Internet Performance Model using End-to-End Delay Analysis

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Internet performance and its state, which changes hourly, is difficult to be caught because of complexity of the network structure and application traffic. This paper proposes a method for modelling Internet performance and its state by measuring packet forwarding delays from one end terminal and analizing them statistically. We also show examples of measurement and analysis on specific paths in real Internet. At the end, convergency of delay statistics to real value is discussed by using order statistics, which is needed to decide sample size to be measured.

1. Introduction

Internet is a network where two or more networks are connected mutually. It is difficult for network managers to obtain information on the network performance of the other networks. In addition, various multimedia applications make it more difficult to detect changes in the condition of the network because of the variety of the traffic. The Internet service providers hope to understand end-to-end performance in the Internet environment. Based on performance measurement results, they will change the construction of the network or replace the existing link with a higher-speed link.

Several previous studies on Internet performance characteristics have been reported. Claffy et al.[4] and Sanghi et al.[10] worked on end-to-end delay performance. Bolot[1] studied on packet loss performance. The IPPM-WG of IETF is also trying to define network performance standards and way of measuring them (see, for example, Ref. 9)).

On our work, we focus on packet delay performance. However, when measured delay is large, it is possible that we assume the network is congested, but we cannot conclude it. The distance between measured points might merely be far. Delay statistics related to network congestion is needed.

Carter and Crovella[3] worked on Internet bandwidth. They modelled bandwidth performance as available bandwidth, subtracting used bandwidth from maximum bandwidth of a bottleneck link along the path. Maximum bandwidth is constant value corresponding to uncongested case, while used bandwidth is determined by the traffic load on the bottleneck link.

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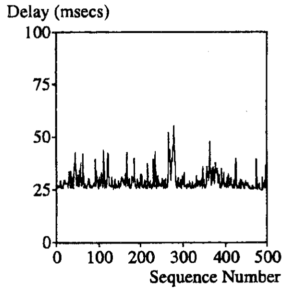

Fig. 1 Measured delay sequence

As a result, this model can be used in network management by detecting available bandwidth, which is difference between maximum and used bandwidth.

We think it is possible to apply a similar idea to delay performance. As shown in Fig. 1, almost all packet delays are close to a minimum value, and the others are apart from the value. By using ICMP echo request/reply messages in the same manner as in the 'ping' program at one end terminal (6Mbps access line), we measured round-trip times of 100 byte packet every 1 sec on 12 hop path between hosts connected with separate ISP with 1.5Mbps and 6Mbps access lines from Ethernet LANs respectively. In general, it is understood that packet forwarding delay can be recognized as sum of constant part and variable part.

In the remaining sections, under the idea, we construct an end-to-end performance model utilizing the piling of network device performance and traffic load effects. And we also study on validity of the proposed model by measuring and analizing packet forwarding delays on specific paths in real Internet. At the last section, convergency of delay statistics to real value is discussed by using order statistics,

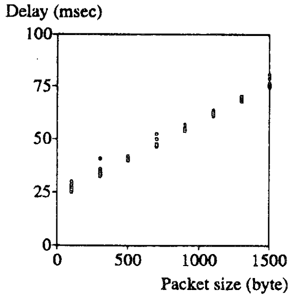

Fig. 2 Measured delay against packet size

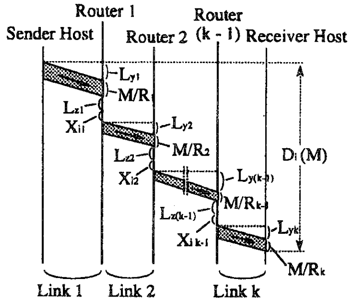

Fig. 3 End-to-end packet delay model

which is needed to decide sample size to be measured.

Changes in the route can affect the measurement results. However, in most cases the route is stable. That is, the route between hosts does not change; in most cases it remains steady in the scale of the period in which the application is used. For example, Paxson[8] examined the route between 37 sites by using the 'traceroute' program. As a result, the end-to-end route changes by a time scale from several seconds to several days. He also showed that two-thirds of the routes continue without change for several days or more. We assume the route between hosts does not change during each measurement.

2. Internet performance model

In this section we show the performance of the packet forwarding delay of the IP network by way of an enterprise network of the LAN-WAN-LAN composition and two or more networks like the Internet. We also present a model for evaluating the performance by means of end-to-end measurement and show an example of measuring using an actual route. The underlying concept of our network performance model is that of deciding the basis of specific performance (constant part), which reflects the network device performance of the router system and the data link medium, and the variable performance (variable part) reflecting the behavior of the router queue influenced by the traffic change. That is, by separating network performance into constant and variable parts, the performance model can offer information for evaluating changes in composition and increase or decrease in link speed, etc., in order to compare and select the network provider to be used as the backbone.

As shown in Fig. 2, it is known that delays increase as packet size increases, which is understood based on packet forwarding characteristics in IP routers.

Based on this concept, end-to-end forwarding time of packet i with length M, $D_i(M)$, is modeled with fixed performance parameters R and L and variable performance parameter X_i:

$$D_i(M) = \frac{M}{R} + L + X_i \qquad (1)$$

where L of the k hop route in Fig. 3 is shown as the sum of propagation delay L_{Yj} (= distance/spread speed) of one bit signal in link j and processing time L_{Zj} in router j ($L = \sum_{j=1}^{k} L_{Yj} + \sum_{j=1}^{k-1} L_{Zj}$). Also R is a link speed for considering end-to-end path as one link, and if R_j is assumed as the link speed of each hop j, the relational expression $1/R = \sum_{j=1}^{k} 1/R_j$ can be derived. X_i is the sum of the waiting time in each router of packet i, and it is expressed as $X_i = \sum_{j=1}^{k-1} X_{ij}$ and changes dynamically.

Notice that packet delays must be measured independent each other in order that Eq. (1) is proper. In our measurements, each packet is sent into the network with enough time interval 1 sec, which is larger than every measured delays. And so we think it is possible to assume independency of measured delays.

The $D_i(M)$ in Eq. (1) is measured directly and separated to R, L and X_i. The measured minimum delays agreed well with the straight line in the delay model (Fig. 4). As a result, by using these parameters as a standard, it is possible to make a multilateral comparison of the characteristics of the providers' networks and to decide on change the network configuration. That is, network managers may decide on whether to make the link speed high if R is small, or to reduce the number of hops if L is large.

Though our model is shown with R, L and

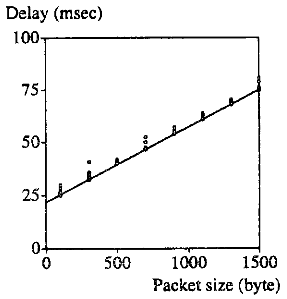

Fig. 4 Comparison with the model and measured delay in Internet

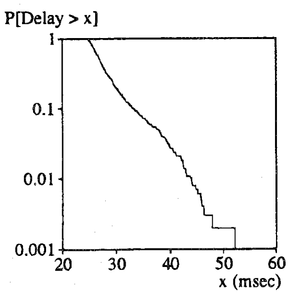

Fig. 5 Delay distribution

X_i, variable part parameter X_i is different in each packet. Here, we discuss distribution of $D_i(M)$. In Fig. 5, measured delay distribution of 100 byte packets is shown. If it is shifted by 24.6 msecs, it is close to exponential distribution. Mukherjee[7] modelled the Internet delay as the sum of the constant value and the Gamma distributed value. Fasbender and Davids[5] also modelled the Internet delay as the sum of the constant value and the Erlang distributed values. Both distributions have exponentially decaying tail. As another result, Borella et al.[2] reported Internet delay distribution is with heavy tailed decay. However, we could not observed heavy tailed distribution in our measurements.

To simply characterize the variable part, appropriate delay statistics are needed rather than its distribution. As statistics of delay $D_i(M)$, minimum, mean, median and percentile are thought of. The change of X_i can be considered to be a change in waiting time if the network is considered as one queue. Therefore, it is possible to use the parameter to predict such factors as the state of the network and network load by using queueing analysis under the assumed traffic model. Because relationship between meanX_i(= mean$D_i(M) - \min D_i(M)$) and traffic load is analytically derived, it is thought most useful statistics.

3. Method for measuring and calculating performance model

We will now present our method for estimating the performance model from the measurement of the forwarding time of the round-trip route in a real network. First of all, two or more $D_i(M)$ are measured for each size M in Eq. (1). The possibility of being forwarded without waiting time in all routers along the route is high ($\min X_i \to 0$), if there is sufficient measurement data. Therefore, we forecast a minimum value $\min D_i(M)$ of each M fitting to straight line $\min D_i(M) = M/R + L$. R and L can be estimated by using a least-square approximation. In addition, we can take X_i of each packet i, after these R and L values are substituted for Eq. (1). 'pathchar'[6], which is link speed measurement software, may also make use of this concept, in which $(M, \min D_i(M))$ convergences to a straight line.

Each parameter in the model is calculated using this idea, according to the following procedure.

(1) Measure forwarding delay of different size packets.
(2) Adopt a minimum value for the forwarding delay for each packet size.
(3) Approximate the minimum value taken in step 2 to the straight line by using the least square method (L and R is calculated).
(4) Decide whether to end or to continue, based on the correlation coefficient value of the approximate straight line.
(5) End the procedure if it is more than the reference value; add the measurement and repeat if it is less than the value.

4. Measurement example of performance model in the real Internet

By using ICMP echo request/reply messages in the same manner as in the 'ping' program, we measured the packet round-trip time between, at one end, terminals in a LAN of 6 Mbps access line and, at the other end, WWW servers in the same LAN, in a domestic remote office, in an overseas office, and connected to a low-speed (128 kbps) link. The values resulting from our procedure (M, $\min D_i(M)$) are plotted in Fig. 6, where the reference value of cor-

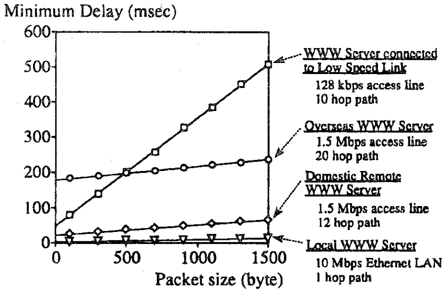

Fig. 6 Examples of constant parts in the model

relation coefficient was 0.9999. The solid line is a straight line of $\min D_i(M) = M/R + L$ with R and L calculated by least-square approximation.

R in the same LAN is about half of the link speed of the Ethernet (10 Mbps), because it is a round-trip route. And it is understood that the R for one hop shows the approximate link speed of the hop. Moreover, the R to the server connected with a low-speed link became extremely small compared with the others. It is likely that this feature can be used as an indicator of a bottleneck link along the route, even though R is not exactly equivalent to the link speed. If servers in an oversea office of the same connected environment as a domestic server are compared only on the basis of distance, R changes very little. But L is a considerably large value for an overseas server.

L is the sum of the propagation time in each link relating to the distance and the processing time of each router, and therefore it is considered to be the lowest and requisite time for packet transfer between the hosts.

Considering Fig. 6 and other results, the parameter values calculated by this technique are expected to be approximately the same order for the same path.

5. Analysis of delay statistics convergency

In this section, we consider convergency of delay statistics, i.e. minimum, mean, median and percentile. It is thought to characterize Internet path performance by using statistics concerning packet forwarding delay. However, size of measured sample used to calculate those statistics is limitated. So, we would like to know sample size in order that calculated statistics are accurate enough. In other words, it is necessary to clarify relationship between sample size and degree of accuracy of calculated statistics.

It is thought that end-to-end delay in the Internet is separated to minimum value which depends on fixed network performance, and the change from the minimum value which depends on traffic variability etc. (Eq. (1)). So, it is thought that measured delay of packet i with size M follows a distribution function $F(x)$ of which real minimum value is ξ. Therefore,

$$F'(x) = \begin{cases} f(x) > 0 & (x \geq \xi) \\ 0 & (x < \xi) \end{cases} \quad (2)$$

In following sections, we discuss statistics on n-size sample $\{D_1(M), D_2(M), \cdots, D_n(M)\}$, which is independently measured and have delay according to distribution function $F(x)$. Constant part of end-to-end delay corresponds to $\min D_i(M)$, while variable part is assumed to be related to either meanX_i(= mean$D_i(M) - \min D_i(M)$) or percentile of X_i (= percentile of $D_i(M)$ minus $\min D_i(M)$).

5.1 Sample minimum

When you assume independence between each element of measured sample abovementioned by using order statistics, distribution of the sample minimum $\min D_i(M)$ is shown to be $F_1(x) = 1 - \exp(-n(x-\xi)f(\xi))$. Therefore, expectation value of $\min D_i(M)$ is $\xi + 1/\{nf(\xi)\}$, and its variance is $1/\{n^2 f^2(\xi)\}$. Here, $f(\xi)$ is related to the traffic load. If n is large enough, $1/\{nf(\xi)\} \to 0$. That is, the expectation value of $\min D_i(M)$ converges to ξ.

5.2 Sample percentile

$100p$ percentile of the population is assumed ζ_p. In short, $F(\zeta_p) = p$, where $0 < p < 1$. In this case, if the sample $100p$ percentile is the vicinity of the mean value of the population, it is known that the percentile is according to normal distribution of mean ζ_p and valiance $p(1-p)/\{nf^2(\zeta_p)\}$. Here, sample median is sample percentile with $p = 1/2$.

5.3 Sample mean

It is assumed that mean value of the population is μ and its valiance σ^2. It is known that sample mean is according to normal distribution of mean μ and valiance σ^2/n.

Therefore, sample minimum rapidly decreases by the order of $1/n^2$, while expectation

Table 1 Summary of convergency of each statistics

Statistics	Expectation value	Variance
Minimum	$\xi + 1/\{nf(\xi)\}$	$1/\{n^2 f^2(\xi)\}$
Median	$\zeta_{1/2}$	$1/\{4nf^2(\zeta_{1/2})\}$
Percentile	ζ_p	$p(1-p)/\{nf^2(\zeta_p)\}$
Mean	μ	σ^2/n

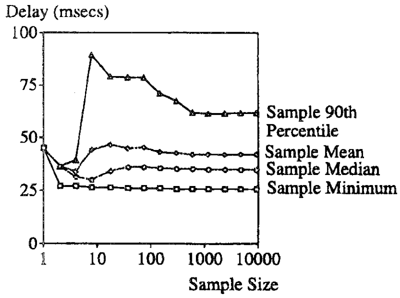

Fig. 7 Measured delay convergency

value of sample percentile and sample mean decreases by the order of $1/n$. Moreover, convergency of sample minimum and sample percentile does not depend on variance of population.

6. Measurement example of delay statistics in the real Internet

Next, we compare measured delay in the real Internet with the analytical result of convergency of each delay statistics. Figure 7 shows measured examples of each statistics of size M packets: sample minimum of round-trip delay, sample median, sample 90th percentile, and sample mean which are measured against different sample size n in actual Internet. They are measured on a 12-hop path between hosts connected with separate ISP with 1.5Mbps and 6Mbps access lines from Ethernet LANs respectively. Moreover, as one sample, 10000 delay values are measured every second. As size-n sample, we adopt a series which had been taken out at interval of $10000/n$ from the measured series. Using these size-n sample, each statistics of size-n sample is calculated.

Sample minimum is shown to convergence fast against sample size, which is compared with the other delay statistics measured in the actual Internet as well as analytical results. Constant part of the performance model can be separated from measured $D_i(M)$ by using smaller sample. However, larger sample is needed to calculate characteristics of its variable part, because of slower convergency of sample percentile or mean.

7. Summary

This paper proposes a method for modelling Internet performance and its state by measuring packet forwarding delays from one end terminal and analizing them statistically. We also show examples of measurement and analysis on specific paths in real Internet. At the end, convergency of delay statistics to real value is discussed by using order statistics, which is needed to decide sample size to be measured. Constant part of the performance model can be separated from measured $D_i(M)$ by using smaller sample. However, larger sample is needed to calculate characteristics of its variable part, because of slower convergency of sample percentile or mean. It is also a future work to decide delay statistics to appropriately express characteristics of its variable part of the performance model.

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