PERFORMANCE EVALUATION OF TWO-PRIORITY NETWORK SCHEMA FOR SINGLE-BUFFERED DELTA NETWORKS

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ABSTRACT

In this paper a novel two-priority network schema is presented, and exemplified through its application on single-buffered Delta Networks in packet switching environments. Network operations considered include conflict resolution and communication strategies. The proposed scheme is evaluated and compared against the single-priority scheme. Performance evaluation was conducted through simulation, due to the complexity of the model, and uniform traffic conditions were considered. Metrics were gathered for the two most important network performance factors, namely packet throughput and the mean time a packet needs to traverse the network. The model can also be uniformly applied to several representative networks providing a basis for fair comparison and the necessary data for network designers to select optimal values for network operation parameters.

I. INTRODUCTION

Multistage Interconnection Networks (MINs) with crossbar Switching Elements (SEs) are frequently employed for interconnecting processors and memory modules in parallel multiprocessor systems. MINs have been recently identified as an efficient interconnection network for communication structures such as gigabit Ethernet switches, terabit routers, and ATM switches. Significant advantages of MINs include their low cost/performance ratio and their ability to route multiple communication tasks concurrently. MINs with the Banyan [10] property as Delta Networks [21] are proposed to connect a large number of processors to establish a multiprocessor system; they have also received considerable interest in the development of packet-switched networks. Non-Banyan MINs, are in general, more expensive than Banyan networks and more complex to control.

The performance of an interconnection or communication network is probably its most important characteristic, thus much research has been performed in investigating network performance in the context of both parallel and distributed systems. Performance evaluation methods mainly include Markov chains, queuing theory, Petri nets and simulation.

Markov chains have been extensively used by many researchers. [3] and [18] used Markov chains in order to approximate the behavior of MINs under different buffering schemes. [3] also enhances Markov chains, with elements from queuing theory. Some authors that dealt with Markov chains also employed Petri nets as a modeling method; [9], [11] and [17] are examples of such works. Diverse approaches have also been taken regarding the modeling of input traffic, with uniform ([12], [23]), hotspot ([14]), multicast ([24]), non-uniform ([2]) and Poison-shaped ([16]) traffic being the most commonly adopted ones. In the industry domain, Cisco has built its new CRS-1 router [4, 5] as a multistage switch fabric. The switch fabric that provides the communications path between line cards is a 3-stage, self-routed architecture.

Packet priority is a common issue in networks, arising when service with different QoS characteristics needs to be offered to different classes of packets. This requirement may stem from the nature of the applications involved in the transmission (e.g. from streaming media) vs. non real-time packets (e.g. teleconferencing vs. file transfer applications) or from protocol-oriented needs (e.g. out-of-band data vs. ordinary TCP traffic [22]). Traffic priority schemes have already been incorporated in several commercial switches, such as [7, 8]. Internally, these switches employ single priority SEs that use two priority queues for each input port, where packets are queued based on their priority level. In [6] a *(N X N)* non-blocking packet switch with input queues built using single-priority SEs is studied. [20] proposes a simple modification for load-sharing replicated buffered Banyan Networks to guarantee priority traffic transmission.

The internal switch structure used in all the above listed studies was a single-priority fabric with controlled inputs. In this paper, we propose a switching fabric architecture that natively supports a dual-priority scheme, aiming to improve the QoS offered to high-priority packets. In the proposed scheme, each SE has two transmission queues per link, with one queue dedicated to high priority packets and the other dedicated to low priority ones. During a single network cycle, the SE considers all its links, examining for each one of them firstly the high priority queue. If this is not empty, it transmits the first packet towards the next MIN stage; the low priority queue is checked only if the corresponding high priority queue is empty. Packets in all queues are transmitted in a first come, first served basis. In all cases, at most one packet per link (upper or lower) of an SE will be forwarded for each pair of high and low priority queues to the next stage. The priority of each packet is indicated through a *priority bit* in the packet header.

The remainder of this paper is organized as follows: in section 2 we present the proposed priority scheme, which is termed as *two-priority* vs. *single-priority.* Subsequently, in section 3 we present the performance criteria and parameters related to the above network schemes. Section 4 presents the results of our simulation-based performance analysis, studying the effect that the proposed priority handling scheme has on the performance of high and low priority traffic, as well as on the overall network performance is investigated. Finally, section 5 provides the concluding remarks

II. ANALYSIS OF AN (N X N) MIN

A MIN can be defined as a network used to interconnect a group of N inputs to a group of M outputs using several stages of small size Switching Elements (SEs) followed (or preceded) by link states. Its main characteristics are its topology, routing algorithm, switching strategy and flow control mechanism. A MIN with the Banyan property is defined in [10] and is characterized by the fact that there is exactly a unique path from each source (input) to each sink (output). Banyan MINs are multistage self-routing switching fabrics. Thus, each SE of k^{th} stage can decide in which output port to route a packet, depending on the corresponding k^{th} bit of the destination address.

An (N X N) MIN can be constructed by $n=\log_c N$ stages of (cxc) SEs, where c is the degree of the SEs. At each stage there are exactly N/c SEs. Consequently, the total number of SEs of a MIN is $(N/c)*\log_c N$. Thus, there are $O(N*\log N)$ interconnections among all stages, as opposed to the crossbar network which requires $O(N^2)$ links.

A typical configuration of an 8 X 8 delta network, a widely used classes of Banyan MINs, is depicted in Figure 1 and outlined below. This network class was proposed by Patel [21] and combines benefits of Omega [15] and Generalized Cube Networks [1] (destination routing, partitioning and expandability). As seen in Figure 1, individual queues have added for both high and low priority packets.

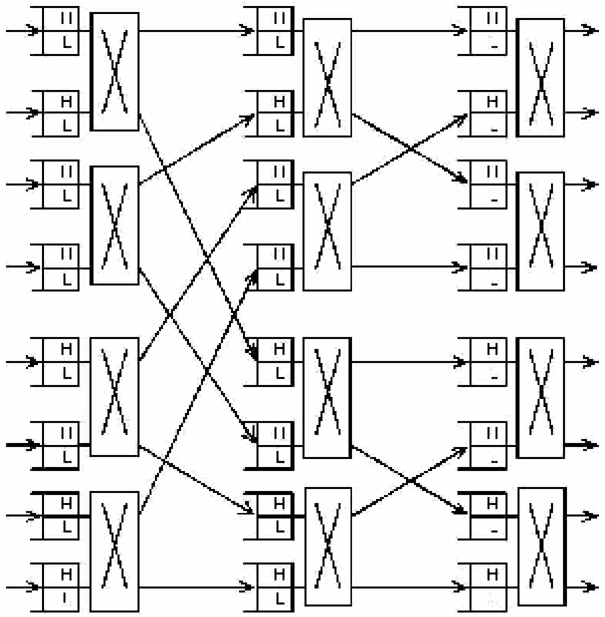

Figure 1. An 8 X 8 delta-2 network employing a two-priority scheme

A MIN is assumed to operate under the following scheme:

- The network clock cycle consists of two phases. In the first phase, flow control information passes through the network from the last stage to the first stage. In the second phase, packets flow from one stage to the next in accordance with the flow control information.
- The arrival process of each input of the network is a simple Bernoulli process, i.e., the probability that a packet arrives within a clock cycle is constant and the arrivals are independent of each other. We will denote this probability as λ. This probability can be further broken down to λ_h and λ_l, which represent the arrival probability for high and low priority packets, respectively. It holds that $\lambda = \lambda_h + \lambda_l$.
- A packet arriving at the first stage (k=1) is discarded if the buffer of the corresponding SE is full.
- All SEs have deterministic service time.
- A packet is blocked at a stage if the destination buffer at the next stage is full.
- The packets are uniformly distributed across all the destinations and each queue uses a FIFO policy for all output ports.
- When two high or low packets at a stage contend for the same buffer at the next stage and there is not adequate free space for both of them to be stored, there is a conflict. One of them will be accepted at random, and the other will be blocked by means of upstream control signals, with high priority packets having precedence over low priority packets at the transmission process.
- Finally, all packets in input ports contain both the data to be transferred and the routing tag. In order to achieve synchronously operating SEs, the MIN is internally clocked. As soon as packets reach a destination port they are removed from the MIN, so, packets cannot be blocked at the last stage.

III. PERFORMANCE EVALUATION METHODOLOGY

In order to evaluate the performance of a (N X N) MIN with $n=\log_c N$ intermediate stages of (cxc) SEs, we use the following metrics. Let T be a relatively large time period divided into u discrete time intervals ($\tau_1, \tau_2, \ldots, \tau_u$).

- *Average throughput* Th_{avg} is the average number of packets accepted by all destinations per network cycle. This metric is also referred to as *bandwidth*. Formally, Th_{avg} can be defined as

$$Th_{avg} = \lim_{u \to \infty} \frac{\sum_{i=1}^{u} n(i)}{u} \quad (1)$$

where $n(i)$ denotes the number of packets that reach their destinations during the i^{th} time interval.

- *Normalized throughput* Th is the ratio of the *average throughput* Th_{avg} to network size N. Formally, Th can be expressed by

$$Th = \frac{Th_{avg}}{N} \quad (2)$$

Normalized throughput is a good metric for assessing the MIN's cost effectiveness

- *Relative normalized throughput* of high priority packets $RTh(h)$ is the *normalized throughput* $Th(h)$ of high priority packets divided by the *offered load* λ_h of such packets.

$$RTh(h) = \frac{Th(h)}{\lambda_h} \quad (3)$$

- *Relative normalized throughput* of low priority packets $RTh(l)$ is the *normalized throughput* $Th(l)$ of low priority packets divided by the *offered load* λ_l of low priority packets.

$$RTh(l) = \frac{Th(l)}{\lambda_l} \quad (4)$$

- *Average packet delay D_{avg}* is the average time a packet spends to pass through the network. Formally, D_{avg} can expressed by

$$D_{avg} = \lim_{u \to \infty} \frac{\sum_{i=1}^{n(u)} t_d(i)}{n(u)} \quad (5)$$

where *n(u)* denotes the total number of packets accepted within *u* time intervals and $t_d(i)$ represents the total delay for the i[th] packet.
We consider $t_d(i) = t_w(i) + t_{tr}(i)$ where $t_w(i)$ denotes the total queuing delay for i^{th} packet waiting at each stage for the availability of an empty buffer at the next stage queue of the network. The second term $t_{tr}(i)$ denotes the total transmission delay for i^{th} packet at each stage of the network, that is just $n*nc$, where n is the number of stages and nc is the network cycle.
- *Normalized packet delay D* is the ratio of the D_{avg} to the minimum packet delay which is simply the transmission delay $n*nc$. Formally, D can be defined as

$$D = \frac{D_{avg}}{n * nc} \quad (6)$$

The following parameters affect the above performance aspects of a MIN.

- *Buffer size* (*b*) is the maximum number of packets that an input buffer of a SE can hold. In our paper we consider a single-buffered (b=1) MIN. Double-buffered SEs in other cases lead to better exploitation of network, while the increase in delay can be tolerated [27].
- *Offered load (λ)* is the steady-state fixed probability of arriving packets at each queue on inputs. In our study λ is assumed to be $\lambda = 0.1, 0.2 \ldots 0.9, 1$.
- *Ratio of high priority offered load* (r_h), where $r_h = \lambda_h/\lambda$. In our study r_h is assumed to be r_h =0.05, 0.10 … 0.25, and 0.30, 0.40 … 1.
- *Network size n*, where $n=\log_2 N$, is the number of stages of an (N X N) MIN. In our study n is assumed to be n=6, 8, 10.

IV. Simulation and Performance Results

The performance of MINs is usually determined by modeling, using simulation [25] or mathematical methods [26]. In this paper we estimated the network performance using simulations. We developed a general simulator for MINs in a packet communication environment, capable of handling several switch types, inter-stage interconnection patterns, load conditions, switch operation policies and priorities. We focused on an *(N X N)* Delta Network that consists of (2 X 2) SEs, using internal queuing. Each (2 X 2) SE in all stages of the MIN was modeled by four non-shared buffer queues, the first two for high priority packets, and the other two for low priority packets. Buffer operation was based on FCFS principle. In the case of single priority scheme MINs, when there was a contention between two packets, it was solved randomly. Moreover, in a two-priority MINs scheme the high priority packets have precedence over the low priority ones, where contentions are resolved by favoring the packet transmitted from the high priority queue (the queue in which the high priority packets are stored in). The simulation was performed at packet level, assuming fixed-length packets transmitted in equal-length time slots, where the slot was the time required to forward a packet from one stage to the next.

The parameters for the packet traffic model were varied across simulation experiments to generate different offered loads and traffic patterns. Metrics such as packet throughput and packet delays were collected at the output ports. We performed extensive simulations to validate our results. All statistics obtained from simulation running for 10^5 clock cycles. The number of simulation runs was adjusted to ensure a steady-state operating condition for the MIN. There was a stabilization process in order the network be allowed to reach a steady state by discarding the first 10^3 network cycles, before collecting the statistics.

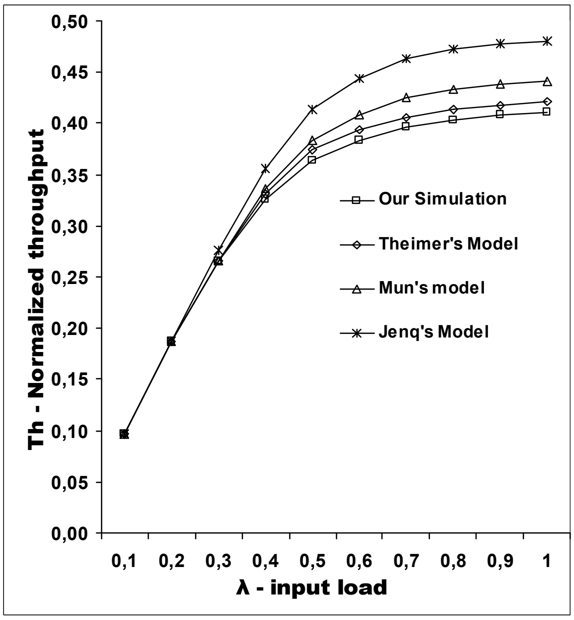

Figure 2. Normalized throughput of a single buffered 6-stage MIN

Figure 2 shows the *normalized throughput* of a single buffered MIN with 6 stages as a function of the *probability of arrivals* for the three classic models [13, 19, 23] and our simulation. All models are very accurate at low loads. The accuracy reduces as input load increases. Especially, when input load approaches the network maximum throughput, the accuracy of Jenq's model is insufficient. One of the reasons is the fact that many packets are blocked mainly at the network first stages at high traffic rates. Thus, Mun introduced a "blocked" state to his model to improve accuracy. The consideration of the dependencies between the two buffers of an SE in Theimer's model leads to further improvement. We performed extensive simulations to validate our results. Our simulation was also tested by comparing the results of the Theimer's model with those of our simulation experiments which were found to be in close agreement (differences are less than 1%).

In figure 3, curve SP[k] depicts the *normalized throughput* of a k-stage MIN employing a single priority scheme, while curves TP[k]H[R_h] show the *relative normalized throughput* of a k-stage MIN using a two-priority scheme, where the probability of high-priority packet appearance is R_h%. Figure

3 illustrates the gains on *normalized throughput* of high priority packets at the following rates (R_h=5%, 10%, 15%, 20%, 25%) of offered loads. We can notice here that the gains on *normalized throughput* of high priority packets for a MIN employing a two-priority vs. non priority scheme are 56.9%, 55.9%, 54.2%, 52.4%, and 50.1%, when R_h=5%, 10%, 15%, 20%, and 25% respectively, under full load traffic. It is noteworthy that the *normalized throughput* approaches the maximum value Th_{max}=1 when R_h=5%, which is equal to *RTh(h)*=0.98 under full load traffic.

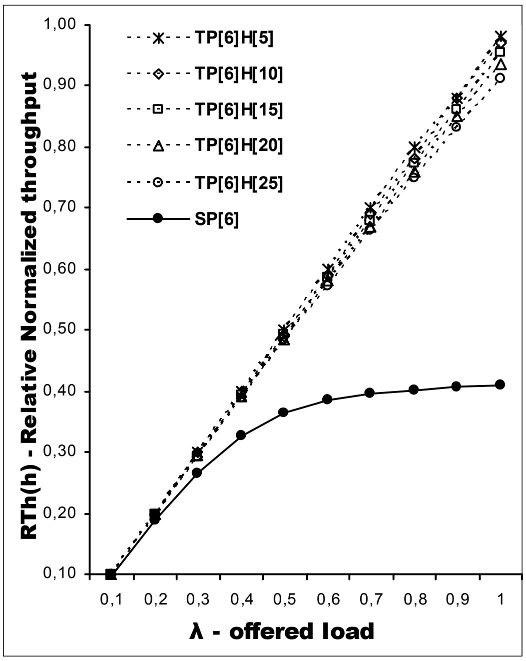

Figure 3. Normalized throughput of high priority packets of a 6-stage MIN employing a two-priority vs. single priority scheme

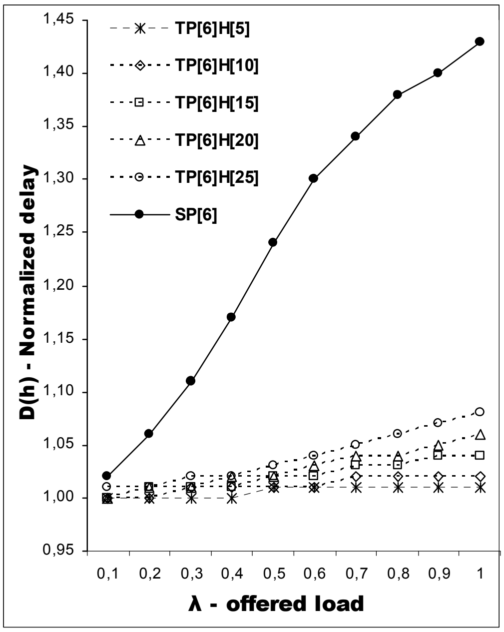

Figure 4. Normalized delay of high priority packets of a 6-stage MIN employing a two-priority vs. single priority scheme

Fig. 4 represents the corresponding decrements on *normalized high-priority packet delays* of two-priority vs. single priority packets for a 6-stage MIN, under different *rates* (R_h=5%, 10%, 15%, 20%, 25%) of high priority offered loads. The minimization of packet delays is considerable for all above rates of high priority packets. It follows that *normalized delay* is reduced dramatically to $D_{(h)}$=1.01 when the *rate* of high priority offered load is R_h=5%, approaching the optimal value D_{min}=1 and gaining 41% as compared to the single-priority scheme.

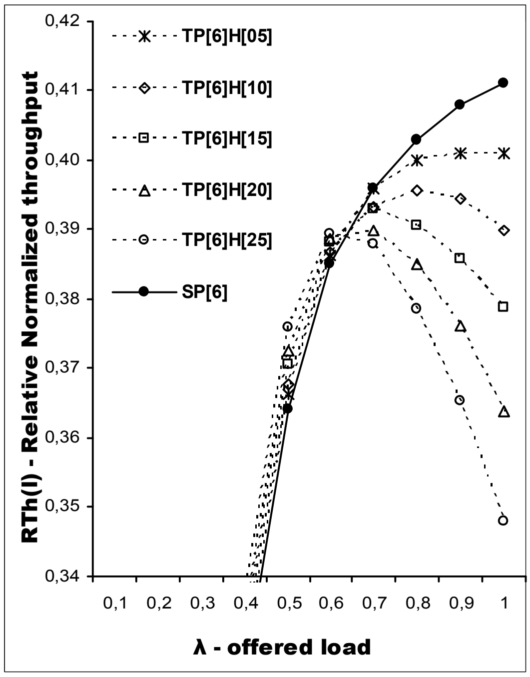

Figure 5. Normalized throughput of low priority packets of a 6-stage MIN employing a two-priority vs. single priority scheme

Fig. 5 presents the opposite case, where the loss of *normalized throughput* of low priority packets depends on the *rates* (R_h=5%, 10%, 15%, 20%, 25%) of high priority offered loads.

We can notice here that the loss on *normalized throughput* of low priority packets for a MIN employing a two-priority vs. non priority scheme is 1%, 2.1%, 3.2%, 4.7%, and 6.3%, when R_h=5%, 10%, 15%, 20%, and 25% respectively, under full load traffic. It is also noteworthy that larger rates of high priority packets reduce the *relative throughput* of low priority packets, because high priority packets have precedence over low priority ones; however the loss in all cases ranges from negligible to tolerable, as compared to the corresponding gains of high priority packets.

Fig. 6 presents the corresponding increments on *normalized packet delays* of low priority packets, which are almost negligible or tolerable for all configuration schemas. The curves clearly show that the increments on *normalized delays* of low priority packets for a MIN employing a two-priority vs. single priority scheme are 1%, 2%, 3%, 5%, and 8%, when R_h=5%, 10%, 15%, 20%, and 25% respectively, under full load traffic. It is also noteworthy that larger rates of high priority packets introduce larger delays for low priority packets, because these packets fill the buffers and stay in the network longer as high priority packets have precedence over low priority ones, thereby increasing queuing delays.

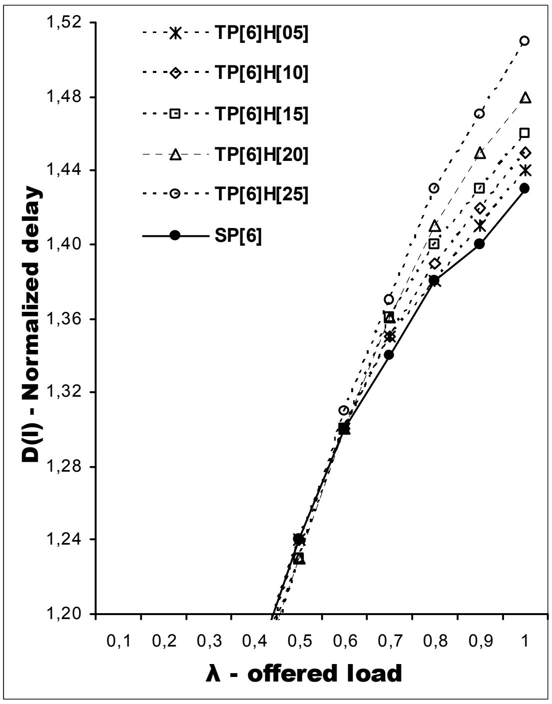

Figure 6. Normalized delay of low priority packets of a 6-stage MIN with a two-priority scheme vs. single priority

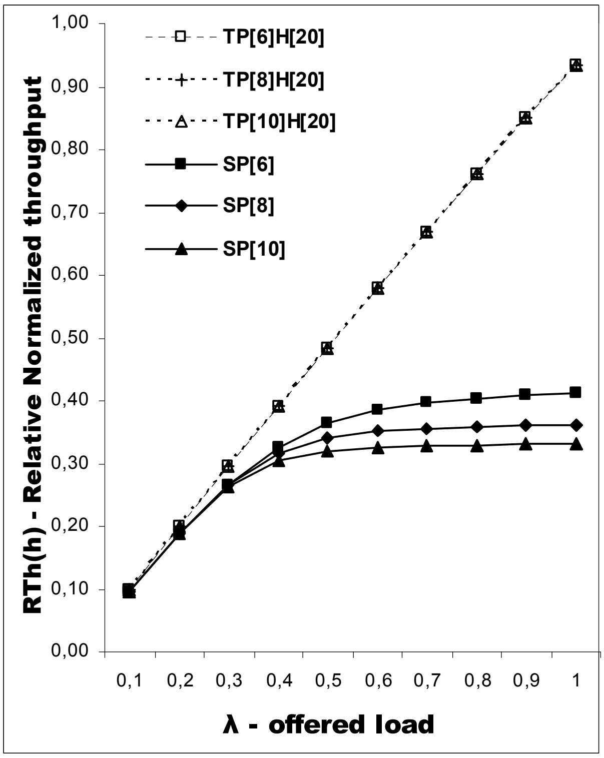

Figure 7. Normalized throughput of high priority packets of a k-stage MIN with a two-priority scheme vs. single priority

Fig. 7 illustrates the gains on *normalized throughput* of high priority packets for various *network size* configurations, in which k=6, 8, 10 denotes the number of stages of the MIN and R_h=20% is the *rate* of high priority offered load. It is clear that the *normalized throughput o*f high priority packets approaches the optimal value (Th_{max}=1) in all *network size* configuration schemas [R$Th_{(h)}$=0.935]. It is also seen that all above curves which depict the *relative normalized throughput* of high priority packets seem to converge. Thus, the gain on *relative throughput* is greater in larger *network size* configurations.

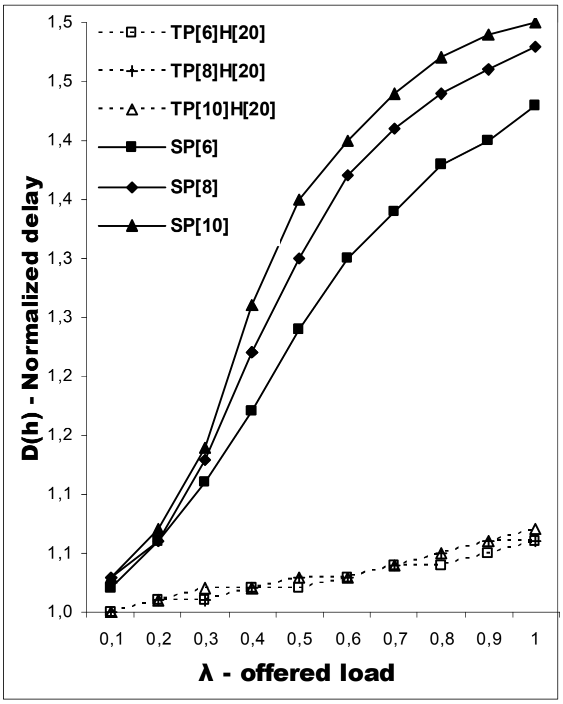

Figure 8. Normalized delay of high priority packets of a k-stage MIN with a two-priority vs. single priority scheme

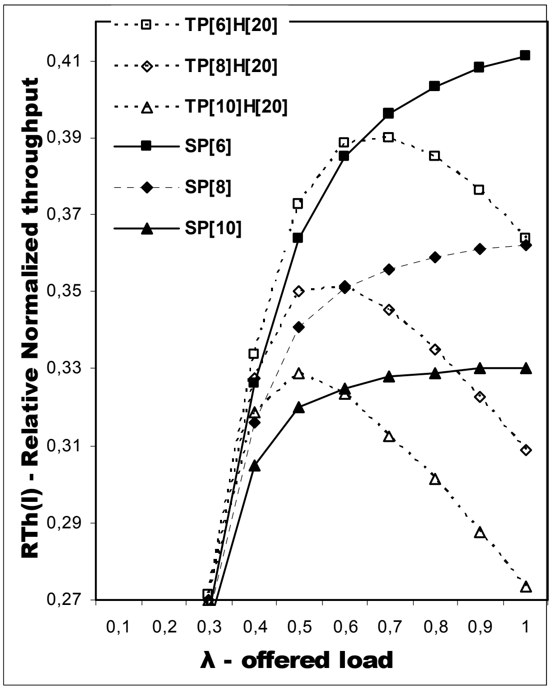

Figure 9. Normalized throughput of low priority packets of a k-stage MIN with a two-priority scheme vs. single priority

Fig. 8 illustrates the benefits related to the *normalized delay* factor of high priority packets for various *network sizes* (number of stages k=6, 8, 10), when the rate of high priority packets is R_h=20. The gains or decrements on *normalized delays* are 0.37, 0.42, and 0.43 for a k–stage MIN, where k=6, 8, 10 respectively, which considered satisfactory for all network setups. It is also obvious that the minimization of *normalized delays* in a two-priority scheme is stronger at larger network configurations, where the *packet delays* have greater values in the corresponding single priority MINs.

Fig. 9 presents the opposite case, where the *normalized throughput* of low priority packets deteriorates slightly; the performance loss is however tolerable (4.7%, 5.3%, and 5.6%) in a k–stage MIN when the *rate* of high priority offered load is R_h=20%, and k=6, 8, 10 respectively. The loss on relative *normalized throughputs* is more obvious under heavy traffic load conditions.

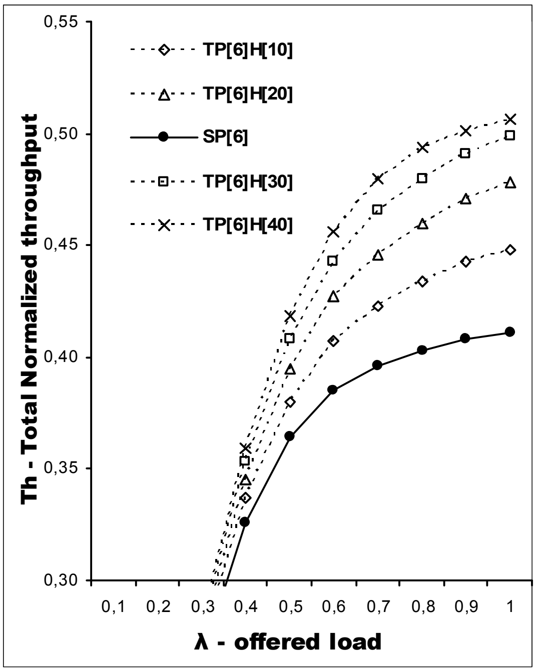

Figure 10. Normalized delay of low priority packets of a k-stage MIN with a two-priority scheme vs. single priority

Similarly, Fig. 10 presents the increments on *normalized packet delays* of low priority packets, which are quite small and thus tolerable (5%, 10%, and 13%) for a k–stage MIN, where k=6, 8, 10 respectively, employing a two- priority vs. single priority scheme, under a *rate* R_h=20% of high priority offered load.

Fig. 11 illustrates the gains on *total normalized throughput* regarding as a common performance metric for both high and low priority packets under various *rates* of high priority offered loads R_h=10%, 20%, 30%, 40%. It follows that the gain on *total normalized throughput* of a 6–stage MIN using a two-priority vs. single priority scheme is 11% when the *rate* of high priority offered load reaches the value of R_h=40%.

Finally, figure 12 presents both the *normalized throughput* of high and low priority packets, and the *total normalized throughput* of a 6–stage MIN, considering as a common performance metric for all packets under full traffic conditions, where the offered load is λ=1. It is worth noting that the *total normalized throughput* grows as the rate of high priority packets increases, until it reaches the value of R_h=40%. It is also obvious that lower rates of high priority loads cause fewer blockings at high priority packets producing better *relative normalized throughputs.* Moreover, it follows that the *relative normalized throughput* of low priority packets has the lowest value when the *rate* of high priority offered load is R_h=60%.

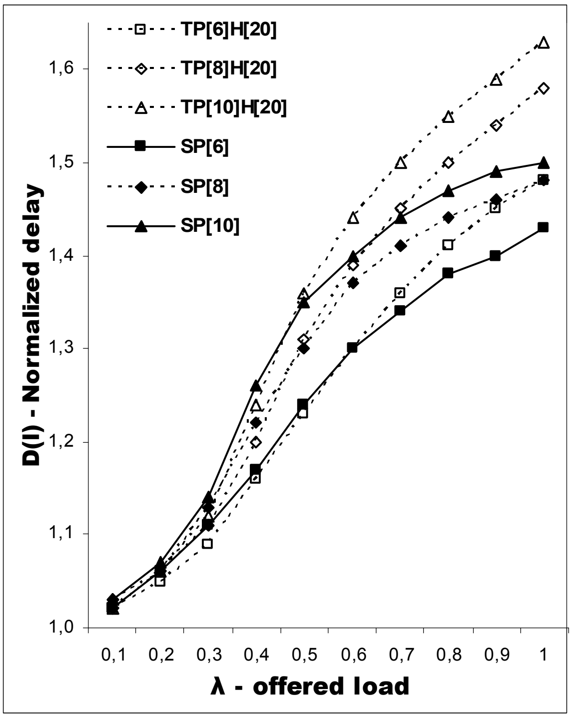

Figure 11. Total normalized throughput of a k-stage MIN employing a two-priority vs. single priority scheme

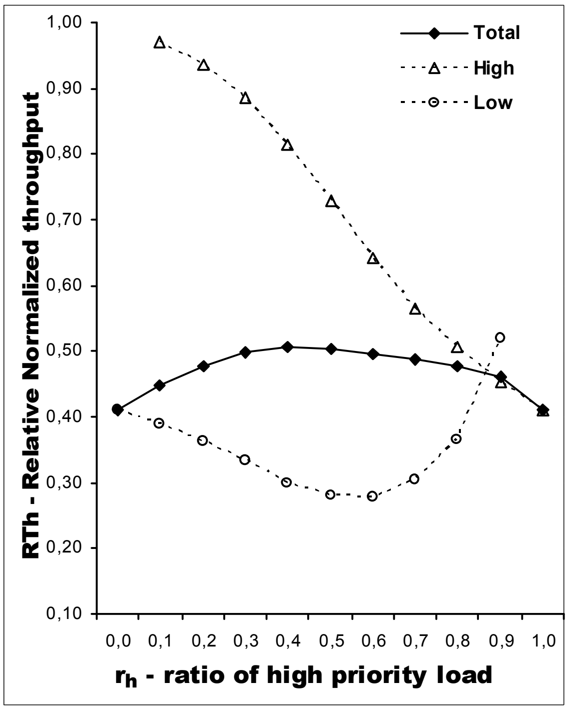

Figure 12. Normalized throughput of a 6-stage MIN vs. ratio of high priority load at a two-priority scheme

V. CONCLUSIONS

In this paper we have presented a switching fabric architecture for MINs that natively supports a dual-priority scheme. This architecture aims to support environments in which packets with different QoS needs enter the MIN, such as transmission of real-time media vs. HTTP traffic. The performance of the proposed scheme was evaluated through simulation experiments, and compared to the performance of single-priority MINs. Performance comparisons addressed the two most important factors, namely throughput and delay, and it was found that the gains for high-priority packets were considerable for both factors, whereas the respective deterioration for low-priority packets ranged from negligible to tolerable. Especially for setups with few high-priority packets (R_h < 10%), both delay and throughput metrics for high-priority packets is very close to the optimal values. Regarding the additional control information needed, the proposed scheme introduces only one bit in the packet header to designate the priority class, and thus this overhead is very small.

The results of this paper can be used by network designers to assess the performance parameters of MINs before their actual implementation. Accurate predictions are a valuable asset for network designers, since their availability can help towards minimizing overall deployment costs and delivering efficient networks.

Future work will focus on assessing the role of SE *buffer sizes* in the performance of MINs and examining both the feasibility and the performance issues related to handling multiple (more than two) packet priority classes.

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