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Title: Packet Loss Distributions and Packet Loss Models

ABSTRACT

This contribution discusses the general problem of modelling packet loss distribution in IP networks, and is intended to provide input to Q.12 study of IP network behaviour and background material for the Q.8 and Q.16 groups.

The factors that cause packet loss and packet discard within jitter buffers are generally transient in nature, typically related to congestion or link failure. This leads to “sparse bursts”, i.e. periods of time ranging from milliseconds to tens of seconds during which packet loss rate can be significant (e.g. 30%). Using a simple consecutive loss definition of packet loss burstiness can hide the fact that these sparse bursts commonly occur and hence may lead to understatement of the degree of impairment of a Voice or Video call.

1 Introduction

It is generally understood that packet loss distribution in IP networks is “bursty” however there is less certainty concerning the use of specific loss models, and in fact some misunderstanding related to some commonly used models, for example the Gilbert Model. This paper outlines some key packet loss models, provides some analysis of packet loss data, discusses the degree of “fit” of models and data and proposes the use of a 4-state Markov model to represent loss distribution.

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2 Common Packet Loss Models

2.1 Historical background

Much of the early work on loss or error modeling occurred in the 1960's in relation to the distribution of bit errors on telephone channels.

One approach used was a Markov or multi-state model. Gilbert [13] appears to be the first to describe a burst error model of this type, later extended by Elliott [10,11] and Cain and Simpson [6]. Blank and Trafton [3] produced higher state Markov models to represent error distributions.

Another approach was to identify the statistical distribution of gaps. Mertz [17] used hyperbolic distributions and Berger and Mandelbrot [2] used Pareto distributions to model inter-error gaps. Lewis and Cox [16] found that in measured error distributions there was strong positive correlation between adjacent gaps.

Packet loss modelling in IP networks seems to have followed a similar course, although the root cause of loss (typically congestion) may be different to that of bit errors (typically circuit noise or jitter).

2.2 Bernoulli or Independent Model

The most widely used model is a simple independent loss channel, in which a packet is lost (or bit error occurs) with a probability P_e. For some large number of packets N then the expected number of lost packets is $N.P_e$. The loss probability can be estimated by counting the number of lost packets and dividing this by the total number of packets transmitted.

2.3 Gilbert and Gilbert-Elliott Models

The most widely known burst model is the Gilbert Model [13] and a variant known as the Gilbert-Elliott Model [10,11]. These are both two state models that transition between a "good" or gap state 0 and a "bad" or burst state 1 according to state transition probabilities P_{01} and P_{11}:

(i) Gilbert Model
    a. State 0 is a zero loss/error state
    b. State 1 is a lossy state with independent loss probability P_{e1}

(ii) Gilbert-Elliott Model
    a. State 0 is a low loss state with independent loss probability P_{e0}
    b. State 1 is a lossy state with independent loss probability P_{e1}

It is often assumed that the Gilbert Model *lossy* state corresponds to a "loss" state, i.e. that the probability of packet loss in state 1 is 1, however this is incorrect (it would be more proper to describe this as a 2-state Markov model). This leads to analysis of packet loss burstiness in terms solely of consecutive loss which misses the effects of longer periods of high loss density. As illustrated in [14], these long periods of high loss density can have significant effect on Voice over IP services.

For example, consider the following:

Loss pattern000001100101010110110000000000000000000

Correct application of Gilbert Model – burst length 15, burst density 60%

Incorrect application of Gilbert Model – mean burst length 1.5 bits

2.4 Markov Models

A Markov model is a general multi-state model in which a system switches between states i and j with some transition probability p(i, j).

A 2-state Markov model has some merit in that it is able to capture very short term dependencies between lost packets, i.e. consecutive losses [1, 4, 15,19]. These are generally very short duration events (say 1-3 packets in length) but occasional link failures can result in very long loss sequences extending to tens of seconds [5].

By combining the 2-state model with a Gilbert-Elliott model it is possible to capture both very short duration consecutive loss events and longer lower density events.

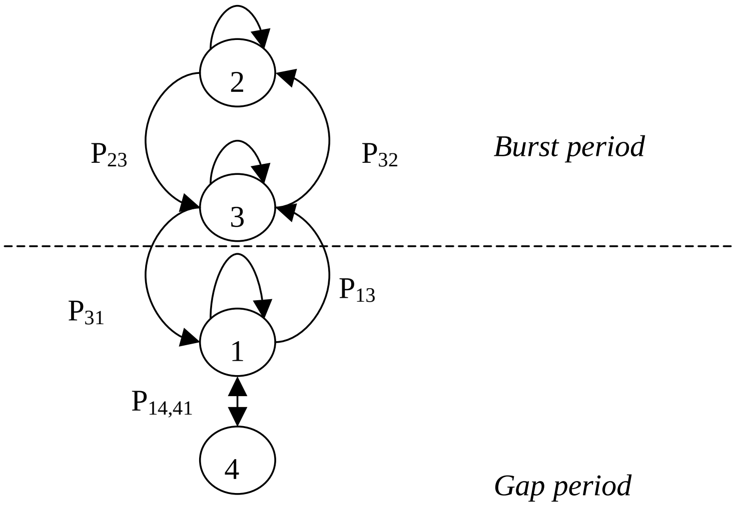

Figure 1 – 4-State Markov Model

This 4-state Markov model [7, 12] represents *burst* periods, during which packets are received and lost according to a first 2-state model and *gap* periods during which packets are received and lost according to a second 2-state model. The states have the following definition:

a. State 1 – packet received successfully
b. State 2 – packet received within a burst
c. State 3 – packet lost within a burst
d. State 4 – isolated packet lost within a gap

For example, using the loss pattern above:-

Loss pattern000001100101010110110000000000000000000000001000000000

State 111113322323232332331111111111111111111111114111111111

It is common to define a gap state with respect to some criteria, for example a loss rate lower than some limit or some consecutive number of received packets. A convenient definition is that a burst must be a longest sequence beginning and ending with a loss during which the number of consecutive received packets is less than some value G_{min} (a suitable value for Gmin for use with Voice over IP services would be 16 whereas for use with Video services a higher value of say 64 or 128 would be preferable).

3 Analysis of Packet Traces

3.1 Trace descriptions

The attached traces are part of a set totaling over 3 million packets obtained from researchers at the Columbia University, University of Massachussetts, Indian Institute of Technology and Telchemy. They are one way traces obtained between different sites in the US, Europe and Asia using UDP/RTP with inter-packet intervals ranging from 10mS to 30mS. Most traces include one way delay and packet loss data, whereas some include only packet loss data.

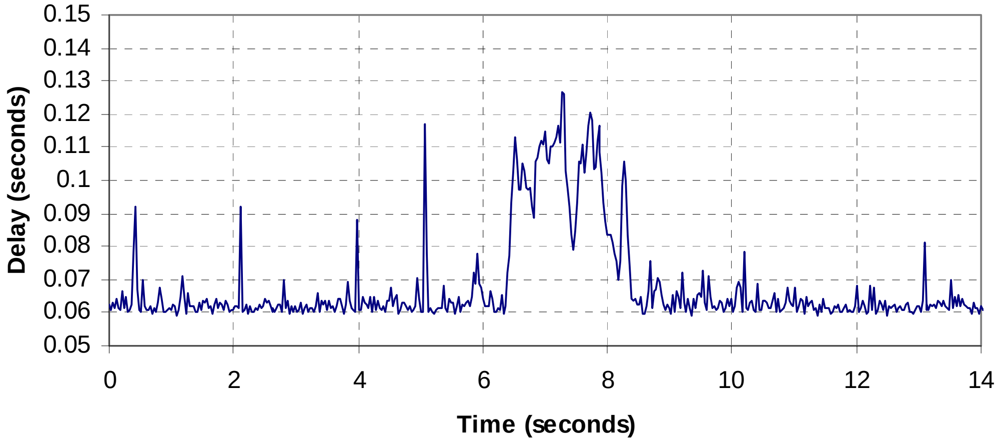

Figure 2 – Example trace used in analysis

To illustrate the nature of the data, the above chart shows an example section of a delay trace. The chart shows a congestion event and also a series of regular minor events (probably due to LAN congestion). As can be seen, associated with congestion over a routed connection there is an overall increase in delay, as well as an increase in packet-to-packet delay variation.

3.2 Trace Analysis

A series of traces were analyzed using the 4-State Markov model described above and the results interpreted as a Gilbert-Elliott model. This results in the definition of Bursts with some given length and (high) loss density and Gaps with some given length and (low) loss density. These were plotted as scatter diagrams of burst length against burst weight for each trace. The examples shown below show consistent results to that seen on many of the traces.

3.3 Trace 1

There are two charts associated with Trace W1. The first chart shows a scatter diagram of burst length versus burst weight. It can be clearly seen that burst of up to 300 packets in length occur, and have a typical loss density of 25%. There are several isolated points on the 45 degree line, corresponding to a number of long bursts of consecutive loss probably due to link failures [5].

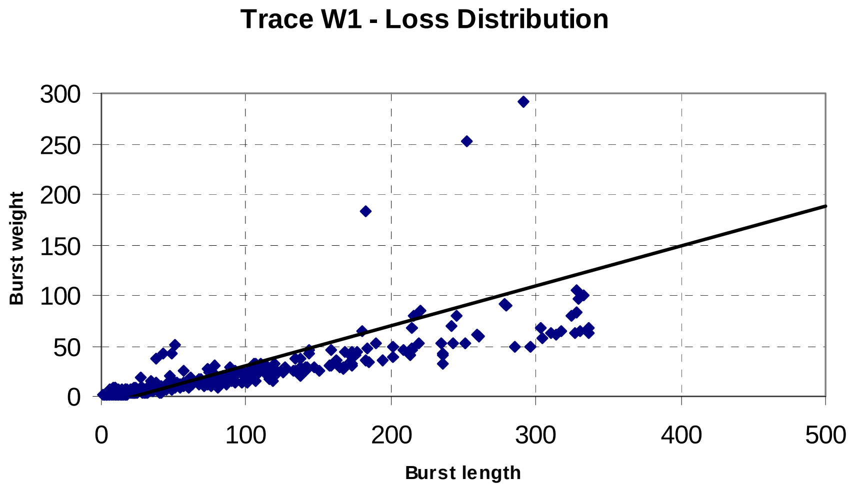

Figure 3 – Trace W1 Scatter diagram of Burst Length vs Weight for packet loss only

The second chart shows a scatter diagram of burst length versus burst weight for losses and discards, assuming a 30mS jitter buffer size. This shows a very similar distribution to the loss-only chart, indicating that jitter was not a significant problem on this trace.

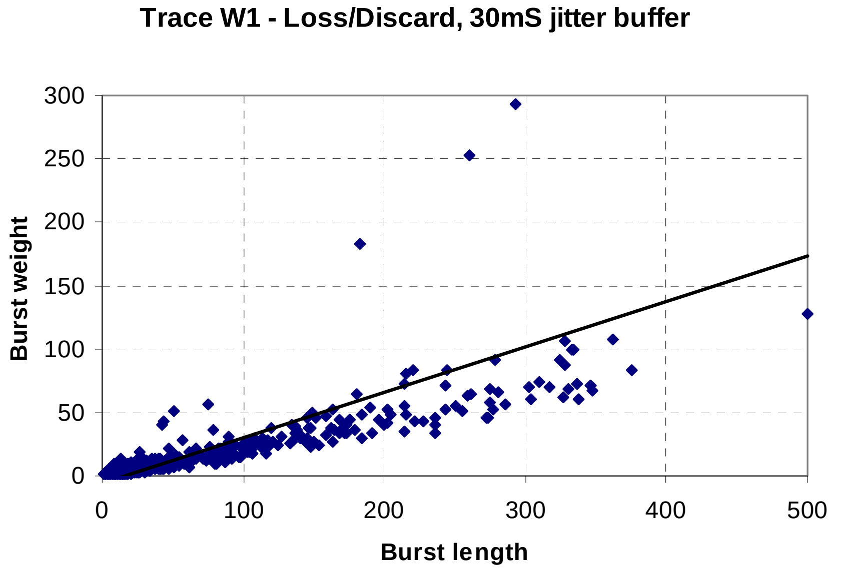

Figure 4 – Trace W1 Scatter diagram of Burst Length vs Weight for combined packet loss and packet discard (30mS jitter buffer)

3.4 Trace 3

There are two charts associated with Trace 3. The first chart shows a scatter diagram of burst length versus burst weight (Gilbert model). It can be clearly seen that burst of up to 100 packets in length occur, and have a typical loss density of 20-25%.

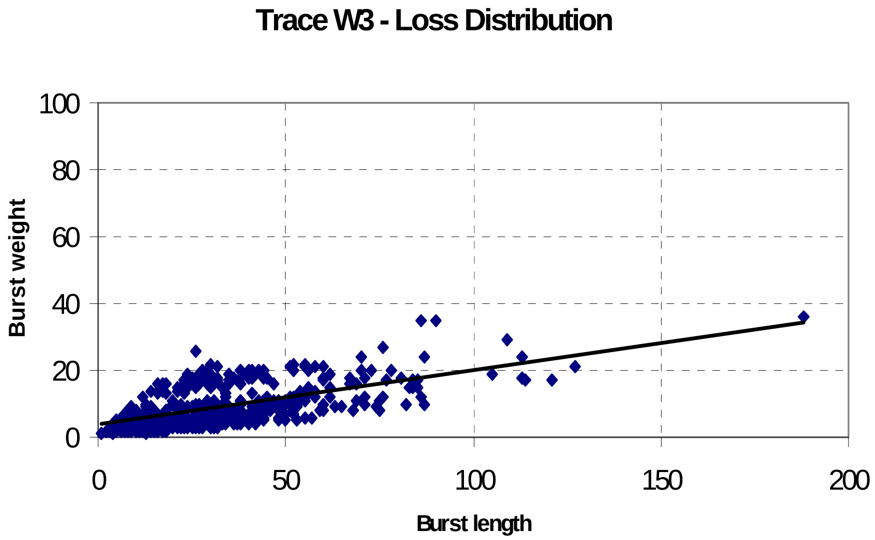

Figure 5 – Trace W3 Scatter diagram of Burst Length vs Weight for packet loss only

The second chart shows a scatter diagram of burst length versus burst weight for losses and discards, assuming a 50mS jitter buffer size. This shows a much larger number of bursts indicating that jitter was a significant problem on this trace. Burst density extends out to 500 packets and mean burst density is approximately 30%.

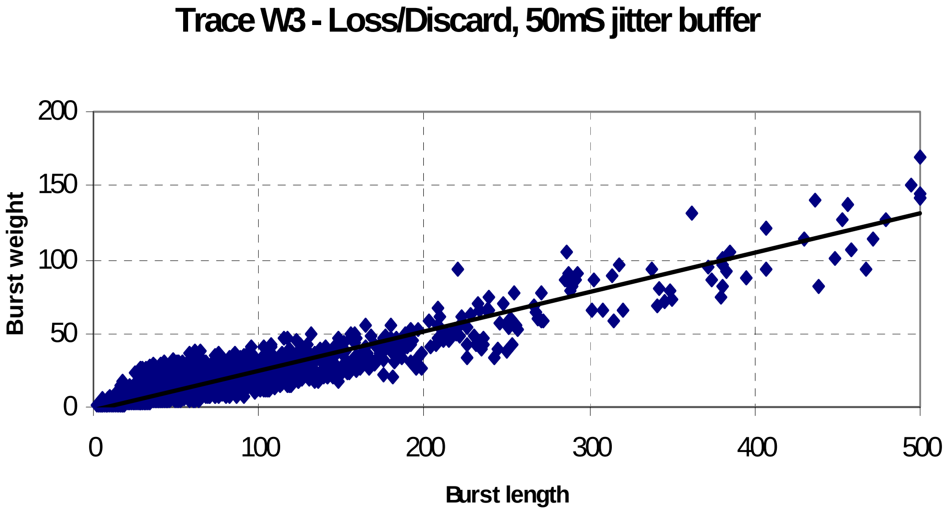

Figure 6 – Trace W3 Scatter diagram of Burst Length vs Weight for packet loss and packet discard (50mS jitter buffer)

3.5 Trace M26

There are four charts associated with Trace M26, a 443,000 packet trace. The consecutive loss distribution, the sparse burst density distribution, the sparse burst length distribution and a scatter diagram of burst length versus burst weight.

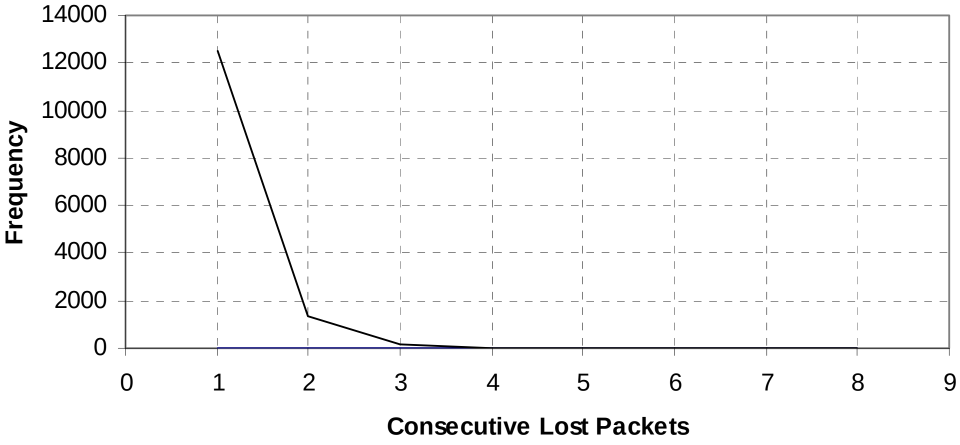

Figure 7 – Trace M26 Histogram of consecutive packet loss run length

The first chart above shows the consecutive loss distribution. This would suggest that bursts of consecutive lost packets are predominantly one packet in length and to a lesser extent two packets. This chart would also lead to the erroneous conclusion that this was not an IP connection that exhibited burst packet loss.

Figure 8 – Trace M26 Histogram of burst length

The second chart, above, shows the distribution of burst lengths defined according to our Gilbert-Elliott model. This shows burst lengths extending to over 50 packets in length with a peak at 15-16 packets, quite a different conclusion to the previous chart.

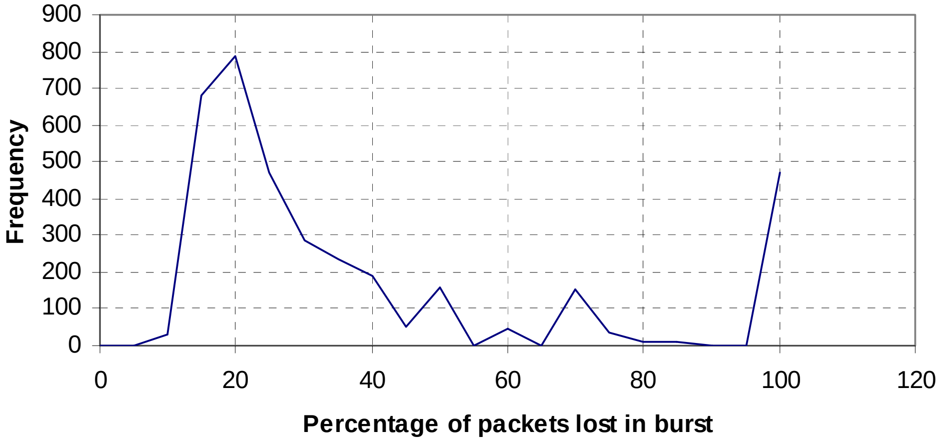

Figure 9 – Trace M26 Histogram of burst density

The third chart, above, shows the distribution of burst packet loss density. As can be seen, the peak occurs at 20% although a significant number of bursts of 100% density do occur.

The final trace, below, shows a scatter diagram of burst length versus burst weight. This shows a concentration of bursts in the region of 2 to 50 packets in length with a 10-20% loss density. It also shows that most of the consecutive loss bursts (which lie on the 45 degree line) were less than 20 packets in length although one was of length 60 packets, probably due to a link failure.

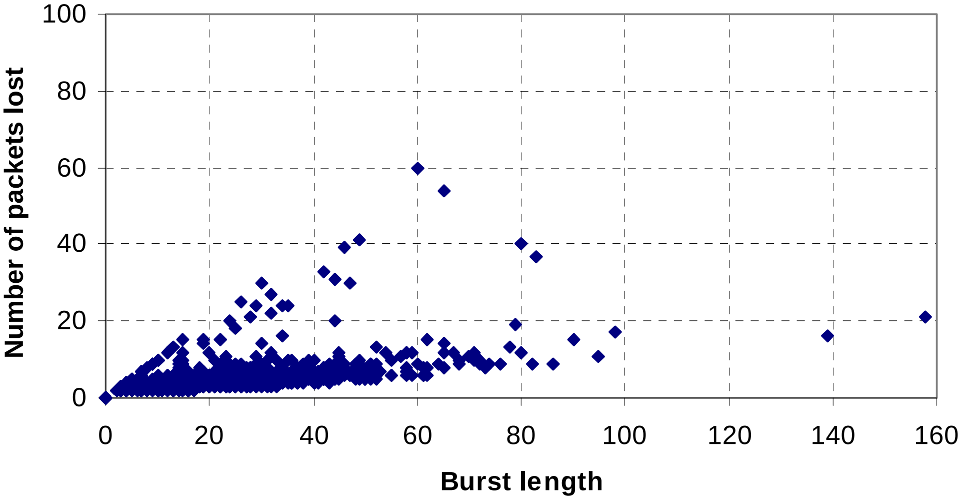

Figure 10 – Trace M26 Scatter diagram of burst length vs weight

3.6 Results Summary

The results above show clearly that the traces exhibited long bursts of packet loss – with typical loss densities of 20-30%. The distribution of packets discarded by the jitter buffer also shows similar properties, with long sparse bursts. The use of a 2-state consecutive loss model gives the impression that burst length was very short, typically 1-3 packets in length whereas the presence of long bursts with a strong length-weight trend line suggests that a Gilbert model is much more appropriate.

4 Example of 4-State Model Parameters

The transition probabilities for the 4-state Markov model were determined for trace M26. They are listed below.

$P_{11} = 0.978707$ $P_{31} = 0.456988$

$P_{14} = 0.012111$ $P_{32} = 0.215691$

$P_{13} = 0.009182$ $P_{33} = 0.327321$

$P_{22} = 0.768041$ $P_{41} = 1.000000$

$P_{23} = 0.231959$

These parameters were used to create a simulated packet loss series, driving the 4-state Markov Model using random input. The chart below shows a scatter diagram of burst length versus burst weight that compares favorably with the measured chart. This does not exhibit the occasional long burst of consecutive loss that can be observed on the measured data – the model can produce long sequences but with low probability.

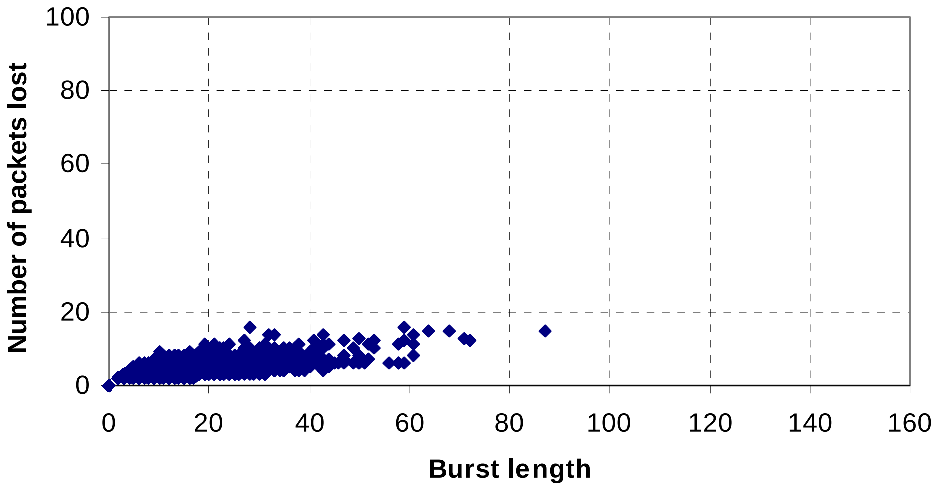

Figure 11 – Simulation of Trace M26 using 4 state Markov model parameters – Scatter diagram of burst length vs weight

5 Applicability to Practical Network Scenarios

In practice IP networks may experience conditions ranging from ideal to abysmal. A high performance core IP network may have “normal” conditions under which no packets are lost and jitter is low but still experience occasional link failures or delay events related to rerouting. Some applications are more difficult, notably:

(i) a service provider accepts Voice over IP traffic originating from a customer/ subscriber’s IP phone

(ii) an Enterprise or Business has deployed a private Voice over IP service

In both cases the packet stream passes through a local area network, a limited bandwidth access link and an IP network. There is much more opportunity for problems to occur due to congestion. Even if the packet transmission problems occur on the customer’s LAN or access link the IP service provider may still be accused of being responsible, and in the case of some types of VoIP service may be responsible for the quality of the connection.

6 Summary and recommendations

This contribution described several burst packet loss models and proposes the use of a 4-state Markov model, combining the ability of the Gilbert-Elliott and 2-state Markov models to represent long and short term burst loss characteristics. This is substantiated by the analysis of trace files that clearly show long sparse bursts of packet loss that would not be detected by the use of a simple 2 state model.

7 References

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