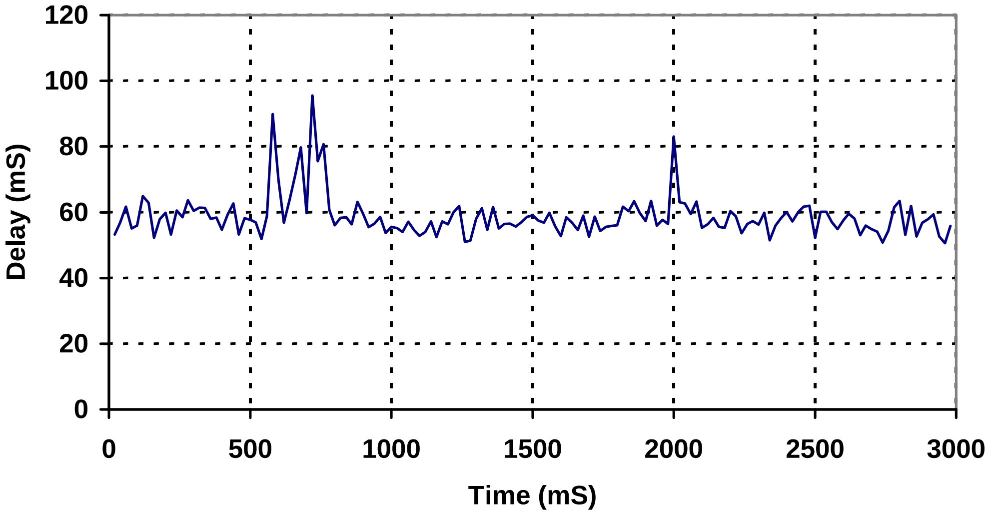
Core IP network characteristics:

```
/* model link failure followed by delay change */
if rand() < link_failure_probability
	consec_loss_count = integer( rand() * consec_loss_factor )
	if base_delay == min_delay
		base_delay = max_delay
	else
		base_delay = min_delay
if consec_loss_count > 0
	/* still losing consec packets */
	d = LOST
	consec_loss_count = consec_loss_count – 1
```

```
else
          /* model route flapping */
          if rand() < route_flap_probability
                    if base_delay == min_delay
                              base_delay = max_delay
                    else
                              base_delay = min_delay
d = d + base_delay
```



Example delay trace showing access link congestion



Example delay trace showing LAN congestion

5 Summary

The impairment model described above is able to represent typical real-world network conditions, removes the need to specify jitter distributions, produces correlated jitter and packet loss and is based on an understanding of the key stages on the IP path.

For complex IP end systems that incorporate jitter buffers and similar dynamic elements it is important to measure performance based on typical conditions. Modem or fax traffic is sometimes directly carried over an IP network rather than by "relay" and datapumps are extremely sensitive to the distribution of packet loss and discard.

Real-world IP networks do not have independent loss probabilities or normally distributed jitter, a close examination of network traces will quickly reveal characteristics that are typified by the model and example traces described above. It is proposed that the impairment model described above is used for the evaluation of MOIP and FOIP devices