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Economics of Internet Packets

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Abstract

In this paper, the economics of packet transfer over the Internet is studied. Packet transfer costs are investigated in detail, based on a simple model restricted to packet transfers in message communications, one of the important applications on the Internet. The packet switching scheme examined is the store-and-forward type, and the queuing system in routers is assumed to be $(M/M/1)^S/N$ with a finite waiting capacity. The numerical results of packet transfer cost examples are shown and optimum packet size for message communications is studied, showing that several kilobytes is the optimum packet size.

1. Introduction

The Internet is now used in many areas of human social activity. Its basic technological concepts, architecture prototype and digital packet switching principle were conceived of by Paul Baran, as shown in the RAND Corporation's URL or Memorandum (Baran, 1964) (Smith, 1964). He published a series of studies between 1960 and 1962, which were published together in 1964, as a part of The Rand Corporation study reports, based on research sponsored by the United States Air Force. Accordingly, the concepts were originally designed for application to military communications networks. Since then, various protocols and digital communications technologies have been developed and applied in the Internet. Now, the so-called Internet, over which communicated data is transferred in the form of packets, has become very popular, and is one packet switched network in that meaning.

In this paper, the economics or cost problems of the Internet or packet switched networks are studied. Two approaches can be used to consider the economics of communications networks. One is a macro approach, involving total cost estimation based on a hypothetical network construction under certain assumptions, including resource configuration in the network, and traffic exchange conditions between covered areas. This is a realistic assumption, and accordingly may be suitable for proceeding directly to network construction. Another is a micro approach, which uses a detailed cost evaluation method to examine resource volume utilized for the purpose of packet transfers. This approach may contribute to obtaining quantitative information such as relative resource volume and relative quantity of cost components. This paper adopts the latter approach.

Packet transfer cost is examined in detail based on a simple model restricted to packet transfers in message communications, one of the important applications used on the Internet. Packet switching scheme is assumed to be of a store-and-forward type for cost evaluations.

In Section 2, the cost components of packet transfer are listed, the evaluation method for total cost of message transfer is introduced, and changes in the total cost are shown as packet size changes. The term "packet size" means maximum user data length in packets.

In Section 3, numerical examples are shown based on the analyses in Section 2. At the same time, optimum packet size for message communications is discussed.

2. Network Resources and a Model for Cost Estimation

2.1 One-Link Transfer Model of Packets

Packet transfers between two end hosts on the Internet are transit-switched repeatedly over one-link transfers, as shown in Figure 1. The essential resources for packet switching on the Internet consist of processors, buffer memory in routers distributed over the network, and transmission lines between routers or between routers and hosts. These resources in the one-link packet transfer model are shown in Figure 2. The packet transfer cost over one link consists of the following three components: processing cost for sending the packet from the sending router and receiving it in the receiving router, buffer memory cost in both routers, and transmission line cost.

For cost evaluation, it is necessary to calculate the time during which resources are occupied by the packet. In the case of the store-and-forward switching scheme, a packet is not sent to the next link until it has been completely received by the router as a whole packet frame, from header to trailer. If all the output transmission lines are occupied by other packets, the packet in question must be queued in the sending router. Normally, when the packet transfer over the link begins, the receiving router must be ready to place the packet into buffer memory space. This process is shown in Figure 3.

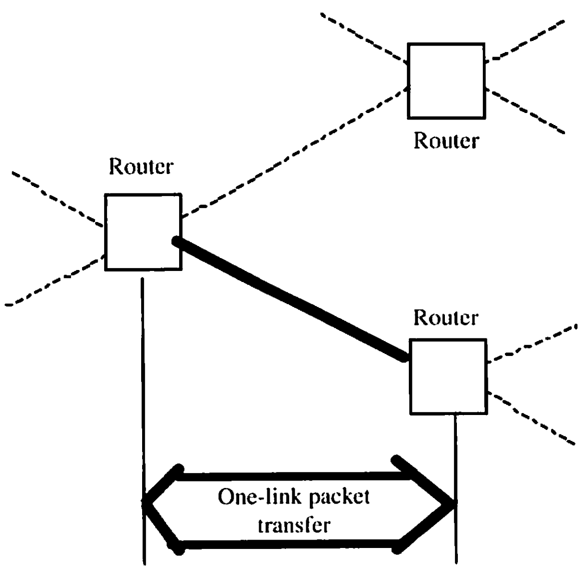

Figure 1. One-link Transfer Model

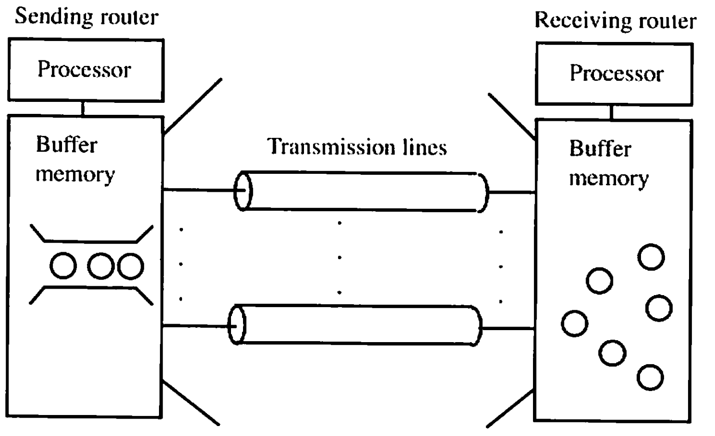

Figure 2. Resources in a One-link Transfer Model

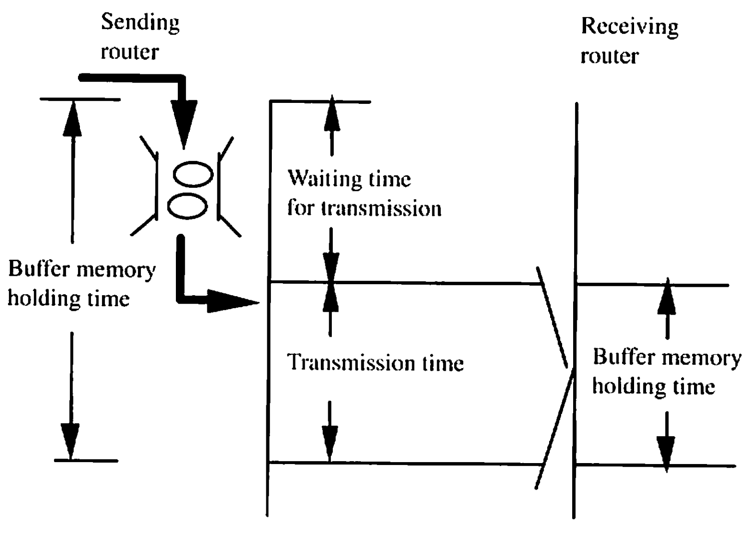

Figure 3. Relationship between Buffer Memory Holding Time and Waiting Time for Transmission, and Transmission Time in a Store-and-Forward Switching Scheme

2.2 Assumptions

The following factors are assumed:

(1) The packet length for message communications is assumed to be constant at P. Here, let all the message lengths be fixed at I, and a message is assumed to be divided into I/P packets. For simplicity, the fraction effect caused by packetizing (assembling a plural number of packets in a prescribed format from a message) bulk messages is ignored, based on the assumption that message length is quite long.

(2) Packets of message communications originate in a Poisson process with parameter A. All the packets split from messages arrive at the send queue in a branching Poisson process if the number of packets included in the message obeys a geometric distribution. However, the packet arrival process for message communications is assumed to be Poissonian with parameter $a = AI/P$. That is, the branching Poisson

process is approximated by a Poisson process under a condition where the input-to-output transmission line speed ratio is less than 1/4. This condition is satisfied, considering that the transmission rate between routers is generally higher than that between router and message communication terminals.

(3) The buffer memory area in a router is shared by packets moving to and from all transmission lines accommodated in the router. Buffer memory utilization γ is assumed to be a fixed value such that buffer memory overflow probability can be suppressed to a certain small value.

(4) In the sending router, the buffer memory is occupied by a packet from its moment of its arrival in the send queue to the instant when its transmission is completed. In the receiving router, the buffer memory is occupied by the packet during its transmission time.

(5) The packet length is assumed as equal to the sum of user data length to be carried by packets plus header and trailer length P_H.

(6) The transmission rate of all the transmission lines is V and the transmission error rate of the transmission lines is negligibly small. Packets are transmitted according to a first-in-first-out rule.

(7) For simplicity, processing time for packet sending and receiving is assumed as constant.

2.3 Estimation of Buffer Memory Utilization

From assumptions (2) and (4), packets in the sending and receiving routers are queued in a parallel $M/D/1$ queuing system with a finite shared waiting room capacity N, which is denoted by $(M/D/1)^S/N$. Regrettably, such a system has never been solved theoretically, and accordingly an $(M/M/1)^S/N$ queuing system is assumed as a fairly good approximation for the estimation of buffer memory utilization.

From the viewpoint of network customers, packet loss probability on the Internet must be as small as possible. Buffer memory overflow is a primary cause of packet loss, and accordingly buffer overflow rate should be controlled below a certain limit B. Overflow rate in $(M/M/1)^S/N$ is as follows:

$$B = \frac{\dfrac{(N+s-1)!}{N!(s-1)!} \cdot \rho^N}{\displaystyle\sum_{i=0}^{N} \frac{(i+s-1)!}{i!(s-1)!} \rho^i} = \frac{\dfrac{(N+s-1)!}{N!} \rho^N}{\displaystyle\sum_{i=0}^{N} \frac{(i+s-1)!}{i!} \rho^i},$$

where ρ is average transmission line utilization. From this equation, the smallest necessary volume of buffer memory cannot be calculated analytically, and therefore can only be obtained by numerical analysis.

The average number $\bar{N}$ of packets in $(M/M/1)^S/N$ corresponding to the average number of packets in the sending router, is as follows:

$$\bar{N} = \frac{\displaystyle\sum_{k=1}^{N} \frac{(k+s-1)!}{k!} k\rho^k}{\displaystyle\sum_{i=0}^{N} \frac{(i+s-1)!}{i!} \rho^i} = \frac{\displaystyle\sum_{k=0}^{N-1} \frac{(k+s)!}{k!} \rho^{k+1}}{\displaystyle\sum_{i=0}^{N} \frac{(i+s-1)!}{i!} \rho^i}.$$

Accordingly, the buffer memory utilization γ of the sending router is as follows:

$$\gamma = \frac{\bar{N}}{N} .$$

The buffer memory utilization vs. the transmission line utilization is shown with the parameter s, which is the number of parallel transmission lines between the sending and receiving routers in Figure 4.

2.4 Relationship between Resource Utilization and Cost

In order for a system to be useful during actual operation, the amount of resources available — processor, buffer memory, and transmission lines — should be above what is actually utilized. For example, if the transmission line utilization is 70% and there are 10 transmission lines, as shown Figure 4, average buffer memory utilization must be kept under 50% in order to keep buffer overflow probability up to 0.0001. In this case, about two times as much buffer memory is necessary.

In general, the utilization cost of each resource should be added up, including the cost of this additional volume. In other words, the evaluation cost should be calculated as the sum of the costs of actually utilized resources and additional resource capacity, and definitely calculated as the value of actual utilization costs divided by the utilization of each resource.

2.5 Average Holding Time of Transmission Lines and Use of Buffer Memory

The transmission time of each packet is as follows:

$$T = \frac{P + P_H}{V} .$$

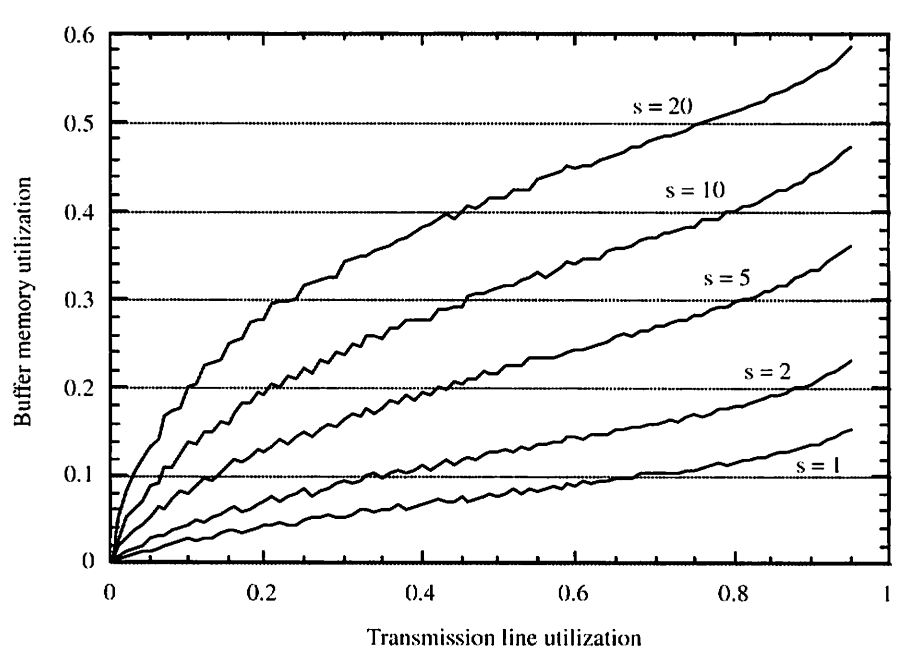

Figure 4. Buffer Memory Utilization of Routers

Assuming that a queuing system in the sending router is modeled approximately in *M/D/1* for the same reason as in 2.3, the average waiting time of each packet in the sending router is as follows:

$$W = \frac{\rho T}{2(1-\rho)} = \frac{\rho(P+P_H)}{2(1-\rho)V}.$$

Accordingly, the total average buffer memory holding time for a one-link packet transfer in the sending and receiving routers is as follows:

$$W + 2T = \frac{(4-3\rho)(P+P_H)}{2(1-\rho)V}.$$

2.6 Cost of Packet Transfer of Message Communications

The necessary cost C for the packet transfer of a single message over one-link, as modeled in 2.1, is represented by the following equation:

$$C = C_P + C_M + C_T,$$

where, C_P, C_M, and C_T stand, respectively, for the processing, buffer memory, and transmission cost necessary for all the packets split from a single message.

Packet processing cost C_P is proportional to the number of packets per message and represented as

$$C_P = \frac{K_P I}{P},$$

where K_P and I are processing cost for packet sending and receiving and the length of a single message, respectively.

Buffer memory cost C_M is proportional to the average holding time of buffer memory, buffer memory size, and number of packets per message, and is inversely proportion to the buffer memory utilization:

$$C_M = \frac{K_M(P+P_H)I}{P\gamma V}(W+2T) = \frac{K_M(4-3\rho)(P+P_H)^2 I}{2(1-\rho)P\gamma V},$$

where K_M is cost of buffer memory per unit volume and per unit time.

The transmission cost C_T is proportional to the packet transmission time and number of packets per message, and is inversely proportion to the transmission line utilization and rate of the transmission lines:

$$C_T = \frac{K_T I(P+P_H)}{P\rho V},$$

where K_T is the cost of the transmission line per unit time. This parameter of transmission cost is naturally dependent on the distance between the sending and receiving routers, and here the distance is assumed as fixed.

In estimating the cost for packet transfer as shown so far, K_P, K_M, and K_T are proportional constants of the various cost components and valuable parameters. Not only do the absolute values of these parameters affect the total packet transfer cost, but also the ratio between these parameter values affects which cost component is dominant. Further, we should not overlook the fact that these parameter values vary with time and with technological progress.

3. Numerical Examples

3.1 Numerical Examples of Cost Components and Total Cost

Based on the results in the previous chapter, a calculated numerical example is shown in Figure 5, with the following assumptions:

Rate of transmission lines: $V = 192$ kBytes/s,
Transmission line utilization: $\rho = 0.7$,
Length of packet header and trailer: $P_H = 50$ Bytes,
Number of transmission lines: $s = 5$,
Overflow probability of buffer memory: $B = 0.001$, and
Cost parameter ratio: $K_P : K_M : K_T = 1000 : 1 : 320000$.

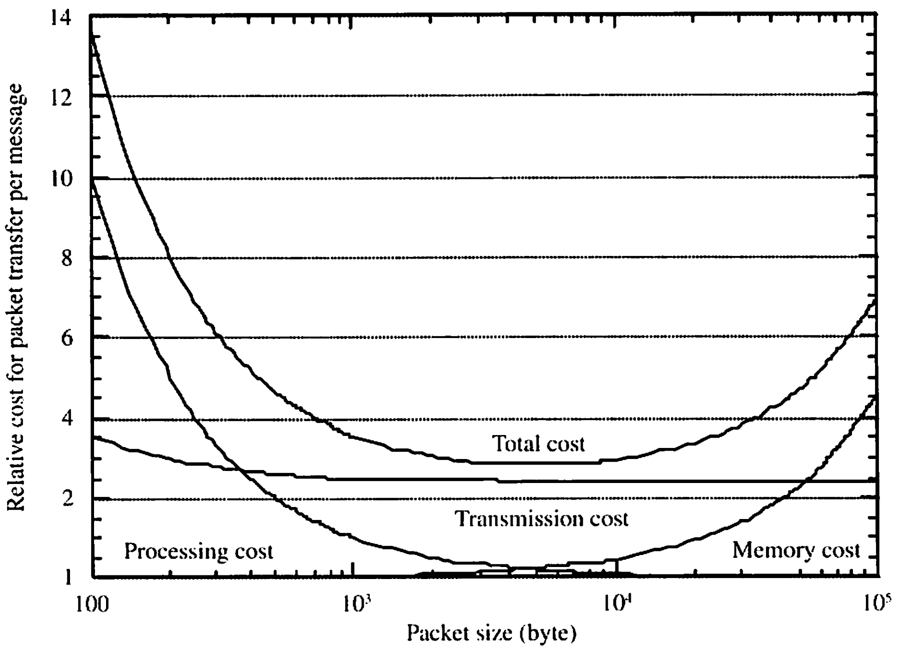

Figure 5. Packet Transfer Cost for Message Communications

Among the components of packet transfer cost, processing and transmission costs decrease as packet size increases. The decrease in processing cost is remarkable, whereas the decrease in the transmission cost component is very gradual. Although the processing cost component is inversely proportion to packet size, the transmission cost component decreases with inefficiency owing to overhead in packet format. In other words, packet header length decreases as packet size increases. On the other hand, the memory cost component increases in proportional to packet size, because buffer memory size per packet increases, and in addition, the occupation time of buffer memory in routers increases with packet size.

3.2 Optimum Packet Size and Its Dependency on Cost Ratio

As seen from Figure 5, the curve representing total cost is concave with a comparatively wide bottom range, and the packet size corresponding to the minimum total cost is several kilobytes. The optimum packet size for minimizing the cost of packet transfer for message communications is analytically determined by the following equation:

$$\frac{dC}{dP} = 0.$$

Therefore, optimum packet size P_{opt} is as follows:

$$P_{opt} = \sqrt{\frac{2(1-\rho)(K_T P + K_P \rho V)\gamma}{K_M \rho (4 - 3\rho)} + P_H^2}.$$

Accordingly, optimum packet size depends on the values of cost parameters K_P, K_M, K_T, and in particular their ratio. As shown in Figure 5, the transmission cost component hardly contributes to the optimum packet size. Under the fixed value $K_T = 320000$, the optimum packet size is plotted in Figure 6, with a variable cost parameter ratio $K_P / K_M = 10\text{~}10^5$.

4. Conclusion

In this paper, a cost evaluation method was developed and numerical results shown based on a simple model limited to message communications on the Internet. The actual Internet environment is very different from that assumed here. However, it is true that a large packet size is better, or more efficient, for message communications including file transfer applications from an economic viewpoint. Heterogeneous packet switching sys-

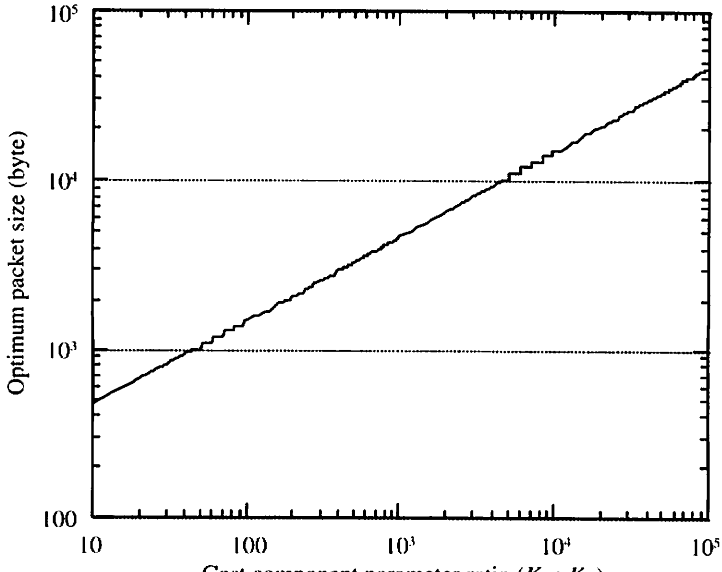

Figure 6. Dependency of Optimum Packet Size on Cost Ratio

tems have was discussed in an earlier paper (Yoshida, 1980), which treats not only the large packet size studied in this paper but also ordinary packet sizes.

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