Buffered Fixed Routing: A Routing Protocol for Real-Time Transport in Grid Networks

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***Abstract*—In this paper we propose a new routing protocol called buffered fixed routing (BFR) for real-time applications on grid networks. While previous routing protocols for grid networks have been designed to improve network throughput, the BFR scheme is proposed to guarantee the end-to-end packet delay and sequencing without loss by using finite buffers at each node. Thus the proposed scheme can satisfy quality-of-service (QoS) requirements of real-time applications. The BFR scheme uses the token on the row ring to provide QoS guarantees. The performance of the BFR scheme is analyzed by using the Geom/Geom/1 queueing system under uniform traffic. In the simulation, the BFR scheme shows the zero-loss, high-throughput performance with the minimum delay variation compared to other routing protocols such as store and forward routing, deflection routing and vertical routing. In addition, it has shown the smallest average delay at intermediate and heavy loads.**

***Index Terms*—Communication network, protocol, routing, routing protocol.**

I. INTRODUCTION

THE OPTICAL network communication is one of the most promising technologies to meet the large bandwidth requirement of future applications. In recent years, a lot of work has been done for optical networks in the research and commercial areas [1]–[12].

The technologies to increase the transmission speed in optical networks can be classified according to the multiplexing method: wavelength-division multiplexing (WDM) and optical time-division multiplexing (OTDM) [1]. Among these, the WDM technology is considered to provide a realistic solution to utilize the abundant bandwidth of the optical fiber. This is because it allows the network to be logically configured in an arbitrary topology independent of its physical connectivity and allows nodes to have electric buffers for packet processing [7], [8].

Optical networks are classified into single hop and multihop networks according to the routing style [1]. Among multihop networks, those with the regular topology attract much attention since their regular structures simplify the routing procedure. Most of the previous works done on multihop networks have been dedicated to maximize overall network throughput only [1]. However, a variety of current and future network services require different levels of QoS, and they require guarantees for the level of service to be maintained during calls. In specific, real-time applications are insensitive to packet loss, but sensitive to packet delay and sequencing.

We briefly describe the previous routing protocols for grid networks and point out the problems they have. Shortest path routing (SPR) [9] is classified into store and forward routing (SFR) and deflection routing (DR) according to whether it uses the routing buffer. SFR uses the routing buffer to hold one of the two contending packets when a contention occurs. SFR shows higher throughput because packets travel through only the shortest paths to reach the destination. However, it requires an infinite size of buffers at each node for lossless communication. As a result, the end-to-end delay cannot be bounded. Furthermore, since there may exist several shortest paths between a source and destination pair, packet sequencing is not guaranteed.

DR is the routing protocol devised for all optical networks where buffering is difficult. It resolves contention by deflecting one of the two contending packets to *an alternative path* instead of buffering it. It cannot satisfy the packet delay and sequencing requirements due to the uncertainty inherent in deflection. Moreover, it shows lower throughput than SFR.

Vertical routing (VR) has been proposed to satisfy the packet delay requirement [4]. VR gives up using the shortest paths. In the VR scheme, an accepted packet proceeds along the row first. Then it turns to the column direction if it meets the destination column where the destination resides, and it proceeds along the column. A row packet has higher priority than a column packet in contention. This means that the column packet is deflected to the row direction when it contends with the row packet. The deflected column packet has become a row packet and naturally has priority at the next contention. The delay bound of VR is N hops for a network of N nodes. VR has less processing overhead than SPR. However, VR shows even lower throughput than DR because packets do not travel through the shortest paths. Moreover, it cannot preserve packet sequencing because it cannot be anticipated how many deflections occur during the delivery. Each deflection in VR costs additional N hops where N is equal to the number of columns of a given network. Thus the deflection cost of VR is larger than that of DR which is 4 hops regardless of the network size [3].

The protocols described above are not suitable for real-time applications because of their inherent pros and cons. In this paper, we propose BFR, a new routing scheme that is suitable for real-time packet transmission due to its ability to guarantee the end-to-end packet delay and packet sequencing. BFR utilizes a finite size of buffers to achieve and guarantee QoS for real-time services.

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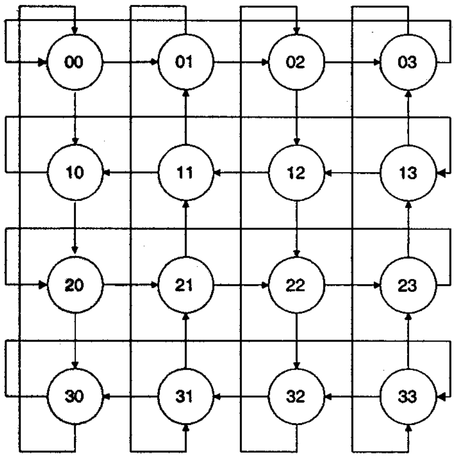

Fig. 1. 4×4 Grid network.

We assume that the considered network for BFR has a grid structure. Since various network structures including the Shufflenet can be transformed to an orthogonal ring structure which can be decomposed into row and column rings, BFR can be applied to many kinds of multihop networks. Fig. 1 shows an example of the grid network called a Manhattan street network or a torus.

This paper is organized as follows. In Section II, the BFR scheme is proposed. Section III analyzes the performance of BFR. Section IV presents a comparative study of SFR, VR, DR, and BFR in terms of throughput and delay followed by the conclusion in Section V.

II. BFR (Buffered Fixed Routing)

BFR routes packets through the fixed routes between source and destination nodes. It puts priority on row packets over column packets in contention as VR does. However, each node has a routing queue of a finite size and holds contending column packets which would otherwise be deflected in VR.

Fig. 2 shows the node structure of BFR. A row packet never experiences buffering, but a column packet is buffered if a row packet crosses to the column or the routing queue is not empty. Therefore the protocols used on the row and column rings are different. A new packet admitted into the network always moves along the row first. When it reaches the destination column, it proceeds along the column until it reaches the destination. When contention occurs, the node buffers the column packet and sends a token over the row ring to reserve a slot for the transmission of the buffered column packet. Note that the output multiplexer is placed after the 2×2 switch. Local traffic can enter the network if a row packet switches to the column or an empty row slot has arrived.

The token bounds the queueing delay at the routing queue. As shown in Fig. 3, the token field in the row slot header consists of N bits for a network of N columns. A row slot, therefore, carries maximum of N tokens. Each token bit is allocated to each column of the network. Only the node in the corresponding column can set or clear its token bit. The token bit set represents that the corresponding column node has a packet waiting to be sent and prevents a new packet destined to that column from entering the slot. After the slot propagates the row ring and returns to the node of originating the token, the node serves a packet from the routing queue because either the slot is empty or contains a packet which does not cross to the column at that node. Therefore the maximum packet service time at a column node is equal to the propagation delay of the row ring.

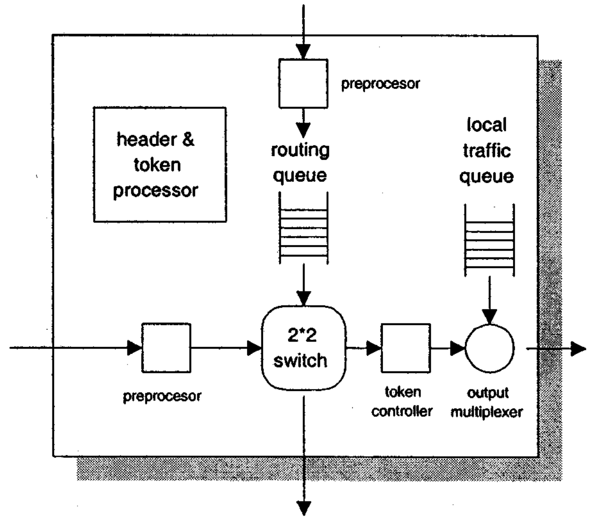

Fig. 2. Node structure.

Fig. 3 shows the packet and slot structures used in BFR. It is assumed that row and column packets arrive at a node simultaneously. If the arrivals are not synchronized, it is difficult to decide which packet to switch, and the packet blocking can occur at the switch. This type of synchronization can be easily achieved by delaying one of the two input links. No further restriction is imposed on the length of a link.

The basic operation of BFR is as follows.

1) A packet generated at a node is considered as a row packet and enters the network when the following conditions are met:
   - there is an empty slot on the row direction;
   - the token bit corresponding to the destination column of the generated packet is not set (i.e., not reserved).
2) The packet travels through the row nodes until it arrives at the destination column.
3) After the packet arrives at the destination column, it travels through the column until it reaches the destination node.
4) When a contention occurs, the column packet is buffered and the node sets the corresponding token bit for the reservation of a slot.
5) The buffered packet can be transmitted to the next column node when the row packet does not cross to the column at the node.

A token counter placed in the token controller of each node counts the number of tokens which are set by that node and are still in propagation. The counter value is increased when the node generates a token, and decreased when the node receives a returned token. It tries to keep the counter value as close to the

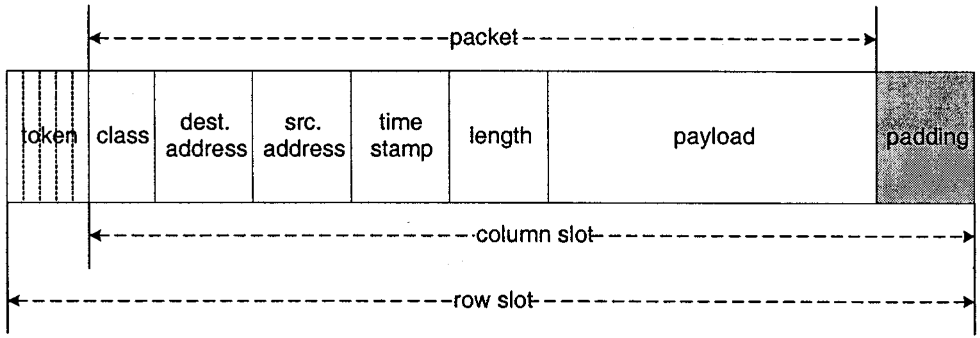

Fig. 3. Structure of slot and packet.

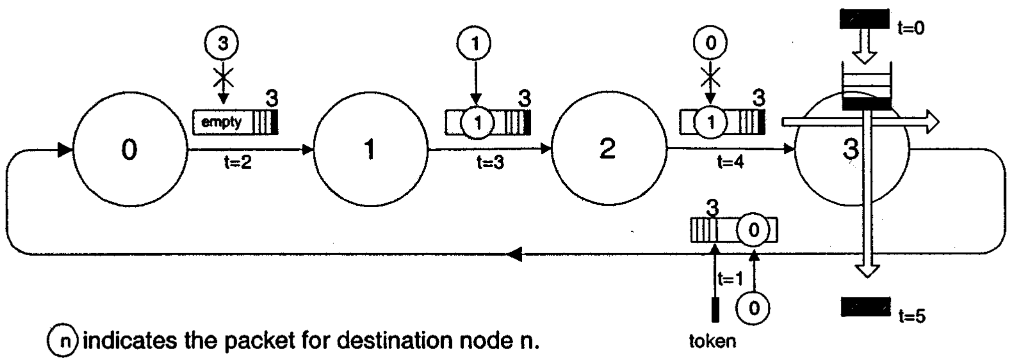

Fig. 4. An example of the token operation.

number of packets in the queue as possible to prevent generation of unnecessary tokens and to improve performance. Need for such mechanism arises because the routing queue can be often served without tokens when a row slot is empty or a row packet does not cross to the column. Therefore the number of tokens in the row ring at any given time can be greater than the number of packets in the routing queue. If this happens, the node does not have to generate a token for the new buffered packet. The counter value is never less than the number of waiting packets in the queue.

Fig. 4 illustrates how the token works. At $t = 0$, a column packet arrives at node 3 and a row packet, which is not shown in the figure, crosses to the column at the node. The column packet is buffered due to the contention. At $t = 1$, node 3 generates a token and sets the token bit corresponding to itself, while sending a packet destined to column 0 (or node 0) in the slot. At $t = 2$, the packet arrives at the destination column (or node) and the slot becomes empty. But the arrived packet at node 0 cannot enter the slot because the corresponding token is already set. At $t = 3$, the slot can carry a packet destined to node 1. At $t = 4$, the packet is blocked at node 2 because the slot is already occupied. At $t = 5$, the buffered packet is served as the token returns (the row packet should not switch to the column).

III. Performance Analysis

In this section, we discuss packet sequencing and delay bound issues briefly, and analyze buffer characteristics and network capacity of the BFR scheme. BFR preserves packet sequencing because it uses fixed paths for delivery. It also guarantees the end-to-end packet delay since the maximum packet service time is bounded by the propagation delay of the row ring. Owing to these characteristics, a finite size of buffers at each node is enough to achieve lossless communication. Packets are not lost in the routing queue but may be dropped in the local queue. However, it is not difficult to control the packet drop in the local queue since the drop can be notified to the transport layer as soon as it occurs. Moreover, since it is acceptable for the local queue to have a larger and slower memory than the routing queue, the packet drop in the local queue can be more manageable.

In order to quantify the delay bound and required buffer size, we assume that slots are of the same length. We also assume that the propagation delay of a row denoted by Q is a multiple of the slot length. These assumptions are deduced from the fact that the row and column arrivals are synchronized. Since the token returns to the node of originating it in Q slots, a packet arriving at the routing queue can be served within Q slots. Therefore the service time and the buffer size at each node are bounded to Q. Theoretically the required buffer size B for lossless communication is equal to Q. However, under the assumption of uniformly distributed traffic environments, it will be shown that B is not much related to the propagation delay of a row. This means that the buffer size of smaller than the propagation delay is sufficient to achieve low loss. Since BFR uses the token on the row ring, the delay bound D is given by $N^2 - 1$ hops, equivalently $((N^2-1)/N)Q$ slots for the considered $N \times N$ network.

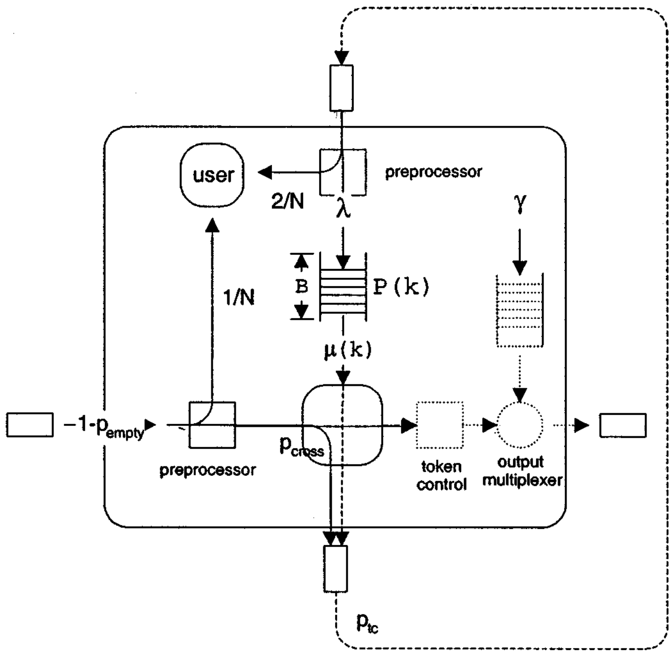

Fig. 5. Illustration of used variables.

A. Buffer Characteristics

In this section, we analyze routing buffer characteristics of BFR with the Geom/Geom/1 system. The basic assumptions for the analysis are given as follows:

- The length of a link is the same for all links as L which is normalized in unit of the slot.
- Only one packet arrival or departure can occur within a slot.
- Destination nodes of packets are uniformly distributed over the network.
- External packet arrival probability γ at a node follows the geometric distribution and is the same for all the nodes.
- Packets arrive at the routing queue with probability λ, following the geometric distribution.[1]
- The service time at the routing queue has the geometric distribution with probability $\mu(k)$, where k is the number of packets in the routing queue.

Fig. 5 illustrates the variables we use in the analysis. Detailed description of the variables are presented in the Appendix. Since the buffer size is bounded by $B = L \times N$, the buffer state can be expressed as the discrete time Markov chain with $B+1$ states. The probability distribution vector at time n is denoted by $P(n) = [p_0(n), p_1(n), \cdots p_B(n)]$. If the transition probability matrix T is defined by $T = [T_{i,j}]$, $i, j = 1, \cdots, B+1$, then $P(n+1) = T \cdot P(n)$. As $n \to \infty$, P becomes $P = T \cdot P$. In order to solve $T_{i,j}$, λ and $\mu(k)$ should be found first. As this discrete time Markov chain is a birth–death process in which state transitions to only neighboring states are possible, it can be analyzed with the Geom/Geom/1 queueing system [14]. With λ and $\mu(k)$, T is expressed as follows:

$$T_{i,j} = \begin{cases} \lambda(1-\mu(i)), & j = i+1,\ i \geq 0 \\ \mu(i)(1-\lambda), & j = i-1,\ i \geq 1 \\ 1 - T_{i,j-1} - T_{i,j+1}, & i = j,\ i \geq 1 j \geq 1 \\ 0, & \text{otherwise} \end{cases} \tag{1}$$

where λ is

$$\lambda = \frac{\left(1 - \frac{2}{N}\right)(1 - P(0)(1-W))}{1 - \left(1 - \frac{2}{N}\right)(P(0)(1-W))} \tag{2}$$

and $\mu(k)$ is

$$\mu(k) = 1 - W\left(1 - \frac{k}{B}\right). \tag{3}$$

The detailed derivations of λ and $\mu(k)$ are presented in the Appendix. P should be solved recursively by updating λ and T until it converges.

B. Maximum Capacity

In multihop networks, the maximum capacity is given by (maximum capacity)=(number of links)×(link capacity)/(average hop distance) [3]. For the $N \times N$ grid network, the average hop distance of SPR is approximately $(N/2+1)$ and the number of links is $2N^2$. Thus the maximum capacity of SPR, C_{SPR}, becomes

$$C_{\mathrm{SPR}} = \frac{2N^2}{\frac{N}{2}+1} \times C_{link} \approx 4NC_{link} \tag{4}$$

where C_{link} represents the link capacity [9]. Since the SFR scheme uses the shortest paths for routing, it exploits all the capacity of the network and its maximum capacity is the same as the maximum capacity of the grid network. However, since the BFR scheme is designed to use the fixed paths rather than the shortest paths, the average hop distance of BFR is greater than that of SFR. For BFR, the number of hops l_{ij} from nodes (0,0) to (i, j) becomes

$$l_{ij} = \begin{cases} i+j, & \text{if } j \neq 0 \\ N+i, & \text{if } j = 0. \end{cases} \tag{5}$$

The case of $j = 0$ occurs when the source and the destination nodes of the packet are on the same column. In this case the packet travels through all the nodes on the row and returns to the originating node. Then it goes down through the column to reach the destination node. This is because the generated packet should be admitted into the network through the row first. As a result, l_{ij} becomes $N+i$ for $j = 0$.

The sum of hops l is

$$\begin{aligned} l &= \sum_{i=0}^{N-1} \sum_{j=0}^{N-1} l_{ij} - l_{00} \\ &= \sum_{i=0}^{N-1} \left[\sum_{j=1}^{N-1} (i+j) + N + i \right] - N \\ &= N^3 - N \end{aligned} \tag{6}$$

[1]We adopt this assumption to overcome the difficulty of analyzing queueing problems involving dependent interarrival and service times among the routing and local traffic queues. This is the same as the Kleinrock's independence approximation [14].

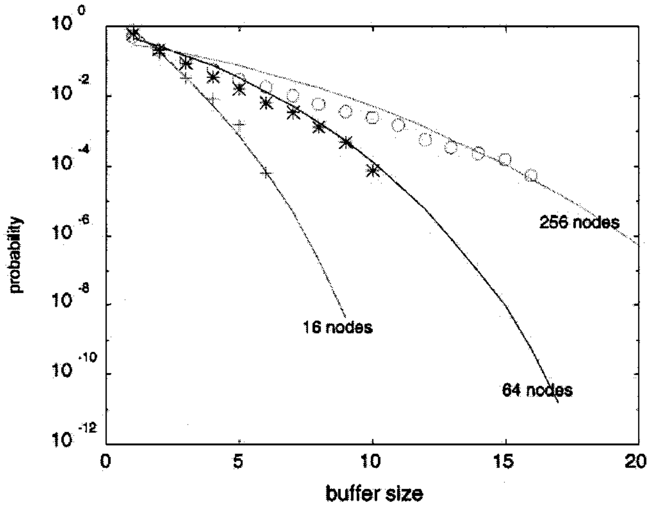

Fig. 6. Packet loss probability versus buffer size (according to the network size).

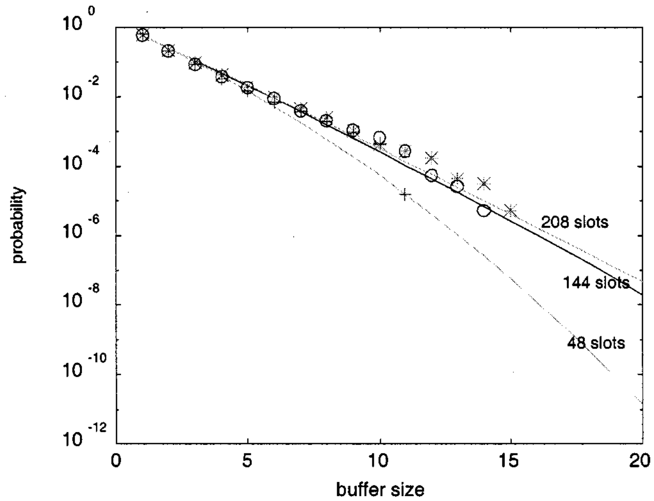

Fig. 7. Packet loss probability versus buffer size (according to the link length).

then

$$\text{(average hop distance)} = \frac{N^3 - N}{N^2 - 1} = N. \quad (7)$$

Thus, the maximum capacity of BFR is given by

$$C_{\text{BFR}} = \frac{2N^2}{N} \times C_{link} = 2NC_{link} \quad (8)$$

This represents that the maximum capacity of BFR is approximately half of that of SFR.

IV. Simulation Results

We have conducted extensive simulations to evaluate the performance of BFR. The simulation was performed by using Ptolemy 0.6[15].

Fig. 6 shows the performance of BFR with respect to the packet loss probability and buffer size where the external packet arrival probability γ at each node is 1 and the link length is two slots. The analysis results are compared with the simulation results for the network of 16, 64, and 256 nodes. The solid lines and marks indicate the analysis and simulation results, respectively. The simulations shows very close results to the analyzes. To achieve the lossless transmission, the buffer sizes of 8, 16, and 32 slots are theoretically needed for the network of 16, 64, and 256 nodes, respectively. However, Fig. 6 shows that approximately less than 20 buffers are enough to guarantee the acceptable packet loss probability. For example, 18 buffers are enough to keep the packet loss probability at less than 10^{-5} for the network of 256 nodes.

Fig. 7 shows the performance of BFR for different link lengths with respect to the packet loss probability and buffer size. The considered row lengths are 48, 144, and 208 slots for the network of 64 nodes and $\gamma = 1$. It is expected that the buffer size increases proportionally in accordance with the propagation delay of the row to guarantee lossless communication. But it is shown that there is no direct proportional relationship between the propagation delay and the buffer size. The buffer size much smaller that the theoretical one is enough to satisfy QoS requirements.

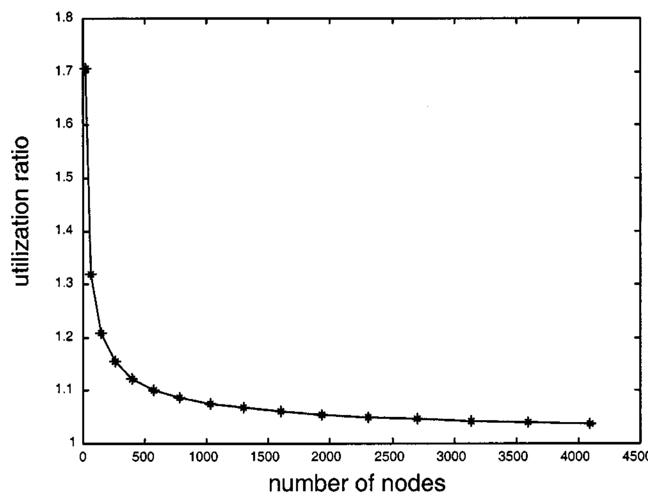

Fig. 8. The utilization ratio of row to column links.

Since BFR employs different protocols on the row and the column, row and column links shows different utilization and under-utilized links degrade overall network throughput. For a row link, the utilization is given by $1-p_{\text{empty}}$. For a column link, it is $p_{tc} = 1-P(0)(1-\lambda)(1-W)$. Then the utilization ratio becomes $(1-p_{\text{empty}})/p_{tc}$. Fig. 8 shows the utilization ratio curve for different network sizes. It shows that the ratio converges to 1 as the network size grows. This means that the traffic is evenly distributed throughout the network.

The performance of BFR is compared with those of SFR, VR and DR in simulation. Fig. 9 shows the maximum capacities of BFR and SFR with respect to the number of network nodes. The simulation results of BFR show the same results as the analytic results derived in (8).

Figs. 10 and 11 show the simulated performance of SFR, DR, VR, and BFR for the 8×8 grid network under uniform traffic condition. The average throughput and delay are plotted according to the external packet arrival probability γ. In Fig. 10,

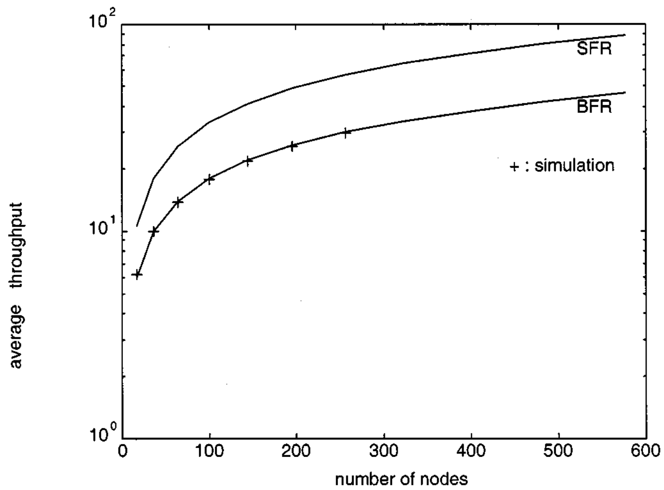

Fig. 9. Maximum capacities of BFR and SFR.

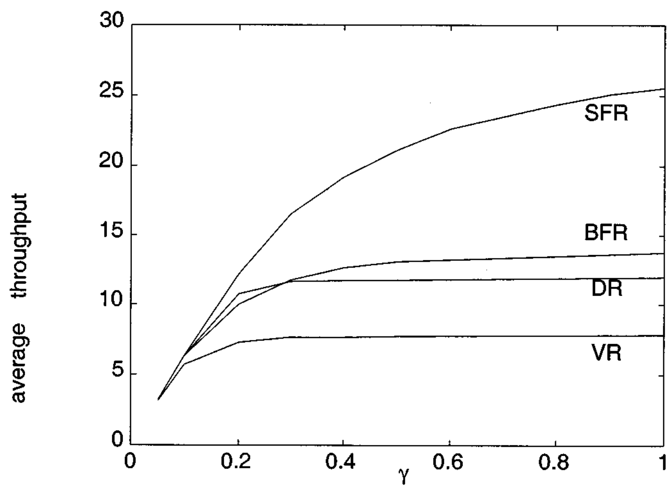

Fig. 10. Throughput comparison.

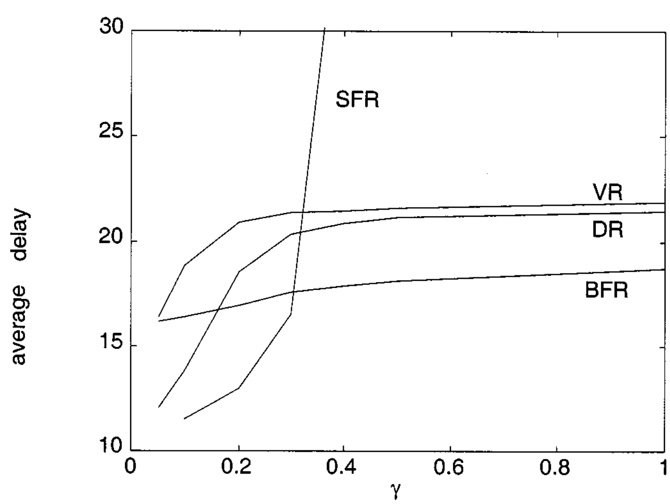

Fig. 11. Average delay versus external packet arrival probability.

SFR shows the best performance in terms of throughput. However, SFR is not appropriate for real-time applications since its average delay diverges to infinity as γ approaches 1. This is shown in Fig. 11. BFR shows reasonable throughput and good performance in terms of delay and delay variance. In case of $\gamma > 0.3$, BFR outperforms DR in terms of the average delay and throughput. Fig. 11 also shows that the average delay of BFR varies very little for different network loads. This means that the delay variation is so small, which is a very important property to provide guaranteed QoS for real-time applications.

V. Conclusion

In this paper, a new routing protocol called BFR has been proposed to support requirements of real-time applications in grid networks. The BFR scheme uses tokens on the row ring to control the admission of user packets into the network. Once the packet enters the network, it can be delivered to the destination with QoS guarantees. BFR can guarantee packet delay and sequencing without loss if each node has the required size of buffers. Therefore it is suitable for supporting real-time services, especially for ATM services which require packets to be delivered in sequence. We expect that BFR can be deployed with the development of WDM technology since WDM allows dense networks such as grid networks to be logically configured in an arbitrary topology. In WDM networks, the abundant bandwidth needs to be partitioned for electrically processing to be possible at each node.

We have analyzed the proposed scheme with the Geom/Geom/1 queueing system and compared it with the other competitive schemes through simulations. The summarized characteristics of BFR are as follows.

- BFR guarantees packet delay and sequencing with high throughput.
- Finite buffer size at each node is required for lossless communications.
- Under uniform traffic condition, the buffer size of far smaller than needed theoretically is suited for achieving very low loss and low queueing delay.
- The utilization ratio of the row to the column links converges to 1 as the network size grows.
- BFR shows the best performance compared to the others in terms of the average packet delay at intermediate and heavy loads.
- The packet delay variation of BFR with respect to the network load is the smallest compared to the others.

Future works such as reliability issues, scheduling algorithms, and signaling protocols for call admission at the connection level are left for further studies.

Appendix

Finding λ: Before obtaining λ, the traffic pattern on a link of the slotted ring needs to be analyzed. In slotted rings, the packet's destination distribution on a link is not uniform even though each node generates packets with uniform distribution of destination nodes. This is because each packet has different sojourn time depending on the location of its destination due to the path dependency of the ring. Thus a link has more packets which are nearer to the destination. In the increasing order of the distance to the destination, the ratio of numbers of packets on a link becomes $N-1:N-2:\ldots:1:0$. "Zero" in the ratio indicates that the node absorbs packets destined to itself and does not generate a packet destined to itself. Then the absorbing probability that a packet on a link arrives at the destination is

$$\frac{N-1}{\sum_{i=0}^{N-1} i} = \frac{2}{N}. \tag{9}$$

In BFR, the absorbing probability at the column ring node is the same as on the slotted ring since the node doesn't generate packets destined to itself. However, the absorbing probability at each node on the row ring becomes

$$\frac{N}{\sum_{i=1}^{N} i} = \frac{2}{N+1}. \tag{10}$$

This is because nodes on the row ring can generate packets to themselves.

Now let us find the packet arrival probability λ at the routing queue. Let p_{empty} be the probability that a row slot is empty. λ depends on γ which affects p_{empty}. Since an analytical approach is not suitable for finding out the relation between p_{empty} and γ, p_{empty} is used to indicate the network load as in [10]. Let p_{cross} be the probability that a row packet is crossed to the column at the switch. This occurs if a slot occupied by a packet arrives from the row $(1-p_{\text{empty}})$ and the packet arrives at the destination column $(2/(N+1))$ and the node is not the packet's destination $(1-(1/N))$. As a result

$$p_{\text{cross}} = (1-p_{\text{empty}})\frac{2}{N+1}\left(1-\frac{1}{N}\right). \tag{11}$$

Now, we will take token effect into account. Assume that the tokens are uniformly distributed on the row ring. Actually, the probability of a token being set depends on the previous state of the queue and the arrival pattern of the row packets. However, if we consider this property of memory, the number of system states increases rapidly and the analysis becomes intractable. We also assume that the number of tokens that will return is the same as the number of packets waiting in the routing queue owing to the token counter. Then we can write the probability of the token being set when the routing queue has k packets as

$$p_{\text{token}}(k) = \frac{k}{B}. \tag{12}$$

Since the packet cannot crossed to the column at a node if its token corresponding to that node is set, $p_{\text{cross}}(k)$ becomes

$$\begin{aligned} p_{\text{cross}}(k) &= (1-p_{\text{token}})(1-p_{\text{empty}})\frac{2}{N+1}\left(1-\frac{1}{N}\right) \\ &= \left(1-\frac{k}{B}\right)(1-p_{\text{empty}})\frac{2}{N+1}\left(1-\frac{1}{N}\right) \\ &= \left(1-\frac{k}{B}\right)W. \end{aligned} \tag{13}$$

where $W=(1-p_{\text{empty}})(2/(N+1))(1-(1/N))$.

Let p_{tc} be the probability that a node transmits a column packet. There will be no column packet transmission if the routing queue is empty and no column packet arrives at the routing queue and a row packet goes straight. Then it is given by

$$\begin{aligned} p_{tc} &= (1-P(0))\cdot 1 + P(0)(1-(1-p_{\text{cross}}(0))(1-\lambda)) \\ &= 1-P(0)+P(0)(\lambda(1-p_{\text{cross}}(0))+p_{\text{cross}}(0)) \\ &= 1-P(0)+P(0)(\lambda(1-W)+W) \\ &= 1-P(0)(1-\lambda)(1-W). \end{aligned} \tag{14}$$

Note that the packet arriving at the empty routing queue can be served immediately without being buffered. Since we assumed that every node has the same probabilistic behavior, transmission and reception probabilities on the column are the same as p_{tc} (see Fig. 5). An arriving column packet enters the routing queue if it has not reached its destination node. Applying the packet absorbing probability, we can write λ as

$$\begin{aligned} \lambda &= \left(1-\frac{2}{N}\right)p_{tc} \\ &= \left(1-\frac{2}{N}\right)(1-P(0)(1-\lambda)(1-W)). \end{aligned} \tag{15}$$

Rearranging the result,

$$\lambda = \frac{\left(1-\frac{2}{N}\right)(1-P(0)(1-W))}{1-\left(1-\frac{2}{N}\right)(P(0)(1-W))}. \tag{16}$$

Finding $\mu(k)$: Since the routing queue is served if a row packet goes straight at a node, the service probability $\mu(k)$ is

$$\begin{aligned} \mu(k) &= 1-p_{\text{cross}}(k) \\ &= 1-W\left(1-\frac{k}{B}\right) \end{aligned} \tag{17}$$

where k is the number of packets in the routing queue. $\mu(k)$ ensures that the full queue should be served without packet drop since $\mu(B)=1$.

REFERENCES

[1] B. Mukherjee, *Optical Communication Networks*. New York: McGraw-Hill, 1997.

[2] C. Baransel, W. Dobosiewicz, and P. Gburzynski, "Routing in multihop packet switching networks: Gb/s challenge," *IEEE Network*, pp. 38–61, May/June 1995.

[3] A. G. Greenberg and J. Goodman, "Sharp approximate models of deflection routing in mesh networks," *IEEE Trans. Commun.*, vol. 41, pp. 210–223, Jan. 1993.

[4] W. Dobosiewicz and P. Gburzynski, "A bounded-hop-count deflection scheme for Manhattan-street networks," in *Proc. IEEE INFOCOM'96*, 1996, pp. 172–179.

[5] E. A. Varvarigos and J. P. Lang, "Performance analysis of deflection routing with virtual circuits in a Manhattan street network," in *Proc. IEEE GLOBECOM'96*, 1996, pp. 1544–1548.

[6] C. Brackett *et al.*, "A scalable multiwavelength multihop optical network: a proposal for research on all-optical networks," *J. Lightwave Technol.*, vol. 11, pp. 736–753, May/June 1993.

[7] O. Gerstel, "On the future of wavelength routing networks," *IEEE Network*, vol. 10, pp. 14–20, Nov./Dec. 1996.

[8] K. Bala *et al.*, "Toward hitless reconfiguration in WDM optical networks for ATM transport," in *Proc. IEEE GLOBECOM'96*, 1996, pp. 316–320.

[9] N. F. Maxemchuk, "Routing in the Manhattan street network," *IEEE Trans. Commun.*, vol. 35, pp. 503–512, May 1987.

[10] A. S. Acampora and S. I. A. Shah, "Multihop lightwave networks: A comparison of store-and-forward and hot-potato routing," in *Proc. IEEE INFOCOM'91*, 1991, pp. 10–19.

[11] F. Borgonovo, L. Fratta, and F. Tonelli, "Circuit service in deflection networks," in *Proc. IEEE INFOCOM'91*, 1991, pp. 69–75.

[12] E. Karasan and E. Ayanoglu, "Performance of WDM transport networks," *IEEE J. Select. Areas Commun.*, vol. 16, no. 7, pp. 1081–1096, 1998.
[13] M. Schwartz, *Broadband Integrated Networks*. Englewood Cliffs, NJ: Prentice Hall, 1996.
[14] L. Kleinrock, *Queueing Systems Volume 1; Theory*. New York: Wiley, 1975.
[15] *Ptolemy 0.6*, http://ptolemy.eecs.berkeley.edu, University of California at Berkeley.

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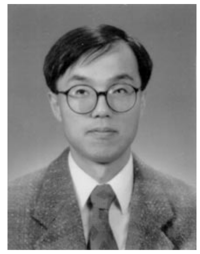

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