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Fairness Studies of the p_i-Persistent Protocol in Unidirectional Bus Networks

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Abstract: The p_i-persistent Medium Access Control (MAC) protocol has been shown to be a suitable candidate for high-speed time-slotted fiber-optic unidirectional bus networks. It is based on a probabilistic scheduling strategy with p_i $(0 \le p_i \le 1)$ being the probability with which the i-th station $(i = 1, 2, \cdots, N)$ on the bus access an empty slot if it has a packet for transmission. This paper examines the main aspects of the fairness provision mechanism employed in the p_i-persistent protocol. The mean packet delay is considered as one of the criterion for fairness measurement. Simulation results show that the p_i-persistent protocol achieving fairness at the price of increased packet delay (both for individual stations and overall network). It actually deteriorates mean packet delays at all upstream stations (in order to equalising the mean delay of all stations) without improving delays at downstream stations.

Key Words: Fairness, Packet Delay, Poisson and Bernoulli Arrival Streams, Simulation

Introduction

In a series of papers by Mukherjee *et al.*, (Mukherjee, 1990 and 1991.,Mukherjee and Meditch, 1988; Mukherjee and Kamal, 1994.) proposed a MAC protocol for high-speed fibre optic unidirectional bus networks, known as the p_i-persistent protocol. The p_i-Persistent Protocol, with its very simple flow control mechanism allowing station *i* to access empty slots with station-dependent probability p_i $(0 \le p_i \le 1)$, has been seen as an alternative for solving fairness problems associated with the original IEEE 802.6 standard for the Distributed Queue Dual Bus (DQDB) for high speed networks (Filipiak, 1989., Hahne *et al.*, 1990., IEEE 1990 and Mukherjee, 1992). Fairness can be defined in several ways. For example, it might mean that the mean packet delay for all packets is equalised, regardless of which station the packet originated at.

In a network with N stations, the probabilities p_i, can be chosen adaptively by sensing the actual traffic on the bus. Corresponding methods have been suggested by (Mukherjee *et al.*, 1991). Mukherjee and Meditch (1988) have dealt with fairness of p_i-Persistent Protocol by introducing different criteria, eg. equal mean packet delay, equal blocking probability of buffers and equal throughput. Miller and Paterakis (1993) have investigated the different priorities of packets (two or more types of teletraffic) in the p_i-persistent protocol where different types of traffic may have different quality of service demands. Various alternative solutions for MAC protocols in time-slotted unidirectional bus networks, including those implemented in Channel Reservation Multiple Access (CRMA), Fasnet and Hangman networks, can be found surveyed eg in (Van As, 1994).

On a unidirectional bus, the opportunity for the stations to access the medium varies with the locations of the stations. The further a station is located along the bus the smaller is the probability that it encounters an empty slot. Thus, the problem of allocating bandwidth fairly to each station in a shared, unidirectional bus network is an important issue. To cope with fairness problem, the p_i-persistent protocol (Mukherjee and Meditch, 1988., Mukherjee, 1990) uses random access strategy governed by access probabilities p_i to randomly skip some of the available transmission opportunities, and consequently, increases mean delays for all stations to the worse achievable delays in the network.

In this paper we show that, in a network with homogeneous Bernoulli arrival streams, protecting fairness of services by lowering the access probability at a station leads only to deterioration of that station's performance without improving performance of other stations. The p_i-persistent protocol actually achieving fairness at the price of increased packet delay, both for individual stations and overall network.

Simulation Model of p_i-Persistent Protocol: All simulation models, whose results are presented in this paper, were coded in C++ and interfaced with AKAROA II[1] (Ewing and Pawlikowski, 1995) system (to obtain results with controlled level of statistical errors) and run on Sun SPARC stations under the UNIX operating system. The AKAROA II transformed the sequential simulation programs into ones for parallel execution on a network of workstations. The length of each simulation run and the precision of the final estimates were controlled by the Spectral Analysis in Parallel Time Streams method (Pawlikowski and Yau, 1992; Pawlikowski, Yau and McNickle, 1994), which stops the simulation automatically when the steady-state estimates of performance measures obtain the required relative precision (defined as the relative width of the confidence interval).We have chosen results with relative precision $\le 5\%$ at 95% confidence level.

Modelling Assumptions: To simplify the simulation models, the following assumptions are made throughout the simulation experiments:

A1. **Traffic:** All traffic is assumed to be of asynchronous type.

A2. **Packet Generation:** Streams of data packets generated at stations are modelled as independent Bernoulli processes, both in the case of single and batched arrivals, assuming that maximum one packet (or one batch in batched stream) can arrive during a slot time. We also consider Poisson arrival processes.

A3. **Packet Size:** Packets are of fixed length. The time axis is divided into slots of equal length and the transmission of one packet takes one slot time.

A4. **Buffer Size:** Each station in the network has a large buffer, modelled as a buffer of infinite size, to store packets. This assumption means that packets cannot be lost due to buffer overflows when the system is under manageable input loads.

A5. **Processing Delay:** The station's latency or processing delay is negligible if compared with slot duration. The processing of control data contained in the header can be done in a fraction of a slot time.

A6. **Destination Addresses:** We assume that the packets arriving at a station are uniformly destined to $N-1$ other stations in the network.

A7. **Stations Spacing:** The stations can be arbitrarily spaced on the bus.

A8. **Analysis:** We study the network performance under steady-state conditions.

Model Description: This section describes the p_i-persistent protocol with respect to a unidirectional single-folded bus network, but it can be operated effectively on a dual bus network as well (Mukherjee, 1990 and 1991). We consider a single-folded bus network (Tseng and Chen, 1983) which consists of N stations interconnected via point-to-point links as shown in Fig.1. Stations are labelled $1, 2, \cdots, N$ according to their relative position on the bus, starting with the station closest to the Head of the Bus (HOB). Each station has a transmitter T on the outbound channel and a receiver R on the inbound channel. N Stations are using the bus for communication, each sensing the outbound (using a sense tap S) and inbound (using receive tap R) channels.

New packets generated by a station are queued at the station in First-Come-First-Served (FCFS) order until they are transmitted. If a slot contains a packet transmitted by a station, it is called "busy" slot otherwise, it is called an "empty" slot. A single bit (B) in the header of each slot is used to indicate whether a slot is empty (B = 0) or busy (B = 1). The Head of Bus (HOB) continuously generates empty slots and slots are dropped off at the End of Bus (EOB). If a station i has a packet to send, it independently attempts to transmit it in the next empty slot with probability p_i. with the probability of $(1-p_i)$ it leaves the slot empty, for use by subsequent stations. Fig. 2 describes the principles of p_i-persistent algorithm. A simulation model of this protocol was constructed from the point of view of packets moving along the bus and visiting stations in sequence. Upon receipt of an empty slot, a station will generate a random number u which is uniformly distributed between 0 and 1. If $u \le p_i$, (p_i is the channel access probability of that station) the packet at the head of queue will be transmitted, otherwise it will leave an empty slot for use by subsequent stations.

Packet Arrival Processes and Channel Access Probabilities: In our simulation model (described above), we assume data packets are generated at each station in the network due to an independent Bernoulli process, with probability λ_i (the offered load at station i) that a new packet is generated at station i during a slot time. The packet interarrival times are geometrically distributed with mean $1/\lambda_i$.

Additionally, we ran also simulation experiments assuming Poisson arrival processes, for the sake of comparison with the work of others (Mukherjee, 1990., Mathar and Pawlikowski, 1997). Under the Poisson arrival process, the packets are generated at each station following an independent process with independent increments, with mean λ_i packets per slot. The packet interarrival times are exponentially distributed with mean $1/\lambda_i$. For infinite buffer case, the p_i-persistent protocol under the equal mean packet delay fairness criterion, should operate using

$$p_i = \frac{2(1-\lambda) + \lambda_i(1+\lambda-\lambda_N)}{(2-\lambda_N)(1-\sum_{j=1}^{i-1}\lambda_j)} \tag{1}$$

Where, p_i is the channel access probability at station i $(i = 1, 2, \cdots, N)$, and $\lambda = \sum_{j=1}^{N}\lambda_j$ is the total offered traffic to the network in packets/slot. The derivation of equation (1) can be found in (Mukherjee, 1990). Note that (1) is an approximate formula for p_i, and is valid for Poisson arrival processes. For Bernoulli arrival processes equation (1) becomes (Manjunath and Molle, 1995)

$$p_i = \frac{1-\lambda+\lambda_i(\lambda-\lambda_N)}{(1-\lambda_N)(1-\sum_{j=1}^{i-1}\lambda_j)} \tag{2}$$

For loads uniformly distributed along the bus (i.e., $\lambda_1 = \lambda_2 = \cdots = \lambda_N = \lambda_i$), we observe that the difference between (1) and (2) is zero.

Packet Delay Definition: The mean packet delay at station i (denoted by $E[D_i]$) is defined as the average time (measured in slots) from the moment the packet is generated until the packet is fully shipped out from that station. A packet arriving at station i experiences the following four components of delay:

1. **Residual Time (τ_r):** This is the residual life time of the slot in which the packet is generated.
2. **Queueing Delay (τ_q):** This is the waiting time of a packet in the station's queue until it reaches the head of the queue. For example, if a packet arrives at a station already filled with k packets, it has to wait a random number of slots until k packets ahead are cleared.
3. **Contention Time (τ_c):** The amount of time a packet spends at the top of the queue before its transmission starts.
4. **Transmission Time (τ_t):** Actual transmission time which is equal to one slot.

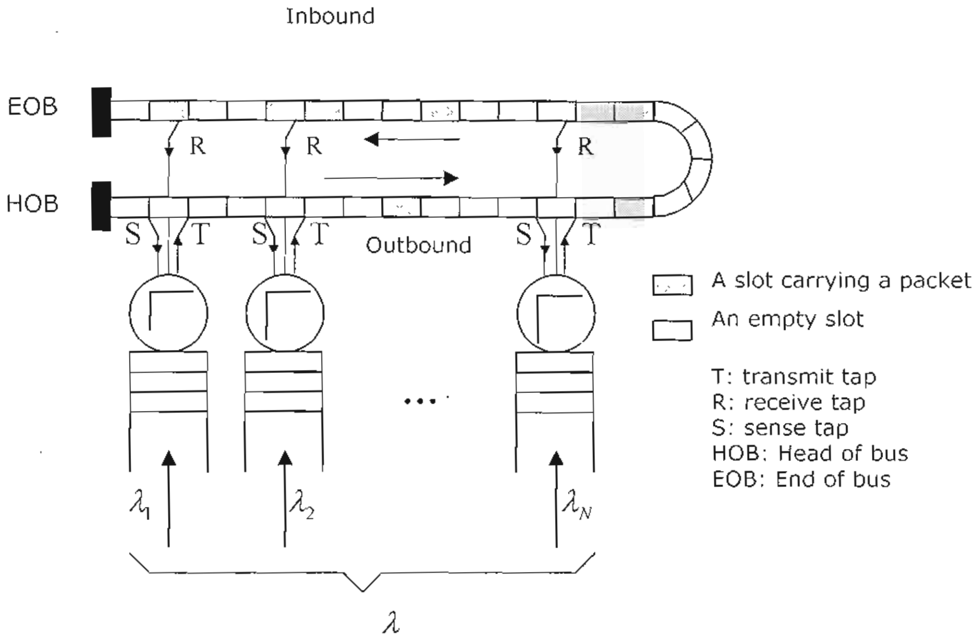


Fig. 1: A Single-Folded Bus Network with N Stations, Station Traffic $\{\lambda_i\}$, Access Probabilities $\{p_i\}$

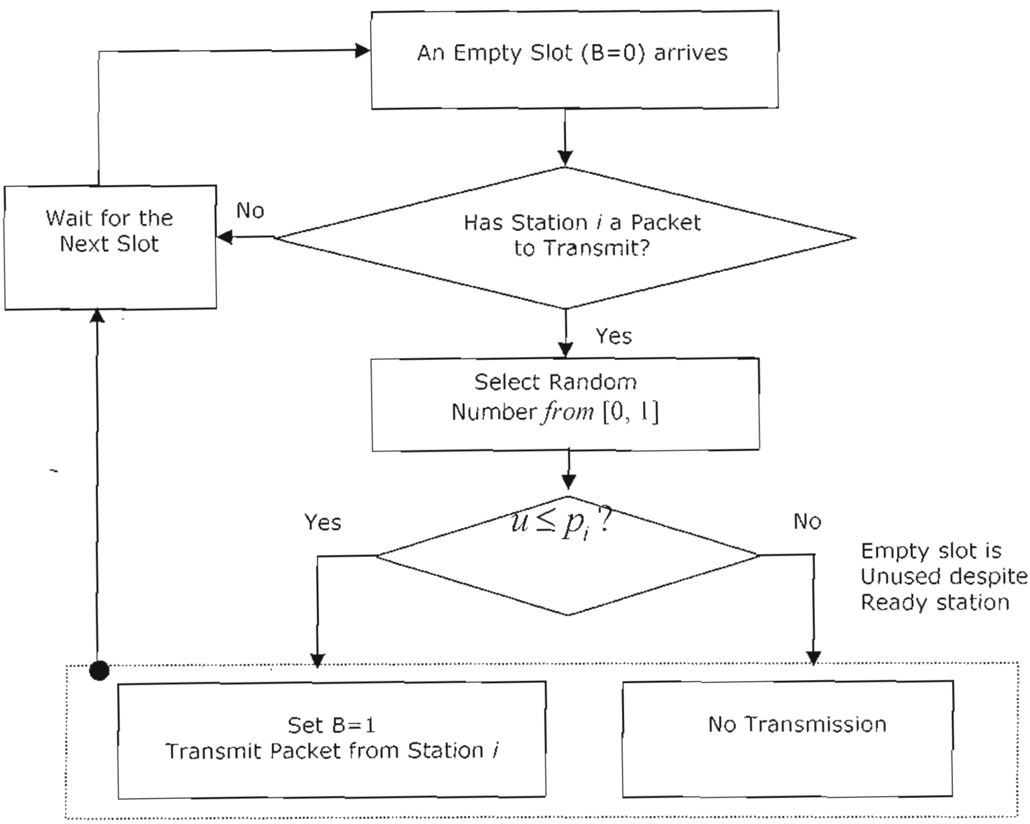


Fig. 2: Flow-Chart of P_i-Persistent Algorithm for Station i $(i = 1, 2, \cdots, N)$

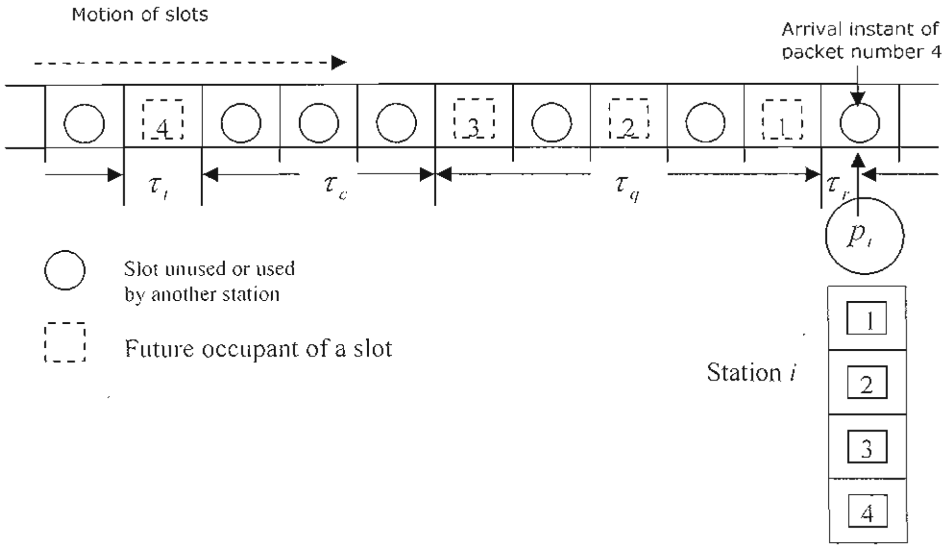


Fig. 3: Example Showing Components of Packet Delay. Delay Experience by Packet no. 4 = (8+1) + τ_r Slots

Fig. 3 shows an example of packet delay. It is looking into the future and indicating the slot that might be occupied by the 4th packet in station i's queue. However, the total delay experience by packet number 4 is (8+1) $+\tau_r$ slots (τ_r is the residual life time of the present slot). In this case, 8 slots are required for both queuing delay and contention time, and 1 slot for packet transmission.

Fairness Ratios: We define the network fairness ratio (F), as the ratio of the lowest mean delay to the highest mean delay among the individual stations in the network for a given load, i.e.,

$$F = \frac{d_{min}}{d_{max}} \times 100\% \tag{3}$$

where,

d_{min} = lowest mean delay among the individual stations in the network.
d_{max} = highest mean delay among the individual stations in the network.
The interval [d_{min}, d_{max}] provides bounds on the individual stations performance measures (in terms of mean delays) compared to the overall network performance.

The fairness ratio for station i, $i = 1, 2, \cdots, N$, is similarly defined as

$$F_i = \frac{d_{min}}{d_i} \times 100\% \tag{4}$$

where d_i is the mean packet delay of station i.

From equation (3) one can see that a protocol would offer better fairness (at any given load) when the difference (d_{max} - d_{min}) is smaller. For instance, a protocol is said to be 100% fair (at a given load) when d_{max} - d_{min} = 0, i.e., when the mean delay of all stations in the network are equal. We use these fairness ratios for studying fairness performance of p_i-persistent.

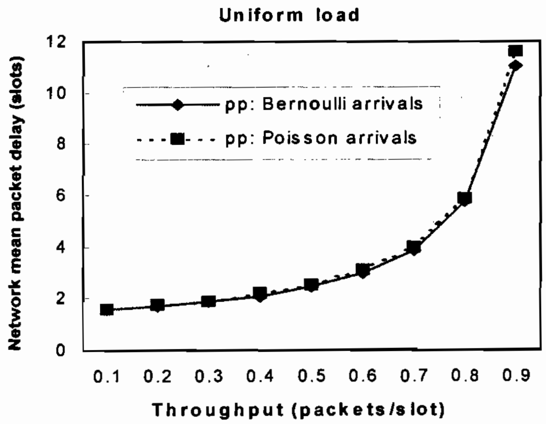
Verification of the Simulation Model: The simulation model has been verified in two ways. Firstly, the detailed status information has been traced throughout the simulation to verify the model. Secondly, we have compared our simulation results with the work of (Mukherjee, 1990; Mathar and Pawlikowski, 1997) to ensure correctness.

Simulation Results

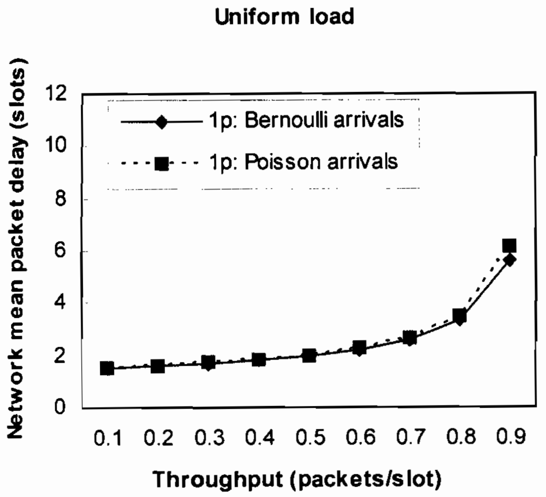
This section presents experimental results obtained from simulation runs for p_i-persistent protocol (abbreviated to pp) on the folded bus network. In the p_i-persistent simulation model, we use the p_i determined by Equation (2) for Bernoulli arrivals processes, and Equation (1) for Poisson arrivals processes. We also include simulation results for 1-persistent protocol (abbreviated to 1p) in which $p_i = 1$ for all i. Recall that all simulation results report the steady-state behaviour of the network and have been obtained with the relative precision below 0.05, at 0.95 confidence level.

Tables 1 - 4 show the mean packet delays, and the fairness ratio of pp and 1p schemes operating under uniform traffic (in which the packet arrival rate is the same for all stations) for λ = 0.2, 0.4, 0.6, and 0.8. The 95% confidence interval of the mean packet delay at each station is shown in the brackets. The mean packet delays for the overall network are shown in the last row of each table.

As can be seen from tables 1-4, the only mean delay in which 1p is larger than pp is station 10 with λ =0.8. In this case the upstream stations have used 0.8*(N-1)/N of the bandwidth and erratic behaviour at station 10 is to be expected. However, under the pp scheme the variability among the stations (in terms of the mean packet delay) is within 2%, 5%, and 15% of the



(a) The p_i-persistent protocol (pp)



(b) The 1-persistent protocol (1p)

Fig.4: Network Mean Delay Versus Throughput Behaviour of PP and 1p Schemes for $N=10$ Stations Operating Under Uniform Loads for Bernoulli and Poisson Arrival Streams

overall network mean delay for λ = 0.2, 0.4, and 0.6, respectively. The variability of mean delay among the stations becomes wider at larger values of λ.. For example, at λ = 0.8, the variability among the stations is within 46% of the network mean delay. In contrast, under the 1p scheme the variability among the stations is within 9%, 25% and 62% of the overall network mean delay for λ = 0.2, 0.4 and 0.6, respectively. At λ = 0.8, we find that the mean delay for the last station is more than six times as large as for the first station; Table 4.

Comparing the network-wide mean delay and fairness ratio F of both pp and 1p schemes, one can observe that both network-wide mean packet delay and F under the 1p scheme is smaller than under the pp scheme for a given load and the differences (both mean delay and F) become wider for larger values of λ.

Network Mean Packet Delay versus Throughput Performance: In this experiment we consider a network with $N=10$ stations operating under uniform loads (in which the packet arrival rate is the same for all stations).

The network mean packet delay versus throughput characteristic of p_i-persistent protocol (pp) and 1-persistent protocol (1p) is shown in Figs. 4(a) and (b), respectively. We present simulation results for both Bernoulli and Poisson arrivals processes for comparison purposes. As can be seen from Figs. 4(a) and (b), the dramatic increase in delay of the p_i-persistent protocol for λ > 0.7 compared with the 1-Persistent Protocol. We also observe that the differences in mean packet delays under Poisson and Bernoulli arrival processes of pp and 1p schemes are not very significant. The mean delays under the Bernoulli arrival processes are smaller than that of the Poisson arrival processes, but the differences are approximately the initial residual delay (0.5 slot) with the two tending to the same value as the mean arrival rate approaches zero. This is because the Bernoulli processes are in fact the Poisson processes in discrete time and the determinism in discrete time reduces delay.

Delay-Throughput Performance of Selected Stations (Bernoulli Packet Arrivals, Uniform Loading): The mean packet delay versus throughput performance of Stations 1, 3, 5, 8 and 10, under pp and 1p schemes in a network with $N=10$ stations, is shown in Fig. 5(a) and (b), respectively.

By comparing Fig. 5(a) and (b) we can see that the delay-throughput performance of Stations 1, 3, 5 and 8 is better (in the sense that they experience lower mean delay) under the 1p scheme than under pp scheme for all λ, $\lambda \leq 1$. It is interesting to observe that although the mean packet delay of stations 1,3,5 and 8 under the 1p scheme is not equal to each other, their mean delay is smaller than in the pp scheme, for a given load. This is because of the work conservation of 1-persistent protocol (i.e. slots are never wasted if a station has packets for transmission).

Going back to Fig. 5(a) and (b), we see that Station 10 under the 1p scheme experiences longer delay than under the pp scheme for $\lambda \geq 0.4$ packets/slot. This is because under the 1-persistent protocol the last station is offered smaller percentage of the idle bandwidth than any other station in the network.

Mean packet Delay Versus Station Position (Bernoulli Batch Arrivals, Uniform Loading): In this experiment we consider a network with $N=20$ stations where packets arrive at each station in batches and the batch sizes are geometrically

Table 1: Mean Packet Delay (with 95% Confidence Intervals) and Fairness Ratio for P_i-Persistent (Pp) and 1-Persistent (1p) Protocols under Poisson Arrival Processes and *Uniform* Loading with $\lambda = 0.2$ Packets/Slot

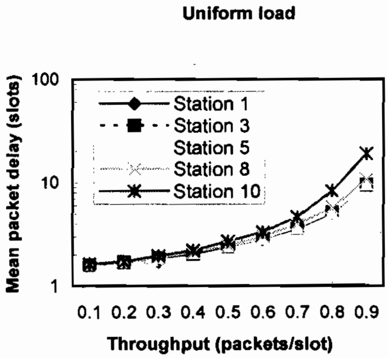
Station i	λ_i	p_i	Simulated $E[D_i]$ (slots)		F_i (In %)	
			pp	1p	pp	1p
1	0.02	0.820	1.743(1.704,1.782)	1.512(1.465,1.559)	99.0	100
2	0.02	0.837	1.737(1.674,1.800)	1.522(1.480,1.564)	99.4	99.3
3	0.02	0.854	1.743(1.694,1.793)	1.565(1.522,1.608)	99.0	96.6
4	0.02	0.872	1.753(1.698,1.808)	1.617(1.558,1.677)	98.5	93.5
5	0.02	0.891	1.726(1.675,1.777)	1.574(1.508,1.639)	100	96.1
6	0.02	0.911	1.744(1.682,1.807)	1.613(1.540,1.687)	99.0	93.7
7	0.02	0.932	1.735(1.681,1.789)	1.646(1.565,1.728)	99.5	91.9
8	0.02	0.953	1.726(1.692,1.760)	1.681(1.630,1.732)	100	89.9
9	0.02	0.976	1.756(1.696,1.816)	1.738(1.663,1.812)	98.3	87.0
10	0.02	1.000	1.779(1.750,1.809)	1.761(1.673,1.849)	97.0	85.9
Overall Network	$\lambda = 0.2$		1.744	1.623	97.0	85.9

Table 2: Mean Packet Delay (with 95% Confidence Intervals) and Fairness Ratio for P_i-Persistent (Pp) and 1-Persistent (1p) Protocols under Poisson Arrival Processes and *Uniform* Loading with $\lambda = 0.4$ Packets/Slot

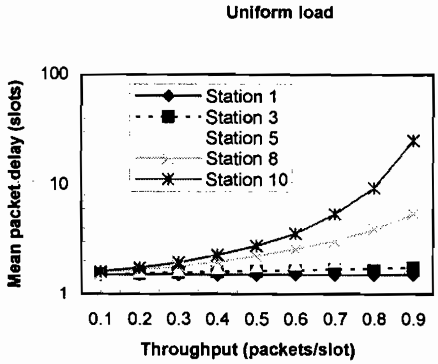
Station i	λ_i	p_i	Simulated $E[D_i]$ (slots)		F_i (In %)	
			pp	1p	pp	1p
1	0.04	0.640	2.176(2.124,2.228)	1.523(1.502,1.545)	96.5	100
2	0.04	0.667	2.160(2.084,2.236)	1.562(1.538,1.585)	97.2	97.5
3	0.04	0.696	2.100(2.018,2.181)	1.610(1.579,1.640)	100	94.6
4	0.04	0.727	2.112(2.032,2.191)	1.674(1.640,1.708)	99.4	91.0
5	0.04	0.762	2.136(2.084,2.188)	1.724(1.683,1.764)	98.3	88.3
6	0.04	0.800	2.159(2.112,2.207)	1.846(1.775,1.918)	97.3	82.5
7	0.04	0.842	2.232(2.125,2.339)	1.948(1.882,2.015)	94.1	78.2
8	0.04	0.889	2.225(2.159,2.291)	2.073(1.982,2.165)	94.4	73.5
9	0.04	0.941	2.233(2.172,2.295)	2.161(2.067,2.255)	94.0	70.5
10	0.04	1.000	2.291(2.207,2.376)	2.305(2.198,2.412)	91.7	66.1
Overall Network	$\lambda = 0.4$		2.182	1.843	91.7	66.1

Table 3: Mean Packet Delay (with 95% Confidence Intervals) and Fairness Ratio for P_i-Persistent (Pp) and 1-Persistent (1p) Protocols Under Poisson Arrival Processes and *Uniform* Loading With $\lambda = 0.6$ Packets/Slot

Station i	λ_i	p_i	Simulated $E[D_i]$ (slots)		F_i (In %)	
			pp	1p	pp	1p
1	0.06	0.460	2.943(2.796,3.089)	1.531(1.522,1.541)	98.6	100
2	0.06	0.489	2.910(2.823,2.996)	1.601(1.581,1.621)	99.7	95.6
3	0.06	0.523	2.902(2.789,3.015)	1.681(1.663,1.700)	100	91.1
4	0.06	0.561	3.016(2.919,3.113)	1.820(1.802,1.838)	96.2	84.1
5	0.06	0.605	3.054(2.941,3.167)	1.961(1.935,1.986)	95.0	78.1
6	0.06	0.657	3.021(2.874,3.168)	2.128(2.080,2.176)	96.1	71.9
7	0.06	0.719	3.076(2.945,3.207)	2.350(2.281,2.419)	94.3	65.1
8	0.06	0.793	3.133(2.980,3.287)	2.663(2.579,2.748)	92.6	57.5
9	0.06	0.885	3.382(3.266,3.499)	3.137(3.049,3.224)	85.8	48.8
10	0.06	1.000	3.563(3.404,3.722)	3.668(3.528,3.808)	81.4	41.7
Overall Network	$\lambda = 0.6$		3.100	2.254	81.4	41.7

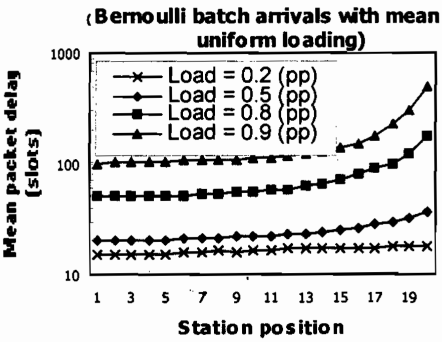


(a) The p_i-persistent protocol (pp)

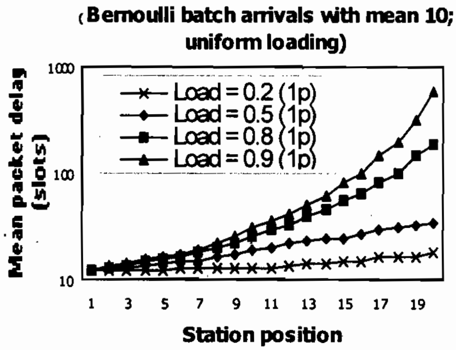


(b) The 1-persistent protocol (1p)

Fig.5: Mean Packet Delay Versus Throughput Performance for Selected Stations of Pp and 1p Schemes in a Network with $N = 10$ Stations Operating Under Uniform Loads for Bernoulli Arrivals

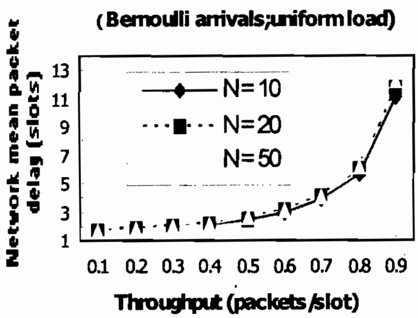


(a) The p_i-persistent protocol (pp)

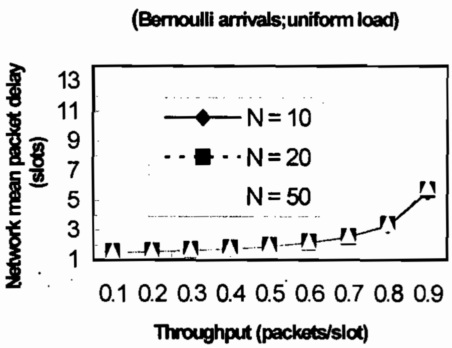


(b) The 1-persistent protocol (1p)

Fig. 6: Mean Packet Delay Versus Station Position Performance of Pp And 1p Schemes With $N = 20$ Stations (Bernoulli Batch Arrivals with Mean 10; Uniform Loading)



(a) The p_i-persistent protocol (pp)



(b) The 1-persistent protocol (1p)

Fig. 7: Effect of Increasing Number of Stations on Delay-Throughput Behaviour of Pp and 1p Schemes Operating under Uniform Loads

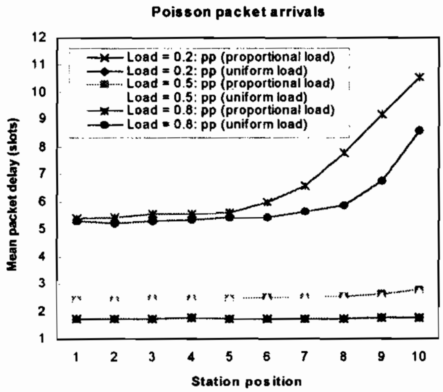


Fig.8: Mean Packet Delay Versus Station Position Performance of P_i-Persistent Protocol with $N = 10$ Stations Operating under Proportional Loads. Also Shown is the Mean Packet Delay under Uniform Loads

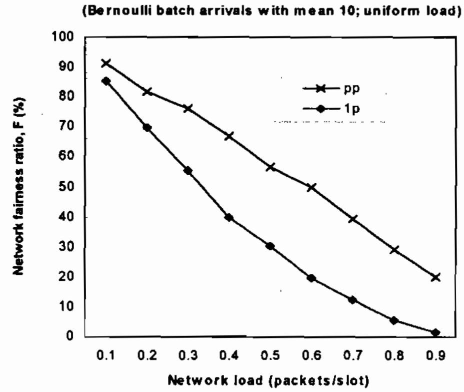


Fig.9: Network Fairness Ratio under PP and 1p Schemes for $N = 20$ Stations Operating Under Uniform Loads (Bernoulli Batch Arrivals; Geometrically Distributed Batch Sizes with Mean 10)

distributed with mean 10. For λ = 0.2, 0.5, 0.8 and 0.9, we plot the mean packet delay versus station position of pp scheme (Fig. 6a) and 1p scheme (Fig. 6b). By comparing Figs. 6(a) and (b) we find that the pp scheme actually equalises the mean packet delays of all stations by increasing the mean delays (of all stations) to that of the last station in the network. In other words, the pp scheme is achieving fairness (in terms of equal mean delay) by deteriorating the performance of the upstream stations. In contrast, under the 1p scheme the mean delays of individual stations depend strongly on their position on the bus. If we compare the performance of first ten stations (Stations 1 to 10) of pp and 1p schemes, we see that stations under the 1p scheme have lower mean delay than the pp scheme at any given load. The difference in mean packet delay under pp and 1p schemes becomes greater at higher load.

Now we compare the performance of last ten stations (Stations 11 to 20) on the bus under the pp and 1p schemes. We can see that under the 1p scheme all stations experience lower mean delay on the average than under the pp scheme, except the last two stations, viz., Station 19 and 20 at λ = 0.9.

Influence of the Number of Stations: In this experiment we ran simulation by considering networks with N = 10, 20 and 50 stations, assuming that packets arrive at stations according to independent Bernoulli process and uniform loading. The effect of increasing N on the delay-throughput performance of pp and 1p schemes is shown in Figs. 7(a) and (b), respectively. We observe that (both in the pp and 1p case) the influence of N on network-wide mean packet delay is insignificant for any loads. This is because when N increases, it causes λ_i to decrease (for a given λ) and consequently almost the same level of performance is maintained. Thus, the delay versus throughput performance is independent of N.

Mean Packet Delay Characteristics Under proportional Load: In this experiment we consider a network with $N = 10$ stations where packets arrive at each station according to independent Poisson processes. For λ = 0.2, 0.5 and 0.8, the mean packet delay versus station position for loads proportionally distributed along the bus (in which packet arrival rate to a station decreases linearly as we move downstream on the bus) are depicted in Fig. 8. The corresponding results for uniform loads are also shown for comparison.

As our simulation results show, the influence of traffic pattern on mean packet delay at each station under p_i-persistent protocol is insignificant for λ = 0.2 and 0.5. At higher traffic level one can see that there is an influence of traffic pattern on the mean packet delay; see the curve for λ = 0.8. For proportional loads, the stations experience a bit longer delay on average than under uniform loads, specially as we move further downstream along the bus.

Network Fairness Ratio versus Network Load (Bernoulli Batch Arrivals, Uniform Loading): In Fig. 9, we compare the network fairness ratio (F) of the p_i-persistent protocol (pp) and 1-persistent protocol (1p) for a 20-station network. The parameter F (expressed in %) is determined by equation (3). One can see that the pp scheme can maintain higher F than the 1p scheme for a given load. Under the 1p scheme, the parameter F could drop to zero at heavy traffic conditions when the size of the network increases. This is because the "spread" in the mean packet delay of the first and the last station in the network increases dramatically under heavy load conditions. In contrast, the pp scheme can maintain non-zero F (by sacrificing network performance in terms of increased packet delay), regardless of network size and load.

Table 4: Mean Packet Delay (with 95% Confidence Intervals) and Fairness Ratio for P_i-Persistent (Pp) and 1-Persistent (1p) Protocols under Poisson Arrival Processes and *Uniform* Loading with $\lambda = 0.8$ Packets/Slot

Station i	λ_i	p_i	Simulated $E[D_i]$ (slots)		F_i (In %)	
			pp	1p	pp	1p
1	0.08	0.280	5.302(5.147,5.457)	1.546(1.541,1.550)	98.3	100
2	0.08	0.304	5.214(5.010,5.417)	1.649(1.643,1.654)	100	93.8
3	0.08	0.333	5.314(5.112,5.515)	1.783(1.775,1.791)	98.1	86.7
4	0.08	0.368	5.360(5.216,5.503)	1.963(1.948,1.978)	97.3	78.8
5	0.08	0.412	5.452(5.305,5.598)	2.225(2.205,2.246)	95.6	69.5
6	0.08	0.467	5.454(5.303,5.605)	2.606(2.570,2.642)	95.6	59.3
7	0.08	0.538	5.640(5.458,5.822)	3.204(3.145,3.262)	92.4	48.3
8	0.08	0.636	5.877(5.701,6.054)	4.168(4.067,4.269)	88.7	37.1
9	0.08	0.778	6.758(6.503,7.013)	5.958(5.771,6.144)	77.2	25.9
10	0.08	1.000	8.590(8.169,9.011)	10.012(9.550,10.474)	60.7	15.4
Overall Network	$\lambda = 0.8$		5.896	3.511	60.7	15.4

Conclusion

Through a number of simulation experiments we investigated the fairness mechanism employed in the p_i-persistent protocol, assuming the mean packet delay as the criteria for fairness measurement. Under the assumptions made, the results showed that the 1-persistent protocol can offers lower mean packet delay than the p_i-persistent protocol at any given load. However, under the 1-persistent scheme the delay-throughput performance of individual stations in the network depends strongly on their position on the bus. In contrast, under the p_i-persistent protocol the network performance deteriorates (in terms of packet delays) if one secures its fairness. Therefore, to achieve optimum network performance, both in the sense of lower mean delay and fairness, the p_i-persistent protocol requires improvement.

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