Adaptive Bandwidth Allocation Schemes for Lightwave LANs with Asymmetric Traffic

G.I.Papadimitriou[1], A.S.Pomportsis[1], M.S.Obaidat[2]

1.Department of Informatics, Aristotle University, Box 888, 54006 Thessaloniki, Greece.
2.Department of Computer Science, Monmouth University, West Long Branch, NJ 07764, U.S.A.
E-mail:{gp, apombo}@csd.auth.gr, obaidat@monmouth.edu

***Abstract*—The bandwidth of a WDM star network that operates under asymmetric traffic must be allocated in such a way, that each station takes a portion of the network bandwidth proportional to its needs. In this paper, a dynamic bandwidth allocation scheme is presented. The proposed scheme is based on the network feedback information in order to be capable of adapting to the changing traffic characteristics. According to the proposed scheme, a set of learning automata processes the network feedback information and dynamically allocates the available bandwidth to the stations according to their needs.**

***Keywords*— WDM Passive Star Networks, Asymmetric Traffic, Network Feedback Information, Dynamic Bandwidth Allocation, Learning Automata.**

1. Introduction

In Wavelength Division Multiplexing (WDM) networks, the available optical bandwidth is divided 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. In this way, the WDM technique allows the implementation of all-optical networks which are capable of providing Gigabit/sec data rates by using current optical and electronic technology.

Passive star networks, which are a special category of WDM networks, use a passive star coupler in order to broadcast all inputs to all outputs. See Fig.1. There are four possible configurations of the passive star architectural form: a) fixed optical transmitters and fixed optical receivers [1, 3]; b) tunable optical transmitters and tunable optical receivers [1]; c) fixed optical transmitters and tunable optical receivers [1, 4, 5, 6, 7], and d) tunable optical transmitters and fixed optical receivers [1, 8, 9, 10, 11, 12]. The third configuration is considered in this paper.

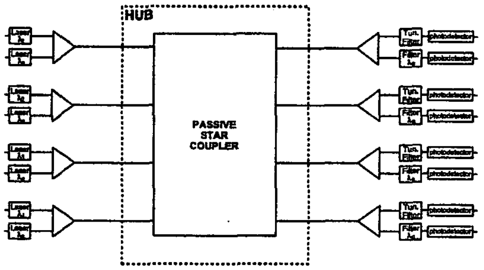

Figure 1: An example of a WDM passive star network using fixed lasers and tunable optical filters.

Network traffic is often asymmetric. Thus, a different traffic intensity is offered to each source-station. When asymmetric traffic is offered to a WDM star network, the available bandwidth must be allocated to the source-stations in such a way that each station takes a portion of the bandwidth proportional to its needs. When the traffic characteristics are fixed and a priori known [8], then the bandwidth allocation scheme can be based on these characteristics. Unfortunately, the traffic characteristics are often unknown and time-variable. In this paper, a dynamic bandwidth allocation scheme, which is based on the network feedback information in order to be capable of adapting to the changing traffic characteristics is presented. According to the proposed scheme, a set of learning automata processes the network feedback information and dynamically allocates the available bandwidth to the stations according to their needs.

The paper is organized as follows. The network model is defined in Section 2. The proposed Dynamic Bandwidth Allocation Scheme (DBAS) is presented in Section 3. This section is followed by the presentation of simulation results in Section 4. Finally, concluding remarks are given in Section 5.

2. The Network Model

The proposed dynamic bandwidth allocation scheme is applied to WDM passive star networks using fixed transmitters and tunable receivers (Fig.1). The network structure is based on the well-known architecture DT-WDMA (Dynamic Time-Wavelength Division Multiple Access) [4, 5], but differs in that the number of stations is not necessarily equal to the number wavelengths.

The set of stations is defined as $U = \{u_1, \dots, u_N\}$, where N is the number of stations. In order to simplify the description of the network we assume that all the stations are equally far from the network hub. Every station is placed $D/2$ slots away from the hub. Thus, the round trip propagation delay from the stations to the hub and back is equal to D slots.

There are W wavelengths that are used for data transmission (data wavelengths), while another wavelength λ_c, which is common for all stations, is used for the transmission of control signals (control wavelength). The set of data wavelengths is defined as $\Lambda = \{\lambda_1, \dots, \lambda_W\}$.

Each source node u_m $(m = 1, \dots, N)$ is provided with two fixed-wavelength lasers: one at a data wavelength λ_{i_m} (where $i_m = \lceil \frac{mW}{N} \rceil$, thus, $1 \leq i_m \leq W$) and one at the control wavelength λ_c. The set of source nodes which are fixedly tuned to transmit on data wavelength λ_k $(k = 1, \dots, W)$ is denoted by S_k. Thus, $S_k = \{u_j : k = \lceil \frac{j}{W} \rceil\}$. In order to simplify the protocol presentation, it is assumed that $\frac{N}{W}$ is an integer. Each data wavelength is shared by $\frac{N}{W}$ source nodes.

The data and the control wavelength are combined by means of a 2×1 combiner. Optical fibers connect the outputs of the combiners to the network hub.

There, the optical signal is fed to a passive star coupler which broadcasts all input signals to all output ports. Each output port of the star coupler is connected to the corresponding receiver, by means of an optical fiber. At each receiver, the optical signal is split into two parts by means of a 1×2 splitter. One part of the signal goes to a fixed optical filter, which lets pass only the control wavelength. The other part is fed to a tunable optical filter which is able to be tuned to let pass any one of the W data wavelengths. In this way, full connectivity of the network is guaranteed.

Whenever a source node has a packet to transmit, it sends a message containing the source and the destination node of the packet through the control wavelength. The packet is transmitted in the next time slot. Each destination node is continuously monitoring the control wavelength and analyzing the control information. When it finds out that a data packet will arrive at the next time slot, it tunes its optical filter to the corresponding wavelength and receives the incoming packet.

3. The Proposed Dynamic Bandwidth Allocation Scheme(DBAS)

The Dynamic Bandwidth Allocation Scheme (DBAS) is based on the learning algorithm which is used by the single-channel learning-automata-based TDMA protocol LTDMA [13]. However, applying this algorithm to a network of the structure described in the previous section is not straight forward.

1) In LTDMA, the propagation delay is assumed to be negligible. In the network model described above, there is a round-trip propagation delay of D slots from the stations to the network hub and back. Therefore, the feedback information is not immediately available to the learning automata. The presence of a delayed feedback negatively affects the learning process.

2) Multiwavelength networks using fixed lasers and tunable receivers suffer from receiver collisions. When two or more source nodes concurrently transmit to the same receiver, then all the transmitted packets, except one, are lost. The need for retransmission of the lost packets lead to a significant performance degradation which is not present in single channel networks or in WDM star networks using tunable lasers and fixed receivers.

3) The traffic offered to LTDMA is assumed to be bursty but symmetric. Thus, all the stations are assumed to have the same traffic. In the present model, the traffic is assumed to be asymmetric. Thus, a different traffic intensity is offered to each station. It remains to study how the asymmetry of traffic affects the network performance.

According to the Dynamic Bandwidth Allocation Scheme (DBAS), each station is provided with a learning automaton [14-18] which contains the basic choice probability $P_i(t)$ of each station $u_i \in S_k$ for $k = 1, \dots, W$. At each time slot t, the basic choice probabilities are normalized in the following way:

$$\Pi_i(t) = \frac{P_i(t)}{\sum_{u_m \in S_k} P_m(t)} \tag{1}$$

Obviously, for each wavelength λ_k, it holds that $\sum_{u_m \in S_k} \Pi_m(t) = 1$. The station which is granted permission to transmit on wavelength λ_k is selected according to the normalized probabilities $\Pi_i(t)$ $(u_i \in S_k)$.

Consider the wavelength λ_k. At each time slot t, the basic choice probability $P_i(t)$ of the selected station $u_k(t) = u_i$ is updated according to the network feedback information. The feedback information suffers a propagation delay of D slots before arriving at the stations. Therefore, at each time slot t, the probability updating is based on the feedback information of slot

$(t-D)$. If station u_i transmits a packet during time slot $(t-D)$, then the basic choice probability of u_i will increase. Otherwise, if the selected station u_i was idle during slot $(t-D)$, then the basic choice probability of u_i would decrease. The following probability updating scheme is used (where: $L, a \in (0,1)$, $P_i(t) \in (a,1)$ for all t and $slot_k(t-D) \in \{busy, idle\}$ denotes the status of wavelength λ_k during time slot $(t-D)$):

$$\begin{aligned} P_i(t+1) &= P_i(t) + L(1-P_i(t)) \\ &\quad \text{if } u_k(t) = u_i \text{ and } slot_k(t\text{–}D) = busy \\ P_i(t+1) &= P_i(t) - L(P_i(t) - a) \\ &\quad \text{if } u_k(t) = u_i \text{ and } slot_k(t\text{–}D) = idle \end{aligned} \tag{2}$$

When the selected station has a packet to transmit, it is probable that this station is heavily loaded and consequently, it will have packets to transmit in the near future. Therefore, its choice probability is increased. On the other hand, when the selected station is idle, it is probable that this station is lightly loaded and consequently, its choice probability is decreased.

When the choice probability of a station converges to 0, then this station is not selected for a long period. During this period, it is probable that the station transits from idle to busy state. However, since the station does not grant permission to transmit, the automata are not capable of "sensing" the transition. The role of parameter a is to prevent the choice probabilities of the stations from taking values in the neighborhood of 0, in order to increase the adaptivity of the protocol.

Consider a station $u_i \in S_k$. In order to implement the above learning algorithm, station u_i must be informed of the status of wavelength λ_k during each time slot. In order to be provided with this feedback information, the station listens to the control wavelength λ_c. If none of the stations in S_k has transmitted a packet during a time slot, then wavelength λ_k is idle. Otherwise, λ_k is busy.

All the stations use the same learning algorithm and the network feedback information is common for all the stations. Consequently, all the automata of stations $u_i \in S_k$ always contain the same choice probabilities. Furthermore, since the same random number generator and the same seed is used by all the stations, it follows that all the stations select the same station which grants permission to transmit. Therefore, although there is no centralized coordination between the stations, the protocol is collision-free. Thus, at each time slot t, only one station grants permission to transmit on each wavelength λ_k, for $k = 1, \ldots, W$. It is assumed that there is a mechanism to synchronize the initial state of all stations [10]. If a new station powers up, it must first learn the current random number.

The exact values of a and L depend on the environment where the automata operate. When the environment is slowly switching or when the environmental responses have a high variance, a and L must be very close to 0 in order to guarantee a high accuracy. On the other hand, in a rapidly switching environment or when the variance of the environmental responses is low, higher values of a and L can be used, in order to increase the adaptivity of the protocol. Thus, when the burst length is high or the queue length is low, then small values of a and L must be selected. On the other hand, when the burst length is low or when the queue length is high, then a and L can be much higher.

Let d_i be the probability that station u_i is not idle ($i = 1, \ldots, N$). It can be proved (for the sake of brevity the proof is omitted) that for any two stations $u_i, u_j \in S_k$ (with $d_j \neq 0$), the DBAS algorithm asymptotically tends to satisfy the relation:

$$\frac{P_i}{P_j} = \frac{d_i}{d_j} \tag{3}$$

This relation also holds for the normalized choice probabilities Π_i and Π_j:

$$\frac{\Pi_i}{\Pi_j} = \frac{\frac{P_i}{\sum_{u_m \in S_k} P_m}}{\frac{P_j}{\sum_{u_m \in S_k} P_m}} = \frac{P_i}{P_j} = \frac{d_i}{d_j} \tag{4}$$

Therefore, each station tends to take a fraction of the available bandwidth, proportional to the probability that this station is not idle. Therefore, the portion of the bandwidth which is assigned to each station tends to be proportional to the station's needs.

4. Simulation Results

In the following, the proposed DBAS scheme is compared to RTDMA (Random TDMA)[10] and TDMA [9]. According to RTDMA, only one station, which is selected at random is granted permission to transmit on each wavelength, at each time slot. In I-TDMA, the station which is granted permission to transmit is selected in a round-robin fashion.

Two other possible candidates for comparison with DBAS could be protocols CWC (Centralized Wavelength Conversion) [7] and CPF (Centralized Packet Filtering) [6]; two high performance protocols for WDM star networks using fixed transmitters and tunable receivers. Both protocols allow the stations to transmit their packets in a slotted ALOHA-like fashion. A packet blocking mechanism is placed at the hub in order to avoid packet collisions. Only one packet per wavelength is allowed to pass to the star coupler, at each time slot. The packet blocking mechanism of

	Percentages of traffic	
station #	Scenario 1 (Highly Asymmetric Traffic)	Scenario 2 (Moderately AsymmetricTraffic)
1	15%	12%
2	5%	2%
3	1%	3%
4	1%	8%
5	1%	3%
6	20%	8%
7	1%	2%
8	5%	12%
9	1%	14%
10	1%	5%
11	1%	2%
12	15%	3%
13	30%	2%
14	1%	3%
15	1%	14%
16	1%	7%

Table 1: The stations' percentages of traffic for scenarios 1 and 2. At each time slot, traffic values are rotated by one place with probability 0.001.

protocol CWC has wavelength conversion capabilities and is capable of distributing the offered traffic to the available wavelengths. However, these protocols can not be fairly compared to DBAS, because they are based on the use of a complex (and costly) packet blocking mechanism which is placed at the network hub.

The protocols which are under comparison were simulated to be applied to a WDM star network which consists of 16 stations. Four wavelengths are available, while four stations are fixedly tuned to transmit on each wavelength. The round-trip propagation delay from the stations to the network hub and back is assumed to be equal to two slots. The capacity of the waiting queue of each station is 30 packets. The traffic is assumed to be asymmetric and non-bursty. Packet arrivals are assumed to be Poisson and destinations of packets are selected uniformly. In the the present simulation, parameters a and L were taken to be equal to 0.02 and 0.99, respectively. Two traffic scenarios are considered. According to scenario 1, the traffic is highly asymmetric. Under scenario 2, the traffic is moderately asymmetric. The stations' traffic (as percentages of the total network traffic) for scenarios 1 and 2 are presented in Table 1. The offered traffic is assumed to be not only asymmetric but also time-variable. After each time slot the values of the stations' traffic are rotated by one place with probability 10^{-3}.

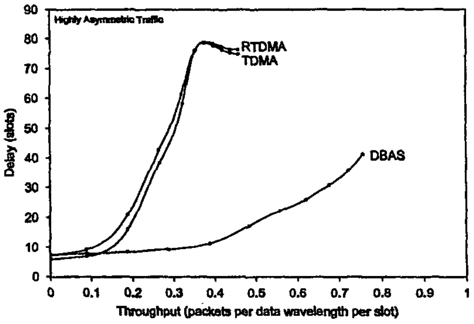

Figure 2: The delay versus throughput characteristics of DBAS, TDMA and RTDMA under highly asymmetric traffic.

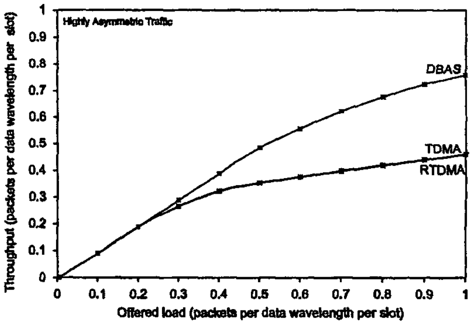

Figure 3: The throughput versus load characteristics of DBAS, TDMA and RTDMA under highly asymmetric traffic.

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

1) The delay versus throughput characteristic.

2) The throughput versus offered load characteristic.

The delay versus throughput characteristics of the compared schemes when operating under traffic scenarios 1 and 2 appear in Figures 2 and 4, respectively. The throughput versus offered load characteristics of the compared schemes under scenarios 1 and 2 are shown in Figures 3 and 5, respectively. As mentioned above the traffic is asymmetric. The values of throughput and load that are illustrated in the graphs are average values for the whole network.

The following results can be extracted from the above graphs:

1) Under low load conditions, due to its determinis-

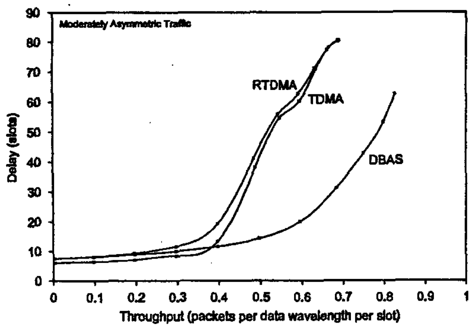

Figure 4: The delay versus throughput characteristics of DBAS, TDMA and RTDMA under moderatelty asymmetric traffic.

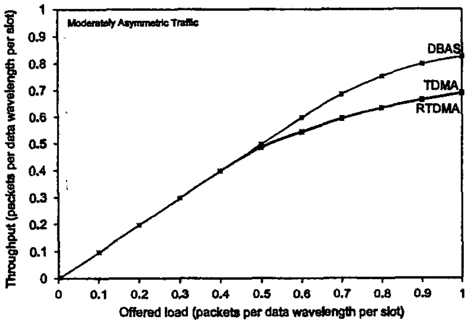

Figure 5: The throughput versus load characteristics of DBAS, TDMA and RTDMA under moderately asymmetric traffic.

tic nature, TDMA achieves a slightly lower delay than the two other schemes. However, under medium or high load conditions DBAS achieves a significantly higher delay-throughput and throughput-load performance than TDMA and RTDMA, when operating under asymmetric traffic. According to RTDMA and TDMA, the station which grants permission to transmit on a wavelength λ_k is selected at random, or in a round-robin fashion. Thus, the bandwidth of wavelength λ_k is statically allocated to the stations, without taking into account their actual needs. Therefore, the throughput of this wavelength is: $T_{RTDMA}(\simeq T_{TDMA}) = \frac{1}{N}\sum_{u_m \in S_k} d_m$. On the other hand, DBAS is based on the network feedback information in order to dynamically allocate the available bandwidth of wavelength λ_k to the stations. Each station takes a fraction of the available bandwidth proportional to its needs. In this case, the throughput of wavelength λ_k is: $T_{DBAS} = \sum_{u_m \in S_k} \Pi_m d_m$. As stations with higher probability of being ready d_m are selected with higher probability Π_m, it follows that: $T_{DBAS} > T_{RTDMA}$.

2) From a comparison of Figures 2 and 3 with Figures 4 and 5, respectively, it becomes clear that the performance improvement which is achieved by the use of the learning-automata-based scheme is higher under scenario 1 (highly asymmetric traffic). As the traffic becomes more asymmetric the number of idle users increases. Under these conditions, the number of idle slots dramatically increases, if the TDMA or RTDMA is used, resulting in a significant performance degradation. On the other hand, DBAS is not significantly affected by the asymmetry of the traffic, because it is capable of using the network feedback information, instead of blindly selecting the stations which grant permission to transmit.

5. Conclusion

This paper has presented a new dynamic bandwidth allocation scheme for WDM star networks. According to the proposed DBAS scheme, the station which is granted permission to transmit on each wavelength is selected by means of learning automata, which are capable of being adapted to the unknown and time-variable traffic conditions.

The main characteristics of the proposed DBAS protocol are summarized below:

a) It achieves a high throughput-delay performance, even when the offered traffic is asymmetric.

b) The protocol is self-adaptive. Each station tends to take a fraction of the available bandwidth proportional to its needs.

c) No centralized control of the stations is required, since the protocol is fully distributed.

d) It is fault-tolerant. Its operation is not affected by a possible node failure. Furthermore, the network hub, which represents a single point of failure, remains a passive unpowered device (in contrast to [6] and [7] where the hub is embellished with a powered mechanism).

e) No significant increase of the implementation cost is introduced, in relation to RTDMA.

The use of learning automata offers a new highly promising approach to the design of fiber-optic LANs. We are currently working in this direction.

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