HARP: A Hybrid Random Access and Reservation Protocol for WDM Passive Star Networks

GEORGIOS I. PAPADIMITRIOU and DIMITRIS G. MARITSAS
C.T.I., Department of Computer Engineering, University of Patras, Patras, Greece.

ABSTRACT: A Hybrid Random Access and Reservation Protocol (HARP) for WDM Passive Star Networks is introduced. According to the HARP protocol, all the ready stations transmit their packets in a slotted ALOHA-like fashion. An array of acoustooptic tunable filters which is placed at the network hub, allows at most one packet per wavelength to pass to the star coupler. In this way, collisions are eliminated. All the blocked packet transmissions are used as reservations for future transmissions. Thus, HARP is a hybrid protocol which stands between Random Access and Reservation Protocols and combines the advantages of both families of protocols. Analytical and simulation results are presented which indicate that a WDM Passive Star network operating under the HARP protocol achieves a high performance under any load conditions.

I. INTRODUCTION

The increasing bandwidth demands of the new generation of Local Area Networks have led to the utilization of optical fiber as a transmission medium.

A first attempt to implement fiber-optic networks was simply to replace the well-known copper wire by an optical fiber. Due to the limited speed of the stations' electronic circuits, single channel optical networks - as FDDI, DQDB, Fasnet, Expressnet, etc - were not proved capable of supporting Gigabit data rates.

The introduction of the Wavelength Division Multiplexing (WDM) technique [1] solved this problem by dividing the available optical bandwidth into multiple channels of lower bandwidth which can be easily supported by the stations' electronic circuits. Both, multiplexing and demultiplexing of the multiple channels, are performed in the optical domain - by using totally passive optical devices - without the need of optical to electronic translation and vice versa.

Passive Star networks (fig.1) - which are a special category of WDM networks - use a Passive Star Coupler in order to broadcast all inputs to all outputs. There are four possible configurations of the Passive Star architectural form: a) Fixed lasers and fixed optical filters [1], [3], b) tunable lasers and tunable optical filters [1], c) fixed lasers and tunable optical filters [1], [2], [8] and d) tunable lasers and fixed optical filters [1], [4], [5], [9], [10].

Channel collisions have been a limiting factor in the application of random access protocols to WDM Passive Star networks. In this paper, a new collision-free random access protocol for WDM Passive Star networks using tunable lasers and fixed optical filters is introduced.

The paper is organized as follows: The proposed HARP protocol is presented in Section II, while Section III discusses the application of HARP to networks with large propagation delay. A performance analysis of the HARP protocol is presented in Section IV. In Section V, extensive simulation results are presented, which indicate the superiority of HARP among other well-known protocols. Finally, concluding remarks are given in Section VI.

II. THE HARP PROTOCOL

According to the HARP protocol, an array of acoustooptic tunable filters is placed at the network hub, in order to control the passing of the transmitted packets to the star coupler. In order to eliminate collisions, only one station per wavelength is allowed to access the star coupler, at each time slot. This station is selected among them, which have tried to transmit on this wavelength during the last time slot, but their transmissions were blocked by the acoustooptic filters.

According to the HARP protocol, each packet transmission has two roles:

Primary Role: To transport data.

Secondary Role: To set a reservation for the next time slot.

When a packet transmission fails to play its primary role, then the secondary role is activated.

Thus, HARP is a hybrid protocol which stands between Random Access and Reservation Protocols and combines the advantages of both families of protocols.

A network using the HARP protocol can be divided into three basic modules which are

0-7803-1820-X/94 $4.00 © 1994 IEEE

described below. The reader can consult Figure 2 in order to study an example of the HARP protocol for three stations and two wavelengths. In this Section, we assume that the round-trip propagation delay is negligible. The application of HARP to networks with large propagation delay will be discussed in Section III.

II.1 The Broadcast-and-Select Module

The set of nodes is defined as $U=\{u_1,...,u_N\}$, where N is the number of nodes. The set of wavelengths is defined as $\Lambda=\{\lambda_1,...,\lambda_W\}$, where W is the number of wavelengths.

Each transmitter is provided with a tunable laser which can be tuned to each one of the W available wavelengths. Optical fibers are used to connect the outputs of the lasers to the network hub.

There, each optical signal passes via an acoustooptic tunable filter (AOTF) which has multiple wavelength selection capability [11],[12]. At any time slot t, each filter F_k $(k=1,...,N)$ is tuned to pass only a subset of wavelengths $\Lambda_k(t)$ (with $\Lambda_k(t)\subseteq\Lambda$). Assume that a user u_k transmits on the λ_i wavelength at time slot t. If $\lambda_i\in\Lambda_k(t)$ then the signal passes to the star coupler. Otherwise, if $\lambda_i\notin\Lambda_k(t)$, then the signal is blocked by the acoustooptic filter F_k. The first output of each acoustooptic filter - which contains the selected wavelengths - is connected to an input port of the Star Coupler.

The output ports of the Star Coupler are connected to the receivers via optical fibers. Each receiver is provided with a fixed optical filter which passes only one wavelength.

II.2 The Control Module

For each wavelength λ_i $(i=1,...,W)$, the passing of the packets is controlled by a separate control circuit. At the end of each time slot t, the passing station $ps_i(t+1)$ of the next time slot, is selected by means of a simple two-step algorithm:

1) Determine the set $B_i(t)$ of stations which transmitted a packet on wavelength λ_i, but their transmissions were blocked by the acoustooptic filters, at time slot t.

2) If $B_i(t)\neq\emptyset$ then the passing station $ps_i(t+1)$ is chosen at random among the stations in set $B_i(t)$. If $B_i(t)=\emptyset$ then the passing station $ps_i(t+1)$ is chosen at random among all the stations.

After selecting the passing station $ps_i(t+1)$ for each wavelength λ_i, the sets $\Lambda_k(t+1)$ for $k=1,...,N$ are constructed in the following way: $\Lambda_k(t+1) = \{ \lambda_i: ps_i(t+1) = u_k \}$

II.3 The Feedback Module

The feedback information needed for the implementation of the above algorithm is the set of stations which transmitted a packet on the λ_i wavelength, but their transmissions were blocked by the acoustooptic filters, at time slot t.

Each acoustooptic filter [11],[12] has two output ports: one output port containing the passing wavelengths and a second output port containing the blocked wavelengths. The second port of each filter is connected to a WDM demultiplexer which separates the different wavelengths. Each wavelength is detected for transmission by means of a photodetector. The outputs of the photodetectors which detect wavelength λ_i $(i=1,...,W)$ are connected to the corresponding control circuit which controls this wavelength. In this way, the control circuit of each wavelength λ_i is informed about which stations have tried to transmit on this wavelength, but their transmissions were blocked. Thus, the $B_i(t)$ set is available for each wavelength λ_i.

II.4 The Operation of the HARP protocol

At the beginning of each time slot, each station u_k which has a packet to transmit, tunes its laser to the receiver's wavelength and transmits the packet. The transmitter can ascertain the result of its transmission by using one of the methods reported in [7]. The round-trip propagation delay was assumed to be negligible. Therefore, the feedback information is immediately available.

If the transmitted packet passes via the F_k filter, then the transmitting station deletes the packet from its queue and continues with the next packet.

If the transmitted packet is blocked by the filter F_k, then the transmitting station repeats the transmission at the next time slot.

It must be noted, that the stations of a network using the HARP protocol are operating in a slotted ALOHA-like fashion. The HARP protocol is implemented at the network hub. Therefore, it is invisible to the stations of the network. The extremely simple operation of the stations is an important advantage of the HARP protocol.

III. THE MAN VERSION OF HARP

In the previous Section, the round-trip propagation delay was assumed to be negligible. However, the HARP protocol can be applied to symmetric networks with large propagation delay, by making use of pipelining [2],[8].

Consider a network with a round-trip propagation delay from the stations to the network hub and back, equal to t_d slots, where t_d is an even integer number. Thus, the stations are placed $(t_d/2)$ slots from the network hub.

When pipelining is used, each ready station is continuously transmitting packets without waiting for an acknowledgement. All the transmitted but unacknowledged packets, are kept at the station, in a buffer. After a round-trip propagation delay equal to t_d slots, the transmitter will be informed about the success or the blocking of its transmission. In the former case, the packet will be deleted from the buffer. In the latter, it will be retransmitted immediately.

Let $B_i(t-t_d)$ be the set of stations which transmitted a packet on wavelength λ_i at time slot $(t-t_d-(t_d/2))$, but their transmissions were blocked by the acoustooptic filters at time slot $(t-t_d)$.

At each time slot t, the passing station $ps_i(t+1)$ $(i=1,...,W)$ of the next time slot is selected in the following way: If $B_i(t-t_d)\neq\emptyset$ then the passing station $ps_i(t+1)$ is chosen at random among the stations in set $B_i(t-t_d)$. If $B_i(t-t_d)=\emptyset$ then the passing station $ps_i(t+1)$ is chosen at random among all the stations.

Of course, this extension of the HARP protocol requires the use of (t_d+1) buffers for keeping the $B_i(n)$ sets, for $n=(t-t_d),...,t$.

Due to the use of pipelining, the waiting time between two successive packet transmissions is eliminated, and consequently, the performance of the HARP protocol remains high, even when the propagation delay is large.

IV. PERFORMANCE ANALYSIS

In order to simplify the calculation, we assume that the network operates under heavy load conditions. Thus, all the users are always ready to transmit. (1)

Let $S_{j_1...j_W}$ be the state where: $j_1,j_2,...,j_W$ users are waiting to transmit on wavelengths $\lambda_1,\lambda_2,...,\lambda_W$ correspondingly. Due to assumption (1) we always have: $j_1+j_2+...+j_W=N$. Let $P_{j_1...j_W}$ be the probability that the network is at the $S_{j_1...j_W}$ state.

Let $\Pi_{i_1...i_W\rightarrow j_1...j_W}$ be the probability that the network transits from state $S_{i_1...i_W}$ to state $S_{j_1...j_W}$ after a time slot. We have the following system of equations:

$$P_{j_1...j_W}=\sum_{\substack{i_1+....+i_W=N\\ i_x\in\{0,...,N\}\\ \text{for } x=1,...,W}} P_{i_1...i_W}\,\Pi_{i_1...i_W\rightarrow j_1...j_W} \qquad (2)$$

$$\text{with:}\quad \sum_{\substack{i_1+...+i_W=N\\ i_x\in\{0,....,N\}\\ \text{for } x=1,....,W}} P_{i_1...i_W}=1$$

In order to solve the above system of equations, we must calculate the transition probabilities $\Pi_{i_1...i_W\rightarrow j_1...j_W}$.

The transition probabilities are calculated as follows:

$$\Pi_{i_1 \ldots i_W \to j_1 \ldots j_W} = \sum_{b_1 \ldots b_W = 0 \ldots 0}^{1 \ldots 1} Z_{b_1 \ldots b_W} A_{(j_1 - i_1 + b_1) \ldots (j_W - i_W + b_W)} \quad (3)$$

where:

$Z_{b_1 \ldots b_W}$ is the probability that $b_1, \ldots, b_W$ successful (not blocked) transmissions (with $b_i \in \{0,1\}$) will occur on wavelengths $\lambda_1, \ldots, \lambda_W$ correspondingly.

Let T_{i_k} be the probability that a successful transmission will occur on a wavelength λ_i, given that i_k packets are trying to transmit on this wavelength. If i_k (for $k=1,\ldots,W$) are the same as in relation (3) then, the probability $Z_{b_1 \ldots b_W}$ is calculated as follows:

$$Z_{b_1 \ldots b_W} = \prod_{k=1}^{W} \left((1-b_k) + T_{i_k} (-1)^{(b_k+1)} \right) \quad (4)$$

$A_{k_1 \ldots k_W}$ is the probability that the $b_1 + \ldots + b_W$ users which have a new packet at the top of their queues, will be distributed to the W wavelengths in the following way: k_1 users to wavelength λ_1, k_2 users to wavelength λ_2, ... , k_W users to wavelength λ_W. If we assume that the destination-station of each packet is chosen at random among all the stations, and that the same number of destination-stations is fixedly tuned to each wavelength, it follows that each wavelength is chosen with equal probability. Therefore, if we define $m = b_1 + \ldots + b_W$, we have:

$$A_{k_1 \ldots k_W} = \begin{cases} \dfrac{m!}{k_1! \ldots k_W! \; W^m} & \text{if } k_1, \ldots, k_W \geq 0 \\ 0 & \text{elsewhere} \end{cases} \quad (5)$$

To calculate the probabilities $Z_{b_1 \ldots b_W}$ by using relation (4) we need the probability T_{i_k}, which is given by the following relation:

$$T_{i_k} = (1 - G_{i_k})(1) + (G_{i_k})(i_k / N) \quad (6)$$

G_{i_k} denotes the probability that no unsuccessful (blocked) transmission has happened on a wavelength λ_i during the last time slot (thus, no reservation has been set), given that i_k users are waiting to transmit on this wavelength during the current time slot. G_{i_k} is calculated as follows:

$$G_{i_k} = \frac{\sum\limits_{\substack{\text{cond. I} \\ \text{and } a_1 = a_2}} R_{a_1 a_2 a_3}}{\sum\limits_{\text{cond. I}} R_{a_1 a_2 a_3}} \quad (7)$$

where conditions I are:

1) $a_2 \in \{0,1\}$, 2) $i_k + 1 \geq a_1 \geq a_2$ and 3) $a_3 = i_k + a_2 - a_1$

and $R_{a_1 a_2 a_3}$ is the probability that: a_1 users tried to transmit on a wavelength λ_i during the last time slot, a_2 users transmitted successfully and a_3 new users were added to this wavelength after the last time slot. Recall that i_k is the number of users which are waiting to transmit on the λ_i wavelength during the current time slot. Therefore, $i_k = a_1 - a_2 + a_3$. The probability $R_{a_1 a_2 a_3}$ is calculated as follows:

$$R_{a_1 a_2 a_3} = P_{a_1} \left((1-a_2) + T_{a_1} (-1)^{(a_2+1)} \right) D_{a_3} \quad (8)$$

where:

a) P_{a_1} is the probability the a_1 packets are waiting to be transmitted on a wavelength λ_i.

We have: $$P_{a_1} = \sum_{\substack{i_2 + \ldots + i_W = N - a_1 \\ i_x \in \{0, \ldots, N\} \\ \text{for } x = 2, \ldots, W}} P_{a_1 i_2 \ldots i_W} \quad (9)$$

b) D_{a_3} is the probability that a_3 new users were added to a wavelength λ_i after the last time slot. We have:

$$D_{a_3} = \sum_{i=a_3}^{W} \left[\binom{W}{i} T^{i} (1-T)^{W-i} \right] \left[\binom{i}{a_3} (1/W)^{a_3} \left(1-(1/W)\right)^{i-a_3} \right] \tag{10}$$

where T is the mean total throughput of the network. It is calculated as follows:

If $T_{i_1 \ldots i_W} = \frac{\sum_{k=1}^{W} T_{i_k}}{W}$ is the mean total throughput of the network when it is at the $S_{i_1 \ldots i_W}$ state, then the mean total throughput of the network is calculated as follows:

$$T = \sum_{\substack{i_1 + \ldots + i_W = N \\ i_x \in \{0, \ldots, N\} \\ \text{for } x=1, \ldots, W}} P_{i_1 \ldots i_W} T_{i_1 \ldots i_W} \tag{11}$$

If we give random initial values to $P_{i_1 \ldots i_W}$ and T, we can cyclically execute the above calculations, up to the convergence of $P_{i_1 \ldots i_W}$ and T.

It must be noted that, in all cases, the simulation results are very close to the analytical ones. In order to satisfy the heavy load assumption of the above analysis, the simulated load were 2 packets per wavelength per slot. Both analytical and simulation results are appeared in Table I.

V. SIMULATION RESULTS

In the following, the proposed HARP protocol is compared to two commonly used protocols for WDM Passive Star networks using tunable lasers and fixed receivers: the Slotted ALOHA, and the TDMA.

Due to its random access nature, the slotted ALOHA protocol [4], [5] achieves a very satisfactory performance when it operates under low load conditions. Therefore, a performance comparison between the Slotted ALOHA and the HARP protocol will be useful in studying the low-load performance of the latter. Furthermore, the HARP protocol can be considered as an extension of the slotted ALOHA one. Therefore, a performance comparison between the two protocols will clearly demonstrate the performance improvement which is due to the use of the proposed filter-based passing mechanism.

NOTE: The performance of the S.ALOHA protocol is dependent on the value of the transmission probability P [4]. For example, a high value of P would lead to a satisfactory low-load performance and an unacceptable high-load performance. For each simulated network, the transmission probability P of the S.ALOHA protocol was appropriately selected, so that it achieves a satisfactory performance under both high and low load conditions.

Furthermore, simulation results for the collision-free TDMA [5] protocol (using the allocation table of [6]) are also presented. Due to the absence of collisions, this protocol achieves a high performance when it operates under high load conditions. Therefore, a performance comparison between this protocol and the HARP one, will be very useful in studying the high-load performance of the latter.

The protocols which are under comparison were simulated to be applied to two different networks (N_1 and N_2). The number of stations N and the number of wavelengths W of each simulated network, were taken to be as follows: Network N_1: N=8, W=4. Network N_2: N=24, W=8.

For all networks, the total bandwidth was taken to be equal to 10 Gbps. The packet size was equal to 1000 bits, while the queue size was 3 packets. The fixed optical filter of each station u_i passes only the λ_j wavelength, with $j = \lceil i/W \rceil$. The propagation delay is assumed to be negligible. Each station is assumed to have only packet switched traffic. All the stations have the same arrival rate of packets, with packet arrivals following the Poisson model.

We have used the following two broadly used performance metrics in order to compare the three protocols:

1) The delay versus throughput characteristic.

2) The throughput versus offered load characteristic.

The delay versus throughput characteristics of the compared protocols when they are applied to networks N_1 and N_2, are appeared at figures 3 and 5 correspondingly. The throughput versus offered load characteristics of the compared protocols when they are applied to networks N_1 and N_2 are appeared at figures 4 and 6, correspondingly. Each characteristic was constructed by using 21 points, with each point corresponding to a different value of the offered load. The load values were taken to be from 0.005 to 1.0 packets per wavelength per slot.

The following two results can be obtained from the above graphs:

1) When the network operates under low load conditions, the HARP protocol achieves a low delay. This is due to the random access nature of the HARP protocol.

2) Under high load conditions, the HARP protocol achieves a high throughput and a low delay. This is due to the absence of collisions and the presence of a reservation mechanism.

Thus, due to its hybrid nature, the HARP protocol is capable of operating efficiently under both high and low load conditions.

VI. CONCLUSION

This paper has presented a new hybrid protocol for WDM Passive Star networks. The proposed HARP protocol stands between random access and reservation protocols and combines the advantages of both families of protocols.

The performance of the HARP protocol was studied via analytical and simulation results. It was found that HARP achieves a high performance under any load conditions.

VII. REFERENCES

[1] C.A.Brackett, "Dense Wavelength Division Multiplexing Network: Principles and Applications", IEEE Journal on Selected Areas in Communications, vol.8, no.6, pp.948-964, August 1990.

[2] M.-S.Chen, N.R.Dono and R.Ramaswami, "A Media Access Protocol for Packet Switched Wavelength Division Multiaccess Metropolitan Network", IEEE Journal on Selected Areas in Communications, vol.8, no.6, pp.1048-1057, August 1990.

[3] M.S.Goodman, H.Kobrinski, M.P.Vecchi, R.M.Bulley and J.L.Gimlett, "The LAMBDANET Multiwavelength Network: Architecture, Applications and Demonstrations", IEEE Journal on Selected Areas in Communications, vol.8, no.6, pp.995-1004, August 1990.

[4] A.Ganz and Z.Koren, "WDM Passive Star - Protocols and Performance Analysis", IEEE INFOCOM'91, 7-11 April 1991, Bal Harbour, Florida, U.S.A.

[5] A. Ganz, "End-to-End Protocols for WDM Star Networks", IFIP/WG6.1-WG6.4 Workshop on Protocols for High-Speed Networks, Zurich, Switzerland, May 1989.

[6] A. Ganz and I.Chlamtac, "Path Allocation Access Control in Fiber Optic Communication Systems", IEEE Transactions on Computers, vol.38, no.10, pp.1372-1382, October 1989.

[7] K.M.Sivalingam, K.Bogineni and P.W.Dowd, "Pre-Allocation Media Access Control Protocols for Multiple Access WDM Photonic Networks", SIGCOMM'92, August 17-20, 1992, Baltimore, Maryland, U.S.A.

[8] G.I.Papadimitriou and D.G.Maritsas, "WDM Passive Star Networks: Receiver Collisions Avoidance Algorithms using Multifeedback Learning Automata", IEEE 17th Conference on Local Computer Networks, 13-16 September 1992, Minneapolis, Minnesota, U.S.A.

[9] G.I.Papadimitriou and D.G.Maritsas, "Learning Automata - Based Random Access Protocols for WDM Passive Star Networks", IEEE GLOBECOM'93, 29 November - 2 December 1993, Houston, Texas, U.S.A.

[10] G.I.Papadimitriou and D.G.Maritsas, "LABON: A Learning Automata - Based Optical Network", IEEE ICC'94, 1-5 May 1994, New Orleans, Louisiana, U.S.A.

[11] K.W.Cheung, "Acoustooptic Tunable Filters in Narrowband WDM Networks: System Issues and Network Applications", IEEE Journal on Selected Areas in Communications, vol.8, no.6, pp.1015-1025, August 1990.

[12] D.A.Smith, J.E.Baran, J.J.Johnson and K.W.Cheung, "Integrated-Optic Acoustically-Tunable Filters for WDM Networks", IEEE Journal on Selected Areas in Communications, vol.8, no.6, pp.1151-1159, August 1990.

	Throughput	
	Analysis	Simulation
N=4, W=4	0.4988	0.4983
N=8, W=4	0.7312	0.7312
N=12, W=4	0.8333	0.8347

Table I: The throughput of the HARP protocol.

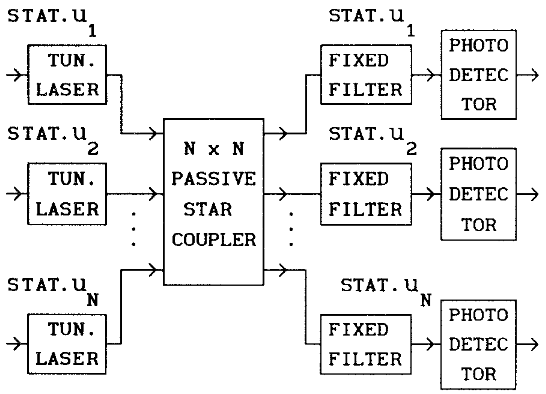

Fig.1: A WDM Passive Star Network.

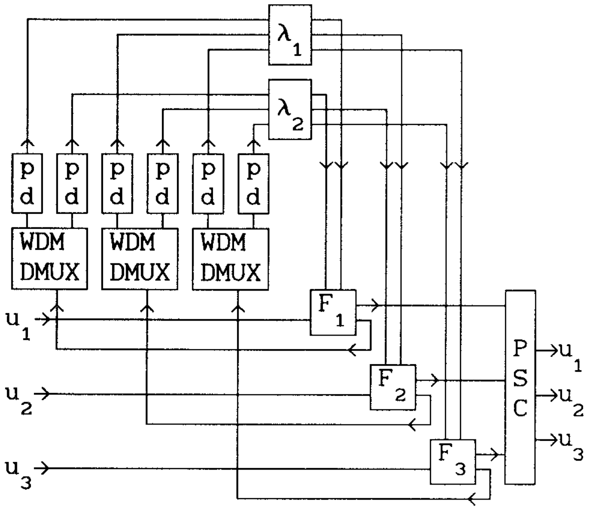

Fig.2: The hub of a HARP network.

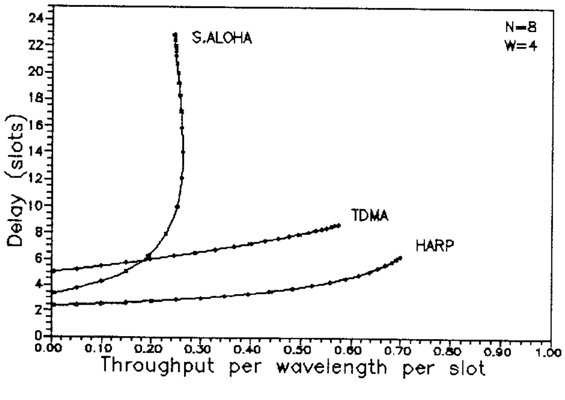

Fig.3: Net. N_1 - Delay vs Throughput.

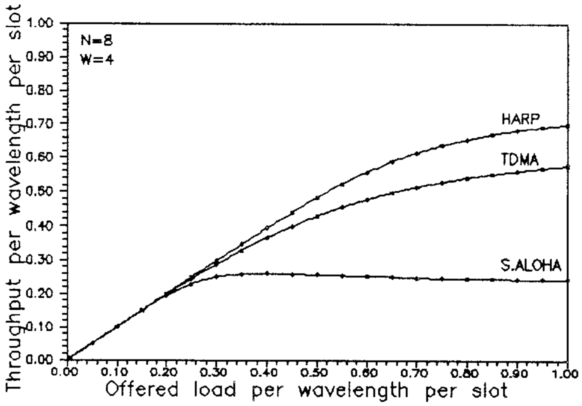

Fig.4: Net N_1 - Throughput vs Load.

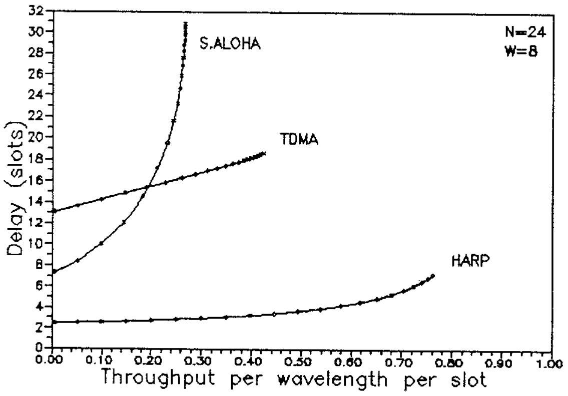

Fig.5: Net. N_2 - Delay vs Throughput.

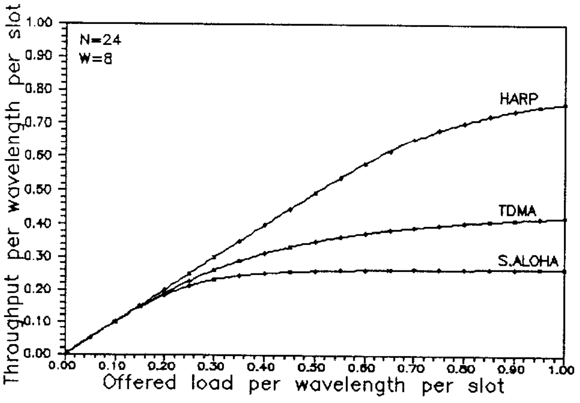

Fig.6: Net N_2 - Throughput vs Load.