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A Resequencing Model for High Speed Networks

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Abstract—In this paper, we propose a framework to study the resequencing mechanism in high speed networks. This framework allows us to estimate the packet resequencing delay, the total packet delay, and the resequencing buffer occupancy distributions when data traffic is dispersed on multiple disjoint paths. In contrast to most of the existing work, the estimation accounts for the end-to-end path delay distribution as well as the packet resequencing delay, the total packet delay, and the resequencing buffer occupancy drop when the traffic is spread over a larger number of homogeneous paths, although the network performance improvement quickly saturates when the number of paths used increases. We find that the number of paths used in multipath routing should be small, say up to three. Besides, an optimal split of traffic occurs at paths with equal loads.

I. INTRODUCTION

The convergence of the computer, communications, entertainment, and consumer electronics industry is driving an explosive growth in multimedia applications [16]. Recent studies show that multimedia traffic exhibits variability or correlation on various time scales [3]. Such long-range dependence property has a considerable unpleasant impact on queuing performance, and is a dominant characteristic for a number of packet traffic engineering problems [7].

Multipath routing has recently been found to be an effective method to alleviate the effects of such traffic correlation [9]. Precisely, multipath routing or spatial traffic dispersion [4, 9, 18] is a load balancing technique in which the total load from a source to a destination is spatially distributed over several paths. However, packets which travel along different paths may arrive out of order. Those packets arriving out of order may have to be stored in a buffer, called a resequencing buffer, until they can be delivered to the end process in the proper order. This is called resequencing, which is an important issue associated with communications using multiple paths.

Multimedia applications generally have stringent quality of service requirements. Multimedia data generated by these applications must arrive correctly to the receiving end within a specified period of time in order to be useful. In addition, those data that do not satisfy such delay constraint have to be dropped with a certain percentage. To see whether and when multipath routing can have a better performance than single path routing, models are required to characterize the resequencing mechanism.

Existing work can be grouped into two major categories. The first category consists of work that characterizes the disordering network as a queuing system with several servers sharing a single queue [5, 6, 20]. In [20], the source node together with the set of outgoing links have been modeled as an $M/M/m$ queue with servers of different rates. The resequencing delay distribution and the average resequencing delay were derived. The model was then used to compare the performance of channel level and virtual circuit resequencing. In [5], the author extended the problem considered in [20] by allowing possibly different packet resequencing delays, the total packet delay, and the resequencing buffer occupancy drop when the traffic is spread over several paths. However, packets which travel along different paths may arrive out of order. Those packets arriving out of order may have to be stored in a buffer, called a resequencing buffer, until they can be delivered to the end process in the proper order. This is called resequencing, which is an important issue associated with communications using multiple paths.

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where \( t[R(m), m] \) is the inter-departure time between packets \( m \) and \( n \) at the source. Therefore, \( t[R(m), m], t[R(m), m] = \delta[R(m), m] \), where \( \delta \) is the bandwidth of path \( i \) in bits and \( \delta \) is the bandwidth of path \( j \) in bits per time unit.

Besides, two packets may arrive out of order only when they are sent on two different paths, i.e., \( R(m) \neq R(n) \). This is true by the in-order channel assumption, which states that if an arbitrary packet \( m \) is transmitted from the source before another packet \( n \) on the same path connecting the source to the destination, packet \( m \) will arrive at the destination before packet \( n \).

### III. RESQUEENCING MODEL

The resequencing delay of the arbitrary packet is determined by the maximum

\[ R_i(\cdot) \]

of the resequencing delay and total delay distributions. An estimation of the resequencing delay and total delay distributions can be found in [1].

Define another random variable \( I_{R(i)} \), where \( I_{R(i)} \) is the inter-arrival time to the system.

The total delay of each customer \( E \) in the system is defined as

\[ D_i + tR(i) \]

The discussion will proceed as follows. Section III-A discusses how to determine the resequencing delay and total delay distributions. An estimation of buffer occupancy distribution is presented in Section III-B.

### A. Determination of Resqueencing Delay and Total Delay Distributions

Because of the in-order channel assumption, the delay analysis can be greatly simplified to merely consider \( N - 1 \) packets by applying the following lemma.

**Lemma 1:** To determine the resequencing delay of an arbitrary packet, it is sufficient to consider the last packet to be transmitted before it on every path other than the one taken by it.

**Proof:** This has been proved in [19] for the case when the routing sequencing function is round robin. We are going to extend it to any general multipath routing discipline. The in-order channel assumption guarantees that the last packet transmitted before the arbitrary packet on a path other than the one taken by it arrives at the destination last among all packets transmitted before it on that path. The resequencing delay of the arbitrary packet is determined by the maximum time it waits for a packet that has been transmitted before it and received after it. Thus, it is sufficient to consider the last packet to be transmitted before it on every path other than the one taken by it.

Define the random variables \( D, R, \) and \( T \), be the end-to-end path delay, the resequencing delay, and the total delay incurred for a packet to be transmitted on path \( i \). Thus,

\[ T_i = D_i + R_i \]

Define another random variable \( I_{R(i)} \), be the inter-arrival time to the system. Suppose a packet transmitted on path \( i \) has to wait in the resequencing buffer until a packet transmitted on path \( j \) arrives. We call path \( j \) the bottleneck path of the packet transmitted on path \( i \). If such a bottleneck path does not exist, \( j = i \). The resequencing buffer occupancy distribution, \( P_R(t) \), can be derived by following these steps:

1. Derive the probability distribution of the resequencing buffer occupancy on the condition that those awaiting packets have been transmitted on path \( j \) after the tagged packet transmitted on path \( i \), \( P_A_j(t) \).
2. Deduce the probability distribution of the resequencing buffer occupancy on the condition that those awaiting packets have been transmitted on any paths other than path \( j \) before the tagged packet and the bottleneck path is path \( j \), \( P_A_j(t) \).
3. Determine the unconditional resequencing buffer occupancy probability distribution, \( P_R(t) \).
B.1 Evaluation of $P_{A(j|i)}(k)$

Suppose the random variable $G_j$ is the inter-arrival time of two consecutive packets transmitted on path $j$. Let the random variable $G_{k}^{*}$ be the sum of $k$ independent, identically distributed random variables, each of which is statistically identical to the random variable $G_j$. If $A(j|i)(k) = k$, this means that the first $k$ packets transmitted on path $j$ later than an arbitrary tagged packet transmitted on path $i$ arrive at the destination before it, and that the $(k+1)^{th}$ packet arrives after it. Thus, the probability mass function of the resequencing buffer occupancy on the condition that those awaiting packets have been transmitted on path $j$ after the tagged packet can be written as:

$$P_{A(j|i)}(k) = \begin{cases} \text{Prob}(D_{i} - D_{j} - I_{i,j} - G^{*}_{k}) < 0 & \text{if } j \neq i, k = 0, 1, 2, \ldots; \\ 1 \text{ otherwise.} & \text{if } j = i, k = 0; \end{cases}$$

where $\text{Prob}(D_{i} - D_{j} - I_{i,j} - G^{*}_{k}) < 0 = \int_{0}^{\infty} f_{D_{i}}(\psi) \otimes f_{D_{j}}(-\psi) \otimes f_{I_{i,j}}(\psi) \otimes f_{G^{*}_{k}}(\psi) \otimes f_{\psi}(\psi) \otimes f_{\psi}(\psi)$, and $f_{\psi}(\psi)$ denotes the $k$-folded convolution of $f_{G_{j}}(\psi)$.

B.2 Evaluation of $P_{M(q|i)}(k)$

Let random variable $M(q|i)$ denote the number of packets transmitted on path $q$ earlier than an arbitrary tagged packet transmitted on path $i$ and which arrive at the destination after it. The probability mass function of $M(q|i)$ can be given by:

$$P_{M(q|i)}(k) = \begin{cases} \text{Prob}(D_{q} - D_{i} - I_{q,i} - G^{*}_{k}) < 0 & \text{if } q \neq i, k = 0, 1, 2, \ldots; \\ 1 \text{ otherwise.} & \text{if } q = i, k = 0; \end{cases}$$

Given that $M(q|i) \leq u$, the conditional probability mass function of $M(q|i)$ can be determined as:

$$P_{M(q|i)}(k|u) = \frac{P_{M(q|i)}(k)}{\sum_{k=0}^{\infty} P_{M(q|i)}(k)}$$

If the tagged packet sees $n$ packets transmitted on path $i$ waiting in the resequencing buffer, it can be inferred that the maximum number of packets transmitted on path $q$ waiting in the buffer is:

$$w(n|q,i) = \left\lceil \frac{(n+1) \cdot p_{q}}{p_{i}} \right\rceil$$

If the tagged packet sees $n$ packets transmitted on path $i$ waiting in the resequencing buffer and the bottleneck path is path $j$, the maximum number of packets waiting in the buffer can be calculated as:

$$Y(j,i) = \sum_{q=1}^{N} w(n|q,i) - \frac{I_{j,i}}{Z}$$

where $G_i > I_{i,j}$, and $Z$ is the random variable denoting the inter-arrival time between any two successive packets to the system.

Given that the tagged packet sees $n$ packets transmitted on path $i$ waiting in the resequencing buffer, the probability mass function of the number of awaiting packets transmitted on any paths before the tagged packet and the bottleneck path is path $j$ can be written as:

$$P_{A(j|i)}(k|n) = P_Y(q,j) \otimes \left\lceil \sum_{q=1}^{N} w(n|q,i) - I_{q,i} \right\rceil$$

$$+ s_{j,k} P_{M(q|i)}(-k|w(n-1|q,i))$$

where $s_{j,k} = \text{Prob}(I_{j,k} > I_{j,i} \mid I_{q,i} \neq I_{j,i})$.

Denote $P_{m}(j|i)$ as the probability that path $j$ is the bottleneck path of the tagged packet transmitted on path $i$. It can be computed as:

$$P_{m}(j|i) = \begin{cases} \text{Prob}(D_{j} - D_{i} - I_{j,i} > 0) \cdot \left\lceil 1 - \sum_{q=1}^{N} \sum_{q \neq j} p_{m}(q|i) \right\rceil & \text{if } j \neq i; \\ 1 - \sum_{q=1}^{N} \sum_{q \neq i} p_{m}(q|i) & \text{otherwise.} \end{cases}$$

The probability that the tagged packet sees $n$ packets transmitted on path $i$ waiting in the resequencing buffer can be found as:

$$P_0(n|i) = \prod_{q=1}^{N} \sum_{k=0}^{\infty} P_{M(q|i)}(k)$$

$$- \left\lceil w(n|q,i) \right\rceil \cdot \frac{(n+1) \cdot p_{q}}{p_{i}} \cdot P_{(q|i)}(w(n|q,i))$$

$$- \sum_{k=0}^{n-1} P_{e}(u|i) - P_{m}(i|i)$$

Finally, the probability mass function of the number of awaiting packets transmitted on any paths before the tagged packet and the bottleneck path is path $j$ can be approximated as:

$$P_{A(j|i)}(k) \approx \sum_{n=0}^{\infty} P_{n}(n|i) \cdot P_{A(j|i)}(k|n) \frac{1}{1 - P_{m}(i|i)}$$

since we have used the average value of $P_0(n|i)$, instead of the corresponding value, conditioned on the bottleneck path being path $j$. We believe this approximation will not cause any inaccuracy.

B.3 Evaluation of $P_{B}(k)$

Denote random variable $A(j|i)$ as the total number of packets waiting in the resequencing buffer and seen by an arrival of a packet from path $i$ and the bottleneck path is path $j$. By using the results in Sections III-B.1 and III-B.2, the probability mass function of $A(j|i)$ can be calculated as:

$$P_{A(j|i)}(k) = \begin{cases} \bigotimes_{h=1}^{N} P_{A(h|i)}(k) & \text{if } j = i; \\ \bigotimes_{h=1}^{N} P_{A(j|i)}(k) \otimes \bigotimes_{h=1}^{N} P_{A(h|i)}(k) & \text{otherwise.} \end{cases}$$

By applying the law of total probability [10], the probability mass function of the resequencing buffer occupancy seen by a packet from path $i$ can be written as:

$$P_{B_{i}}(k) = \sum_{j=1}^{N} P_{m}(j|i) \cdot P_{A(j|i)}(k)$$

Further application of the law of total probability results in the resequencing buffer occupancy probability mass function:

$$P_{B}(k) = \sum_{i=1}^{N} p_{i} \cdot P_{B_{i}}(k)$$

where $k$ is any non-negative integer, and $\sum_{h=0}^{\infty} P_{h} = 1$.

The packet loss probability can also be estimated as follows. Let $B$ be the size of the resequencing buffer, which is in terms of packets. From the system point of view, it is more realistic to assume that packets are all fixed size. However, the loss probability of any packet from path $i$ can be approximated as:

$$P_{L_{i}}(k) \approx \text{Prob}(B_{i} \geq B) = 1 - \sum_{k=0}^{n-1} P_{B_{i}}(k)$$

since we have neglected the effect on the queueing performance due to lost packets because of overflow at the resequencing buffer.

Using the law of total probability, the packet loss probability can be computed as:

$$P_{L_{i}} = \sum_{i=1}^{N} p_{i} \cdot P_{L_{i}} \approx 1 - \sum_{i=1}^{N} \sum_{k=0}^{\infty} p_{i} \cdot P_{L_{i}}(k)$$
IV. END-TO-END PATH DELAY MODEL

Generally, a path consists of several hops. Traffic measurements on the ARPANET2 indicated that two sites were separated by 5.32 hops, on the average. Moreover, the distribution of round-trip delay appeared to be roughly normally distributed [14]. Modern high-speed networks are much more complex in terms of domain architectures and connectivity. Thus, the mean path length between any two sites in a high-speed network tends to be higher than the above value.

The central limit theorem [10] strongly suggests that the end-to-end path delay, which is the sum of a large number of independent hop delays, is approximately normally distributed. The mean and the variance of the end-to-end path delay provide sufficient information to generate an approximate distribution, which can then be utilized to compute the resequencing delay, the total delay, and the buffer occupancy distributions. This approach, which was used to solve the end-to-end percentile-type delay objective allocation problem for networks supporting Switched Multi-megabit Data Service (SMDS), has been shown to provide the best approximation to the reference values [17].

To complete our end-to-end path delay model, an L-hop path is modeled as a multiple-node M/M/1 tandem network as illustrated in Figure 3. L M/M/1 queues are connected in tandem. The ith queue receives input from two traffic sources: the tagged dispersed traffic of rate $\lambda_i$ and the interfering or background traffic of rate $b_i$. The service rate of the ith server is $\mu_i$. Denote $D$ and $\sigma_D^2$ as the mean and the variance of the end-to-end path delay. It can be shown [13] that:

$$D = \sum_{i=1}^{L} \frac{1}{\mu_i(1-\rho_i)} \quad \text{and} \quad \sigma_D^2 = \sum_{i=1}^{L} \frac{1}{\mu_i^2(1-\rho_i)^2}$$

where the utilization of the ith server, $\rho_i = \frac{k_i b_i}{\mu_i}$.

V. ANALYTICAL INVESTIGATION

This section discusses the numerical results based on the analytical expressions obtained in Sections III and IV. With the help of some numerical examples, we can illustrate the effectiveness of multipath routing by answering the three basic questions posed in Section I. Without loss of generality, packets, called cells, are all fixed size. The inter-sending time between any two consecutive cells from the source, denoted as the inter-cell spacing time, is a constant. A path is modeled as a five-node M/M/1 tandem network. Each server serves a packet with an average service time of one time unit. Its end-to-end path delay is assumed to be Gaussian or normally distributed with its mean and variance computed from the path model exhibited in Section IV.

The results are provided in two sets. The first set studies the effectiveness of multipath routing with different number of homogeneous paths used, where the relative load to each path is the same. It provides the mean total delays, the mean path delays, the mean resequencing delays, the mean resequencing buffer occupancies, and the bounds on the complementary functions for the resequencing buffer occupancies, for each of the 40 cases (two background loads, two inter-cell spacing times, and ten path configurations). It also provides the resequencing buffer distributions for three cases (three path configurations). The second set studies the effectiveness of multipath routing using two heterogeneous paths, with possibly different relative loads according to a given dispersion ratio. The study includes the mean total delays, the mean path delays, the mean resequencing delays, the mean resequencing buffer occupancies, and the bounds on the complementary functions for the resequencing buffer occupancies, for each of the eight cases (eight dispersion ratios).

We examine the first set of results. Figure 4 shows the mean total delays, the mean path delays, and the mean resequencing delays. Two different background loads, namely link utilizations of 0.5 and 0.75, and two different inter-cell spacing, namely five and ten time units, are chosen. The mean total delay and the mean path delay drop as the number of paths used increases. Clearly, the decrease in the mean path delay comes from the decrease in utilization of each path. However, the improvement flattens with further increases in the number of dispersed paths. Surprisingly, the mean resequencing increases slightly and then flattens (or falls slightly) as the number of paths used increases. This results from the fact that when the number of dispersed paths is sufficiently large (say three), the fluctuation of delays between different paths is offset by the reduction in variances of path delays. Furthermore, the performance improvement is more significant when inter-cell spacing is smaller, as the load from the dispersed traffic to each path is higher. Thus, multipath routing is effective in performance improvement when the dispersed traffic load and the network load are both high.

Figure 5 exhibits the mean resequencing buffer occupancies, and two bounds of their complementary distributions, namely at 10^{-6} and 10^{-6}. They represent, to some extent, the system cost of multipath routing, because network administrators need to allocate sufficient buffer resources before a multipath connection can be established. From the figure, the mean resequencing buffer occupancy flattens as the number of dispersed paths increases, but this may not be the case when a cell loss bound is considered. This means that in order to provide the cell loss quality of service guarantee, possibly a much larger buffer size has to be allotted for resequencing when a larger number of dispersed paths is used. Besides, the probability distribution of the resequencing buffer occupancy tends to have a heavier tail for the cases when a larger number of paths is used, as shown in Figure 6. Thus, this argument does not favor using a large number of paths, say more than three, in multipath routing.

The second set of results demonstrates how to adjust the load distribution to each dispersed path to further improve the performance. Consider there are two heterogeneous paths, with background traffic of different loads. Define $R$ as the dispersion ratio such that cells are transmitted on these two paths in a ratio of $R:1$. Our result in Figure 7 shows that the resequencing delay and the resequencing buffer occupancy attain their minima when the total traffic load along these paths are the same. In other words, an optimal split of traffic is to ensure that the total load of each dispersed path is more or less the same, which is intuitively satisfying.

VI. CONCLUSIONS

In this paper, we have proposed a framework to study the resequencing mechanism in high-speed networks. This framework allows us to estimate the packet resequencing delay, the total packet delay, and the resequencing buffer occupancy distributions when traffic are dispersed on multiple disjoint paths.
The traffic model has been constructed in a flexible manner so that any multipath routing mechanisms can be modeled easily. The resequencing model has been devised to allow us to compute all necessary performance metrics for a tandem network with unreliable components. Proceedings of the Eighth Annual International Phoenix Conference on Computers and Communications, pp. 231-235, Scottsdale, AZ, USA, 22-24 March 1989.


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