Learning Automata-Based Receiver Conflict Avoidance Algorithms for WDM Broadcast-and-Select Star Networks

Georgios I. Papadimitriou, *Member, IEEE*, and Dimitris G. Maritsas

***Abstract*— A new receiver conflict avoidance algorithm for wavelength-division multiplexing (WDM) broadcast-and-select star networks is introduced. The proposed algorithm is based on the use of learning automata in order to reduce the number of receiver conflicts and, consequently, improve the performance of the network. According to the proposed scheme, each node of the network is provided with a learning automaton; the learning automaton decides which of the packets waiting for transmission will be transmitted at the beginning of the next time slot. The asymptotic behavior of the system, which consists of the automata and the network, is analyzed and it is proved that the probability of choosing each packet asymptotically tends to be proportional to the probability that no receiver conflict will appear at the destination node of this packet. Furthermore, extensive simulation results are presented, which indicate that significant performance improvement is achieved when the proposed algorithm is applied on the basic DT-WDMA protocol.**

***Index Terms*—Wavelength-division multiplexing, WDM broadcast-and-select star network, receiver conflict avoidance algorithm, learning automaton.**

I. Introduction

The INCREASING bandwidth demands of the emerging new generation of computer communication networks have led to the utilization of optical fiber as a transmission medium. The wavelength-division multiplexing (WDM) technique [1] is an efficient way to implement optical networks capable of providing gigabit data rates by using present-day optical and electronic technology.

WDM broadcast-and-select star networks [1] (Fig. 1) use a passive star coupler in order to broadcast transmitted packets to all destination nodes. Since each destination node is provided with only one tunable filter, it is impossible to concurrently receive multiple packets coming from different wavelengths. Such a situation, which is known as "receiver conflict," causes the loss of all the packets which are involved in the conflict, except one. A large number of receiver conflicts would lead to a serious decrease of the network's performance.

The extent of the receiver conflict problem strictly depends on the strategy used for choosing which of the waiting packets will be transmitted at each time slot. Two different transmission strategies have been proposed. According to the first-in first-out (FIFO) transmission strategy [2], the top (oldest) packet of the queue is always chosen for transmission. According to the random transmission strategy [3], [4], one of the waiting packets is chosen at random. When the FIFO strategy is used, the receiver conflict problem is intense, due to the consecutive conflicts of the same packets. The random transmission strategy limits the extent of the problem by shuffling the waiting packets.

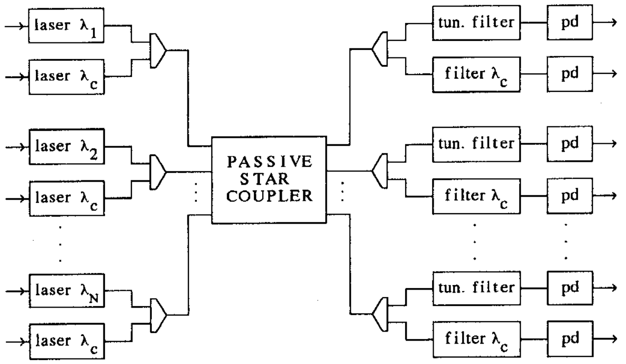

Fig. 1. A WDM broadcast-and-select star network which operates under the DT-WDMA protocol.

In this paper, a receiver conflict avoidance algorithm, which is based on the use of learning automata, is introduced. According to the proposed scheme, each node of the network is provided with a learning automaton (Fig. 2). At the beginning of each time slot, the learning automaton decides which packet will be transmitted. An analysis of the asymptotic behavior of the proposed automata-based algorithm proves that the probability of choosing each packet asymptotically tends to be proportional to the probability that no receiver conflict will appear at the destination node of this packet. In this way, the number of receiver conflicts is reduced and, consequently, the performance of the network is improved.

The paper is organized as follows. The receiver conflict avoidance learning algorithm (RCALA) is presented in Section II. An analysis of the asymptotic behavior of the system, which is composed of both the network and the learning automata, is presented in Section III. In Section IV, extensive simulation results are presented that indicate the performance improvement which is due to the use of the proposed automata-based algorithm. Finally, conclusion and remarks for future work are made in Section V.

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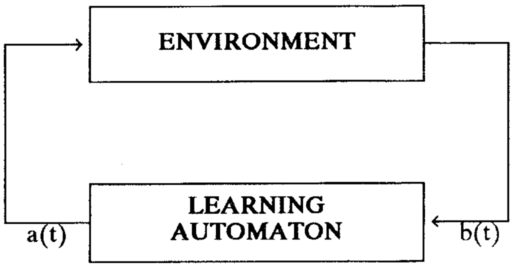

Fig. 2. A learning automaton that interacts with a stochastic environment.

II. THE RECEIVER CONFLICT AVOIDANCE LEARNING ALGORITHM

The architectural form considered in this paper is the one presented in [2] and [3] (Fig. 1). Even when the random transmission strategy [3], [4] is used, the receiver conflict problem restricts the performance of the network.

We propose a receiver conflict avoidance algorithm which is based on the use of learning automata and tends to minimize the probability of occurring concurrent transmissions from different source nodes to the same destination node. According to the proposed RCALA, each node is provided with a learning automaton which decides which of the packets waiting for transmission will be transmitted at the beginning of the next time slot. The operation of the RCALA at a source node is described below.

A. The Selection of the Destination Node

Let N be the number of nodes (N is also the number of data wavelengths). The set of nodes is defined as $U = \{1, \cdots, N\}$. The queue of packets which are waiting for transmission at a source node i ($i = 1, \cdots, N$), at time slot t, is defined as $\mathbb{Q}_i(t)$. Let $Q_{i,j}(t)$ be the set of packets in $\mathbb{Q}_i(t)$ which are destined for node j ($j = 1, \cdots, N$). We define $z_{i,j}(t) = |Q_{i,j}(t)|$ and $D_i(t) = \{\text{node } k | Q_{i,k}(t) \neq \emptyset\}$.

A learning automaton is placed at each source node. Each waiting packet corresponds to an action of the automaton. Therefore, at any time instant t, the automaton contains a probability distribution over the set waiting packets. The probability of selecting each packet in $\mathbb{Q}_i(t)$ depends on the destination node of this packet and is computed in the following way: For each destination node j, the automaton contains a "basic transmission probability" $P_j(t)$ which is updated after each time slot, according to the network feedback information. As will be seen in the next section, the feedback is common for all stations. Therefore, all the automata contain the same basic transmission probabilities.

The probability of selecting a packet in $\mathbb{Q}_i(t)$ depends on the destination node of this packet. Thus, each packet in $Q_{i,j}(t)$ is selected with the same probability $\pi_{i,j}(t)$. The choice probability $\pi_{i,j}(t)$ is computed by scaling [10] the basic transmission probability $P_j(t)$, in the following way:

$$\pi_{i,j}(t) = \frac{P_j(t)}{\sum_{k \in D_i(t)} z_{i,k}(t) \times P_k(t)} \quad \text{for} \quad j \in D_i(t). \quad (1)$$

At each time slot t, each source node i which has packets to transmit chooses one of the waiting packets according to the scaled probabilities $\pi_{i,j}(t)$ and transmits this packet. The probability that node i transmits to node j at time slot t is

$$r_{i,j}(t) = z_{i,j}(t) \times \pi_{i,j}(t).$$

We have

$$r_{i,j}(t) = \frac{z_{i,j}(t) \times P_j(t)}{\sum_{k \in D_i(t)} z_{i,k}(t) \times P_k(t)} \quad \text{for} \quad j \in D_i(t). \quad (2)$$

B. The Probability Updating Scheme

All the transmissions that take place in the network (successful or unsuccessful) are preannounced to all the stations through the common control wavelength. After a round trip propagation delay of t_d slots from the nodes to the network hub and back, this information arrives to all the nodes of the network. Therefore, after a delay of t_d slots, each station is informed about the occurrence or not of a receiver conflict at each one of the destination nodes.

This information is used by the automata—which are placed at each node—as network feedback information, in order to update the probability of selecting each destination node for transmission. The following probability updating scheme is used: $P_j(t+1) = P_j(t) - L \times P_j(t)$ if a receiver conflict has occurred at the destination node j during the $(t - t_d)$th time slot, and $P_j(t+1) = P_j(t) + \varepsilon \times L \times (1 - P_j(t))$ if no receiver conflict has occurred at the destination node j during the $(t - t_d)$th time slot, for $j = 1, 2, \cdots, N$, where $L \in (0, 1)$ is an internal parameter of the automaton, i.e., the "step size parameter," and ε is a very small positive real number $0 < \varepsilon \ll 1$.

Parameter ε must be small enough in order to guarantee the accurate convergence of the automaton. The L parameter determines the step size of the probability updating. When L is relatively high, then the automaton is rapidly adapted to the changes of the network state. However, in this case, the accuracy of the automaton is low. For example, an accidental receiver conflict at a relatively unloaded destination node j is able to cause a serious decrease of the basic transmission probability $P_j(t)$. On the other hand, a relatively low value of the L parameter leads to a high accuracy and a slow adaptation rate. Since there is a trade-off between speed and accuracy, the value of the step size parameter L must be appropriately selected in order to achieve the combination of speed and accuracy, which maximizes network performance.

In order to study how the choice of the step size parameter L affects network performance, the reader may refer to Table I. Consider an exemplary network N_1 (a detailed description of N_1 is given in Section IV). Initially, the network performance is gradually improved as L increases. This is due to the increase of the adaptation speed as L increases. After reaching the maximum at a specific value of L ($L = 0.3$, in our example), the network performance gradually falls as L further increases. This happens because, as L increases, the accuracy of the probability updating scheme is significantly reduced.

TABLE I
RCALA PROTOCOL PERFORMANCE FOR VARIOUS VALUES OF THE STEP SIZE PARAMETER L and $e = 0.025$

LOAD	L=0.0 (dt - wdma random tr.)		L=0.1		L=0.2		L=0.3		L=0.4		L=0.5	
	thr.	del.	thr.	del.	thr.	del.	thr.	del.	thr.	del.	thr.	del.
1.0	0.559	18.9	0.604	17.6	0.608	17.4	0.609	17.4	0.607	17.5	0.604	17.6
0.8	0.557	16.9	0.595	15.7	0.598	15.6	0.599	15.5	0.597	15.6	0.596	15.6
0.6	0.526	11.8	0.544	10.8	0.545	10.6	0.546	10.6	0.545	10.6	0.544	10.6
0.4	0.396	5.3	0.397	4.9	0.397	4.9	0.397	4.9	0.397	4.9	0.397	4.9
0.2	0.200	2.3	0.200	2.3	0.200	2.3	0.200	2.3	0.200	2.3	0.200	2.3

TABLE II
PACKET LOSSES DUE TO RECEIVER CONFLICTS

	Packet losses due to receiver conflicts (node traffic = 1 p/slot)		
NETWORK	FIFO	RANDOM	RCALA
N_1	19.5	17.6	15.6
N_2	18.4	17.1	15.6
N_3	17.2	16.0	14.9
N_4	22.9	20.5	18.8
N_5	16.3	15.0	14.5

An increase of L causes an improvement of the adaptation speed, but also causes a fall of the accuracy. On the other hand, a decrease of L causes an improvement of the accuracy, but also causes a fall of the adaptation speed. Therefore, the network performance is *slowly* modified with L, since it depends on both the accuracy and the adaptation speed.

When $L = 0$, the network feedback information is not taken into account. Consequently, all the waiting packets have the same probability to be selected for transmission. In this case, the RCALA protocol degenerates to the random transmission strategy of the DT-WDMA. Therefore, the RCALA protocol can be considered as an extension of the random transmission strategy, which takes into account the network feedback information.

III. PERFORMANCE ANALYSIS

It can be proved that the receiver conflict probability of each destination node is a monotonically increasing function of the basic transmission probability of this node. The above proposition is formally expressed as follows:

Proposition 1: If $c_j(t)$ is the probability that a receiver conflict will occur at the destination node j, at time instant t, then, for a given distribution of packets waiting for transmission at the source nodes, $c_j(t)$ is a monotonically increasing function of the basic transmission probability $P_j(t)$.

According to the proposed RCALA protocol, the basic transmission probability of each destination node asymptotically tends to be proportional to the probability that no receiver conflict will occur at this destination node and inversely proportional to the probability that a receiver conflict will occur at this destination node. In other words, if the receiver conflict probability of a destination node is relatively low, because the number of packets destined for this node is low, then the RCALA protocol tends to increase the choice probability of this node. On the other hand, if the receiver conflict probability of a destination node is relatively high, due to the existence of a large number of packets destined for this node, then the RCALA protocol tends to decrease the choice probability of this destination node. The formal expression of the above discussion is given by the following proposition:

Proposition 2: Let $d_j(t) = 1 - c_j(t)$ be the probability that no receiver conflict will occur at the destination node j, at time instant $t (j = 1, \cdots, N)$. If $0 < d_j(t) < 1$, then, for a given distribution of packets waiting for transmission at the source nodes, for any two destination nodes i and j, the RCALA protocol asymptotically tends to satisfy the following relation:

$$\frac{P_i(t)}{P_j(t)} = \frac{\dfrac{d_i(t)}{1 - d_i(t)}}{\dfrac{d_j(t)}{1 - d_j(t)}}.$$

For the sake of brevity, the proofs of Propositions 1 and 2 are omitted.

Note: It is possible to have $d_j(t) = 1$ (when less than two source nodes have packets destined for node j) or $d_j(t) = 0$ (when all the waiting packets of two or more source nodes are destined for node j). When $d_j(t) = 1$, then $P_j(t)$ is

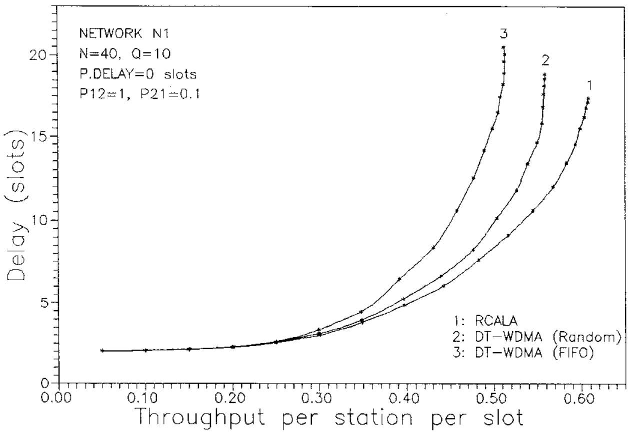

Fig. 3. Delay versus throughput characteristics of the RCALA and the DT-WDMA protocols when they are applied to network N_1.

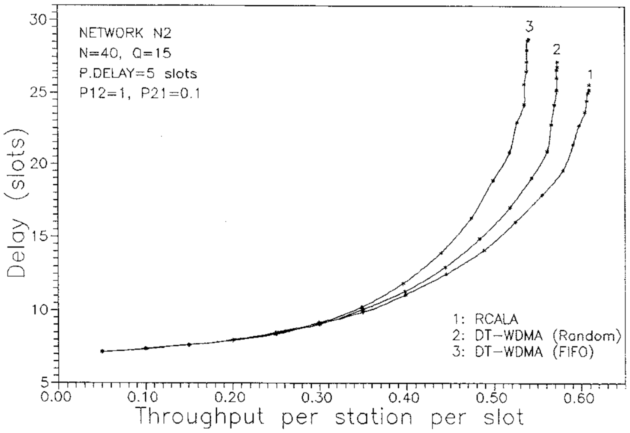

Fig. 4. Delay versus throughput characteristics of the RCALA and the DT-WDMA protocols when they are applied to network N_2.

continuously increased so that it asymptotically tends to one. On the other hand, when $d_j(t) = 0$, then $P_j(t)$ is continuously decreased so that it asymptotically tends to zero.

IV. SIMULATION RESULTS

In order to study the performance of the proposed RCALA protocol, we compare it to the basic DT-WDMA protocol which is introduced in [2]. Separate simulation results for the FIFO [2] and the random transmission strategy [3], [4] of the DT-WDMA protocol are presented. Protocol DT-WDMA was chosen because the proposed RCALA is applied on the basic DT-WDMA architectural form. Therefore, a performance comparison between the two protocols will clearly demonstrate the performance improvement which is due to the use of the RCALA.

Both protocols were simulated to operate on WDM broadcast-and-select star networks of the architectural form described in the previous sections.

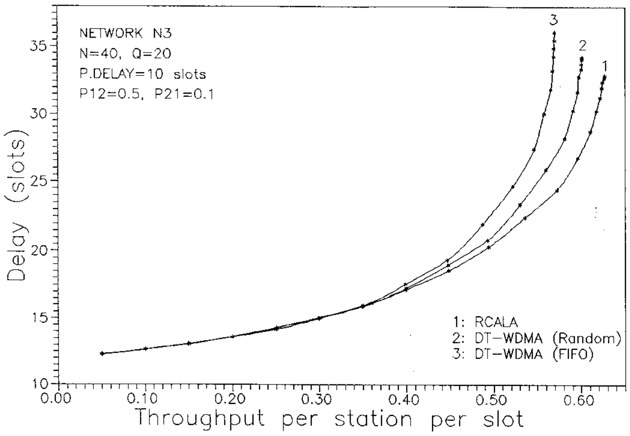

Fig. 5. Delay versus throughput characteristics of the RCALA and the DT-WDMA protocols when they are applied to network N_3.

Each node of the network is assumed to be provided with a finite queue with a maximum length equal to Q packets, including the transmitted but unacknowledged packets. Each node is assumed to have only packet switched traffic. If the total traffic offered to each one of the nodes is h packets/slot (with $0 < h \leq 1$), then, it is assumed that one packet arrives at each station during each slot with probability h.

Each source node can be in one of the following two states: S_1 and S_2. When a source node is at state S_1, the destination node of a newly arriving packet is selected at random among all the other nodes. On the other hand, when a source node is at state S_2, the destination node of a newly arriving packet is the same with the destination node of the previously arriving packet. After each time slot, a source node which is at state S_1 transits to state S_2 with probability P_{12}, while a source node which is at state S_2 transits to state S_1 with probability P_{21}. When P_{12} is high relative to P_{21}, then the packet arrivals are correlated. On the other hand, when P_{12} is low relative to P_{21} then the packet arrivals are uncorrelated.

We have used the following two performance metrics in order to compare the RCALA protocol with the DT-WDMA one: a) The mean number of packets which are destroyed due to receiver conflicts during one slot and b) the delay versus throughput characteristic.

The protocols under comparison were simulated to operate in five different networks (N_1 to N_5) of the above-described form. In all cases, the total bandwidth was taken to be equal to 1 Gb/s, while the packet size was equal to 1000 bytes. The characteristics of the five simulated networks were taken to be as follows: N_1: $N = 40$ users, $Q = 10$ packets and $t_d = 0$ slots. N_2: $N = 40$ users, $Q = 15$ packets and $t_d = 5$ slots. N_3: $N = 40$ users, $Q = 20$ packets and $t_d = 10$ slots. N_4: $N = 50$ users, $Q = 3$ packets and $t_d = 0$ slots. N_5: $N = 40$ users, $Q = 3$ packets and $t_d = 0$ slots.

The packet arrivals in networks N_1 and N_2 are assumed to be highly correlated. In these networks, the transition probabilities are taken to be $P_{12} = 1.0$ and $P_{21} = 0.1$. In network N_3, the packet arrivals are less correlated. The transition probabilities are taken to be: $P_{12} = 0.5$ and $P_{21} =$

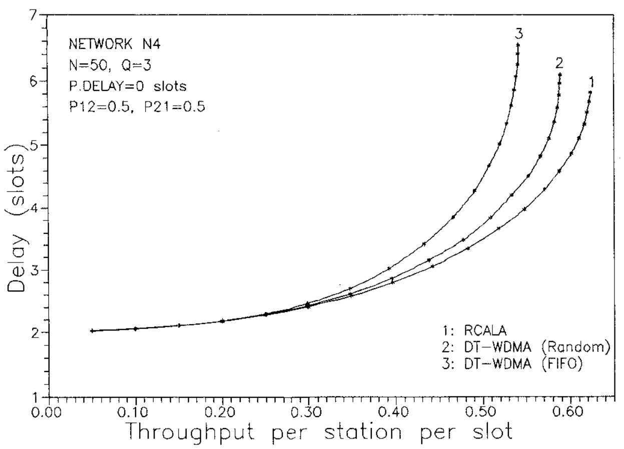

Fig. 6. Delay versus throughput characteristics of the RCALA and the DT-WDMA protocols when they are applied to network N_4.

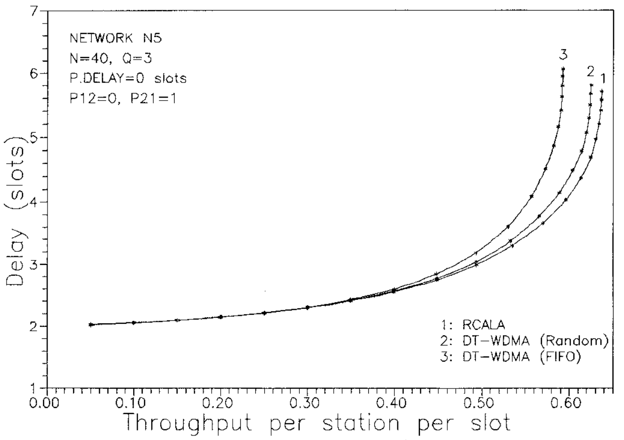

Fig. 7. Delay versus throughput characteristics of the RCALA and the DT-WDMA protocols when they are applied to network N_5.

0.1. In network N_4, the packet arrivals are even more uncorrelated. The transition probabilities are the following: $P_{12} = 0.5$ and $P_{21} = 0.5$. In network N_5, the packet arrivals are assumed to be completely uncorrelated. Therefore, the transition probabilities are taken to be $P_{12} = 0$ and $P_{21} = 1$.

For each network, the step size parameter L of the RCALA protocol was chosen after testing a large number of possible values in a way similar to the one used in Section II-B (see Table I). The step size parameter was chosen to be $L = 0.3$ for network $N_1, L = 0.4$ for network N_4, and $L = 0.2$ for all other networks. The ε parameter was taken to be equal to 0.025 for all the simulated networks.

The mean number of packets which are destroyed due to receiver conflicts during one slot when protocols RCALA and DT-WDMA are applied to networks N_1 to N_5 are shown in Table II. We can see that the application of the proposed RCALA leads to a reduction of the number of packet losses which are due to receiver conflicts. The reduction is up to 20% compared to the FIFO transmission strategy and up to 11% compared to the random transmission strategy.

The delay versus throughput characteristics of the RCALA and the DT-WDMA protocols when they are applied to networks N_1, N_2, N_3, N_4, and N_5, are shown in Figs. 3, 4, 5, 6, and 7, respectively.

The following main results can be extracted from the above graphs:

1) The RCALA protocol achieves a higher performance than the DT-WDMA protocol; either the latter uses the FIFO or the random transmission strategy.
2) The improvement that the RCALA protocol achieves on the random transmission strategy is approximately equal to the improvement that the random transmission strategy achieves on the FIFO transmission strategy.
3) The efficiency of the RCALA protocol depends on the validity of the network feedback information which, in turn, depends on the round-trip propagation delay and the correlation of the packet arrivals. Thus, the RCALA protocol operates more efficiently in networks with low propagation delay and relatively high correlation of the packet arrivals. However, even when the propagation delay is high (e.g., networks N_2 and N_3) or the packet arrivals are not highly correlated (e.g., networks N_3, N_4, and N_5), the RCALA protocol achieves a satisfactory performance.

V. CONCLUSION AND FUTURE WORK

The receiver conflict problem of WDM broadcast-and-select star networks has been a limiting factor of their performance. In this paper, we presented a learning automata-based algorithm which reduces the number of receiver conflicts and improves the performance of the network. The use of learning automata is also applicable in the field of WDM broadcast-and-select star networks that use tunable input lasers and fixed output receivers. We are currently working in this direction. The first results of this work can be found in [6] and [8].

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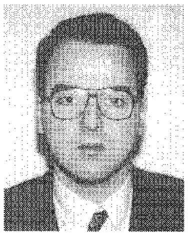

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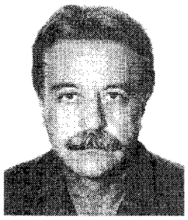

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