行政院國家科學委員會專題研究計畫成果報告

未來高速多媒體導向 Internet 之
下一代寬頻路由器架構設計與分析研究 －(2/2)
Research on Design and Analysis of Next-Generation Broadband Router Architecture in Future High-Speed Multimedia-Oriented Internet – (2/2)

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一、中文摘要

此為一兩年期計畫之第二年計畫，主要之目的係延續上一年之研究成果，研究下一代寬頻路由器架構設計與分析。

關鍵詞：路由器、寬頻、網際網路

Abstract

This project is the second part of a two-year project. The main purpose is to study the design and analysis on the next-generation broadband router architecture based on the research results made in the first year.

Keywords: Router, Broadband, Internet

二、緣由與目的

下一代寬頻路由器絕對是未來高速多媒體導向網際網路之瓶頸，而下一代寬頻路由器之架構扮演著核心部份，其重要性不言可喻，全世界均在關注。本計畫之主要目的就是為了探討此主體，提出具體之結果，產生實質之貢獻。

三、研究報告

Introduction

It is well-known that the bottleneck of Internet is the router. If we can increase the processing power of router, the throughput of global Internet will be improved considerably. Although the processing power of router's hardware is enhanced rapidly, the limit will be reached soon. On the other hand, the traffic on Internet is growing quickly. This situation is similar to that of computer architecture. It is very clear that multiprocessor is an effective solution to the computer organization. Similarly, it might be one of the best approaches to have a generalized multi-module next-generation broadband switching router system architecture for future multimedia-oriented Internet in order to achieve high performance. In this paper, we propose this expected switching router system architecture based on [9]. In addition, we use queueing theory to evaluate the proposed architecture; we conduct queue length, waiting time and throughput analyses. Furthermore, because some packets entering router might be lost, the transmission rate is analyzed and Pollaczek-Khinchin (P-K) transform equation well-known in the traditional queueing theory is generalized.

The rest of this paper is organized as follows. In Section 2, we propose the generalized multi-module next-generation broadband switching router system architecture. In Section 3, we conduct the queue length analysis. In Section 4, we analyze the waiting time. In Section 5, we discuss the throughput. Furthermore, in Section 6, we calculate the transmission rate and performance. Finally, some conclusions are made.

Generalized Multi-Module Next-Generation Broadband Switching Router System Architecture

The generalized multi-module next-generation broadband switching router system architecture, illustrated in Fig. 1, has N input lines, N output lines and M same router modules [9]. Assume that the packets arrive randomly at any particular input line with an average rate of λ packets per time slot. Each packet has equal probability 1/N of being destined for any output line. Every packet in $Q_{i,j}$ arrives from the i-th input line, and will be destined for the j-th output line. The average rate of packet arriving into $Q_{i,j}$ is λ/N packets per time slot. Similarly, every packet in $Q_{i,j}$ will be served by one of M router modules. Each module has the same chance to serve any packet in $Q_{i,j}$. If one packet in $Q_{i,j}$ is served by the k-th module, it will be transmitted into $Q_{i,j,k}$. In other words, $Q_{i,j,k}$ denotes the queue where the packets are coming from the i-th input line, destined for the j-th output line, and served by the k-th router module. The average rate of packet entering $Q_{i,j,k}$ is λ/MN packets per time slot.

Let the random variable A_T denote the number of packets arriving in $Q_{i,j,k}$ during T-based time slot. The arriving process can be modeled as Poisson Process [1, Sect. 2-1]. And, we have the following.

$$\Pr[A_T = k] = \frac{((\lambda / MN)T)^k e^{-(\lambda / MN)T}}{k!}, \text{ k=0, 1, 2, …} \tag{1}$$

Let T_r–based time slot denote the time to transmit one packet through the router module, if there are more than one packets in $Q_{i,j,k}$. Equation (1) can be modified as Equation (2).

$$\Pr[A_{T_r} = k] = \frac{((\lambda / MN)T_r)^k e^{-(\lambda / MN)T_r}}{k!}, \text{ k=0, 1, 2, …} \tag{2}$$

From Equation (2), its mean value is $(\lambda/MN)T_r$. The average number of packets arriving in any given particular input line during T_E–based time slot in the steady state is P, where $0<P\le 1$, that is,

$$\lambda T_E = P \tag{3}$$

From Equation (3), we can rewrite Equation (2) as

$$\Pr[A_{T_r} = k] = \frac{((P / MN)n_r)^k e^{-(P / MN)n_r}}{k!}, \text{ k=0, 1, 2, …} \tag{4}$$

where

$$n_r = \frac{T_r}{T_E} \tag{5}$$

The probability generating function (PGF) of Equation (4) is derived as follows.

$$A_{T_r}(z) = e^{\left(-n_r P/_{MN}\right)(1-z)} \tag{6}$$

For each router module, packets of N queues are put into one queue. The queues, which are destined for the j-th output line for the k-th router module, are $Q_{1,j,k}$, $Q_{2,j,k}$, $Q_{3,j,k}$, …, and $Q_{N,j,k}$. Let $B_{j,k}$ denote the number of packets which are destined for the j-th output line and served by the k-th router module, and $A_{i,j,k}$ denote the number of packets in $Q_{i,j,k}$, during a T_r-based time slot. We obtain

$$B_{j,k} = \sum_{i=1}^{N} A_{i,j,k} \tag{7}$$

We take the exponent of z on both sides of Equation (7), and obtain the following equation.

$$z^{B_{j,k}} = z^{\sum_{i=1}^{N} A_{i,j,k}} \tag{8}$$

By the definition of PGF, $z^{B_{j,k}}$ is equal to $B_{j,k}(z)$, and $z^{A_{i,j,k}}$ is equal to $A_{i,j,k}(z)$. The PDFs of $A_{i,j,k}$, where $1\le i\le N$, are the same as Equation (4), and the PGFs of $A_{i,j,k}$, where $1\le i\le N$, are the same as Equation (6), too. Then, we can derive the following equation.

$$B_{j,k}(z) = \prod_{i=1}^{N} A_{i,j,k}(z) = e^{\left(-n_r P/_M\right)(1-z)} \tag{9}$$

Queue Length Analysis

Let $Q_{m_{j,k}}$ denote the number of packets which are destined for the j-th output line and queued in the k-th router module at the end of the m-th T_r-based time slot, and $B_{m_{j,k}}$ denote the number of packet arrivals in $B_{j,k}$ during the m-th T_r-based time slot. Consider two cases occurring in the physical transmission in $Q_{j,k}$. They are illustrated in Figures 2 and 3.

From Figures 2 and 3, we have

$$Q_{(m+1)_{j,k}} = \max\left(0, Q_{m_{j,k}} + B_{(m+1)_{j,k}} - 1\right)$$

From Appendix A, we obtain the PGF of $Q_{j,k}$ for the steady-state queue size:

$$Q_{j,k}(z) = \frac{(1 - E(B_{j,k}))(1-z)}{B_{j,k}(z) - z}$$

Substituting $E(B_{j,k})$ and Equation (9) into Equation (11), we have

$$Q_{j,k}(z) = \frac{\left(1 - {n_r P}/_M\right)(1-z)}{e^{\left(-n_r P/_M\right)(1-z)} - z}$$

Differentiating Equation (12) and letting z→1, we have

$$\overline{Q_{j,k}} = \frac{\left({n_r P}/_M\right)^2}{2\left(1 - {n_r P}/_M\right)} \qquad when\ \frac{n_r P}{M} < 1$$

From Equation (13), it is interesting that when $(n_r P/M)\ge 1$, $\overline{Q_{j,k}}$ will go to infinite or be negative. This situation can be explained physically, because $n_r P/M$ is the mean arrival number of packets, and 1 is the fixed transmission rate, during one T_r-based time slot. If $(n_r P/M)\ge 1$, the mean arrival number of packets is larger than the fixed transmission rate during one T_r-based time slot. The mean queue length of $\overline{Q_{j,k}}$ is nonsense and will go to infinite, when $(n_r P/M)\ge 1$.

The total mean queue length, where these queues are destined for the j-th output line, is the summation of $\overline{Q_{j,k}}$, where k=1, 2, …, M. Let $\overline{Q_j}$ denote the total mean length of these queues destined for the j-th output line. We obtain $\overline{Q_j}$ as follows.

$$\overline{Q_j} = M \cdot \frac{\left({n_r P}/_M\right)^2}{2\left(1 - {n_r P}/_M\right)} = \frac{(n_r P)^2}{2(M - n_r P)} \qquad when\ \frac{n_r P}{M} < 1$$

From Equation (14), it is obvious that $\overline{Q_j}$ will decrease when M increases. Because each Q_j has the same mathematical form, let $\overline{\ }$ denote this mathematical form, where $1\le j\le N$. The mean queue length $\overline{\ }$, as a function of P, is shown in Fig. 4. It is obvious that the total mean queue length will increase if n_r increases. But, if we add some router modules into this architecture, the total mean queue length will decrease down significantly.

Using the Markov chain state transition diagram, the queue size of $Q_{j,k}$ can be illustrated in Fig. 5.

Where

$$b_i = \Pr\left[B_{j,k} = i\right] = \frac{\left(n_r P / M\right)^i}{i!} e^{-\left(n_r P / M\right)} \qquad i = 0, 1, 2, \ldots$$

The matrix of transition probabilities Ψ is derived as Equation (16).

$$\psi = \begin{bmatrix} b_0 + b_1 & b_2 & b_3 & b_4 & \cdots \\ b_0 & b_1 & b_2 & b_3 & \cdots \\ 0 & b_0 & b_1 & b_2 & \cdots \\ 0 & 0 & b_0 & b_1 & \cdots \\ 0 & 0 & 0 & b_0 & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{bmatrix}$$

Let $q_{j,k}$ denote the random variable of the p.d.f. of $Q_{j,k}$. Φ is the vector of the state probability, that is, $\Phi=\{\Pr[q_{j,k}=0], \Pr[q_{j,k}=1], \Pr[q_{j,k}=2], \ldots\}$. We have $\Phi=\Phi\Psi$. From the Markov chain balance equations, we have Equation (17).

$$\Pr\left[q_{j,k} = 1\right] = \frac{1 - b_0 - b_1}{b_0} \cdot \Pr\left[q_{j,k} = 0\right]$$

$$\Pr\left[q_{j,k} = 2\right] = \frac{1 - b_1}{b_0} \cdot \Pr\left[q_{j,k} = 1\right] - \frac{b_2}{b_0} \cdot \Pr\left[q_{j,k} = 0\right]$$

$$\vdots$$

$$\Pr\left[q_{j,k} = n\right] = \frac{1 - b_1}{b_0} \cdot \Pr\left[q_{j,k} = n - 1\right] - \sum_{i=2}^{n} \frac{b_i}{b_0} \cdot \Pr\left[q_{j,k} = n - i\right]$$

From Equation (12) and the definition of PGF, we obtain **Pr**$[q_{j,k}=0]$ as follows.

$$\Pr\left[q_{j,k} = 0\right] = \left(1 - n_r P / M\right) \cdot e^{n_r P / M}$$

Substituting Equation (18) into Equation (17), we have

$\Pr[q_{j,k}=1], \Pr[q_{j,k}=2], \ldots$, iteratively.

$$\overline{Q} = \frac{n_r P\left[\frac{n_r P}{M} - r(r-1)\right]}{2\left(r - \frac{n_r P}{M}\right)}$$

Conclusions

The traffic on Internet is growing rapidly [8] and the router is the main bottleneck on Internet. It is noted that there are two advantages in our proposed generalized multi-module broadband switching router system architecture. One is to achieve high performance of the router. The other is to expand capability of router easily and flexibly, even if the traffic on Internet grows in the future. It is very interesting that if there are sufficient router modules, the throughput of the proposed router system can achieve 1. It means that the router system is not the bottleneck of the global Internet, even the traffic grows.

In the real situation, the time slot of one packet entering the router system may be different from that of transmitting one packet through it. This characteristic is considered in our proposed switching router system architecture and in the performance analyses, such as queue length, waiting time and throughput. In addition, a packet entering the router system may be lost. Therefore, the transmission rate is another important characteristic considered in this paper. If the characteristic is considered, the performance of the router system is affected. Pollaczek-Khinchin (P-K) transform equation is a well-known one in traditional queueing theory. In this paper, we generalize the P-K transform equation to analyze the performance of router system by considering some characteristics, such as transmission rate, etc. Furthermore, we present a thorough and detailed discussion on the performance by using the generalized P-K transform equation under the consideration of the characteristics.