Centralized Packet Filtering Protocols: A New Class of High Performance Protocols for Single-Hop Lightwave WDM Networks

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Abstract

A new protocol for WDM star networks is introduced. According to the proposed Centralized Packet Filtering (CPF) protocol, more than one stations share each wavelength and transmit their packets in a random access fashion. An array of electrooptic tunable filters, which is placed at the network hub, allows at most one packet per wavelength to pass to the star coupler, at each time slot. In this way, channel collisions are eliminated. Furthermore, the selection of the passing packets is implemented in such a way that receiver conflicts are avoided.

1. Introduction

Due to limited speed of the stations' electronic circuits, single channel optical networks - such as FDDI, DQDB, Fasnet, etc - were not proved capable of supporting Gigabit data rates. The introduction of the Wavelength Division Multiplexing (WDM) technique [1],[2] 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. In this way, the WDM technique allows the implementation of purely optical networks which are capable of providing Gigabit data rates by using present-day optical and electronic technology. Broadcast-and-Select 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 Broadcast-and-Select Star architectural form: a) Fixed optical transmitters and fixed optical receivers [1],[4], b) tunable optical transmitters and tunable optical receivers [1],[12]-[16], c) tunable optical transmitters and fixed optical receivers [1],[6],[7],[17],[19],[20] and d) fixed optical transmitters and tunable optical receivers [1],[3],[5],[9]-[11],[18]. The latter configuration is considered in this paper.

The small number of available wavelengths has been a limiting factor in the development of WDM Broadcast-and-Select Star Networks, since most protocols require the number of wavelengths be equal to the number of stations.

Some protocols attempt to overcome this limitation, by assigning each wavelength to more than one stations. Up to now, some well-known protocols - like S.ALOHA and TDM [6],[7],[17] - have been proposed for sharing each wavelength between several stations. Since, these protocols are derived from single-channel protocols they do not take into account the special characteristics of the WDM Broadcast-and-Select Star architectural form.

The performance of S.ALOHA is poor, since it suffers from channel collisions. Therefore, its efficiency does not exceed 0.36 [6],[7],[17]. On the other hand, TDM achieves a quite satisfactory performance. However, due to its round-robin nature, TDM is characterized by a high delay when operating under low load conditions. This problem becomes more intense, when the number of users that share each wavelength is high. Furthermore, TDM suffers from receiver conflicts when operating under medium or heavy load conditions.

In this paper, a new protocol which takes into account the special characteristics of the WDM Star architecture in order to efficiently share a limited number of wavelengths between an arbitrary number of users is introduced. According to the proposed Centralized Packet Filtering (CPF) protocol, more than one stations share each wavelength and transmit their packets in a random access fashion. An array of electrooptic tunable filters which is placed at the

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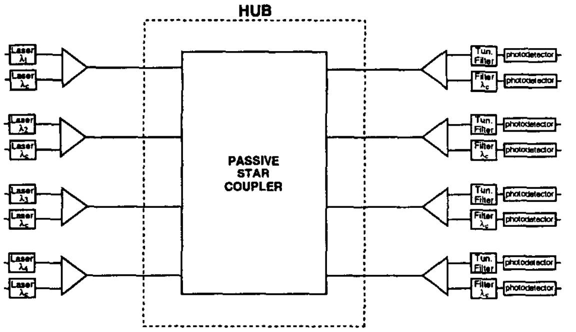

Figure 1: A WDM Broadcast-and-Select Star Network operating under the DT-WDMA protocol.

network hub, allows at most one packet per wavelength to pass to the star coupler, at each time slot. In this way, channel collisions are eliminated. Furthermore, the selection of the passing packets is performed in such a way, that receiver conflicts are avoided. Analytical and simulation results are presented which indicate that a WDM Star network operating under the proposed protocol achieves a high performance under any load conditions. The paper is organized as follows: The presentation of the proposed CPF protocol in Section 2, is followed by its its performance analysis in Section 3. In Section 4, extensive simulation results are presented. Finally, concluding remarks are given in Section 5.

2. The CPF Protocol

A WDM star network operating under the CPF protocol can be divided into two basic modules which are described below: The Broadcast-and-Select Module and the Centralized Packet Filtering Module. The reader can consult figure 2 in order to study an example of the CPF protocol for four stations and two wavelengths.

2.1. The Broadcast-and-Select Module

The Broadcast-and-Select module is based on the well-known DT-WDMA [3] architectural form, but differs in that the number of stations is not necessarily equal to the number wavelengths.

The set of stations is defined as $U = \{u_1, \ldots, u_N\}$, where N is the number of stations. All the stations are placed $D/2$ slots from the network hub. Therefore, the round trip propagation delay from the stations to the network hub and back is equal to D slots.

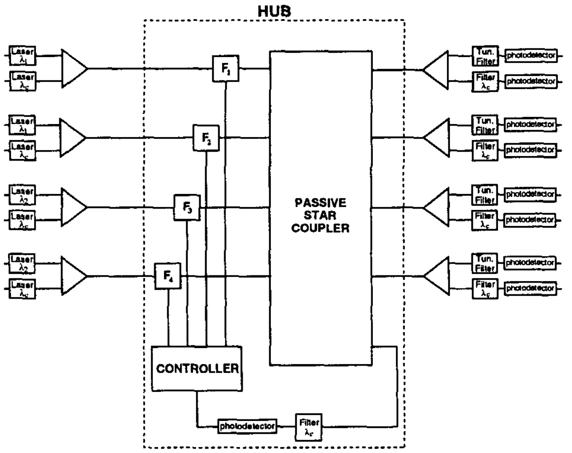

Figure 2: A WDM Broadcast-and-Select Star Network operating under the CPF protocol.

W wavelengths 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 $\Lambda = \{\lambda_1, \ldots, \lambda_N\}$.

Each source node u_k $(k = 1, \ldots, N)$ is provided with two fixed-wavelength lasers: one at a data wavelength λ_{i_k}, with $i_k = \lceil \frac{kW}{N} \rceil$ and one at the control wavelength λ_c . In order to simplify the protocol presentation, it is assumed that N/W is an integer. Thus, each data wavelength is shared by 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 after passing through a packet filtering mechanism, which will be described in Section 2.2. 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 passes only the control wavelength. The other part is fed to a tunable optical filter which is able to be tuned to pass any one of the W data wavelengths. In this way, the 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 at the corresponding wavelength and receives the incoming packet.

2.2. The Centralized Packet Filtering Module

An array of tunable optical filters, which control the passing of the transmitted packets to the Star Coupler, is placed at the network hub. The optical signal of each source node u_k passes through a tunable optical filter F_k $(k = 1, \ldots, N)$. At any time slot t, each filter F_k can be in ON or OFF state. When $F_k = ON$, then it passes both wavelengths λ_{i_k} and λ_c . When $F_k = OFF$, then only λ_c passes while λ_{i_k} is blocked. In other words, the control wavelength λ_c always passes through the filter, while the data wavelength λ_{i_k} passes only when $F_k = ON$.

Electrooptic Tunable Filters, which have a complementary output port containing the unselected wavelength [21], are used for implementing the above function. Thus, the OFF state is implemented by tuning the filter at wavelength λ_{i_k}. In this case, the complementary port of the filter contains λ_c but does not contain λ_{i_k}. The ON state is implemented by tuning the filter at any other wavelength except λ_{i_k} and λ_c. In this case, both λ_{i_k} and λ_c are contained at the complementary port. The complementary output port of each filter is connected to an input port of the Star Coupler.

The state of the centralized filters F_k $(k = 1, \ldots, N)$ is determined by a Controller according to a Packet Selection Algorithm. The main objectives of this algorithm are the following:

1) At most one packet per data wavelength must be allowed to pass to the star coupler. All other packets which are transmitted on the same wavelength must be blocked in order to avoid channel collisions.

2) All the passing packets must have different destination nodes, in order to avoid receiver conflicts.

3) The algorithm must be simple, in order not to introduce a high computational overhead.

Let $X_{i,j}(t)$ be the set of source nodes which have transmitted on wavelength λ_i a packet destined to node u_k , at time slot t. Now, lets define: $S_j(t) = \{$ wavelength $\lambda_k : X_{k,j}(t) \neq \emptyset\}$ and $D_i(t) = \{$ destination node $u_k : X_{i,j}(t) \neq \emptyset\}$. In order to avoid channel collisions, the Packet Selection Algorithm selects one destination node u_j for each wavelength λ_i , such that $u_i \in D_i(t)$ and allows only one source node $u_k \in X_{i,j}(t)$ to access the star coupler. Since only one packet per wavelength is allowed to pass to the star coupler, channel collisions are avoided. Furthermore, the selection of u_j is implemented in such a way that receiver conflicts are eliminated. The algorithmic description of the Packet Selection Algorithm is presented below:

```
PROCEDURE PACKET_SELECTION;
BEGIN
    FOR $k$ := 1 TO $N$ DO $F_k := OFF$;
    $G := \{$ wavelength $\lambda_i : D_i(t) \neq \emptyset\}$;
    $R := \{$ destination node $u_j : S_j(t) \neq \emptyset\}$;
    WHILE $G \neq \emptyset$ DO
    BEGIN
        Randomly select a wavelength $\lambda_i \in G$;
        $G := G - \{\lambda_i\}$;
        IF $(R \cap D_i(t)) \neq \emptyset$ then
        BEGIN
            Randomly select a dest. node $u_j \in (R \cap D_i(t))$;
            $R := R - \{u_j\}$;
            Randomly select a source node $u_k \in X_{i,j}(t)$;
            Set $F_k := ON$;
        END;
    END;
END;
```

In order to implement the above algorithm, the Controller must be informed of the source and the destination nodes of the packets that will arrive at the network hub during the next time slot. The wavelength where each packet is transmitted is immediately derived from its source node. In order to be provided with the above information, the Controller listens to the control wavelength. One of the output ports of the star coupler is connected to a fixed optical filter which passes only the control wavelength λ_c. The output of the filter is fed to the Controller after passing through a photodetector which performs O/E conversion.

2.3. The Operation of the CPF protocol

At the beginning of each time slot t, each ready station u_k randomly selects a packet from its queue and sends a message containing the source and the destination node of the packet, through the control wavelength λ_c . The packet is transmitted on wavelength λ_{i_k} at the next time slot $t + 1$. Packet transmission is based on pipelining. Thus, a ready source node, continuously transmits packets without waiting for an acknowledgement. All the transmitted but unacknowledged packets, are kept in a buffer.

When the control information arrives at the network hub, after a propagation delay of $D/2$ slots, the Controller processes it according to the Packet Selection Algorithm, in order to determine the state of centralized filters F_k $(k = 1, \ldots, N)$ for the next time slot. If $F_k = ON$ then the data packet is allowed to pass to the Star Coupler. Otherwise, it is blocked by the filter. The tuning time of the centralized filters does not affect the network performance, since it is overlapped by the tuning time of the filters of the receiving stations.

All the passing packets are broadcasted by the Star Coupler to all the destination nodes.

The same Packet Selection Algorithm, is executed by all the stations when the control information arrives at them, after a round-trip propagation delay of D slots. In this way, the destination nodes are informed about the imminent packet arrivals while the source nodes find out whether their transmissions were blocked or not. When a destination node is informed that a data packet will arrive from station u_k at the next time slot, it tunes its optical filter at wavelength λ_{i_k} and receives the incoming packet. When a source node finds out that a transmitted packet was not blocked, it deletes the packet from the buffer. Otherwise, the packet is rescheduled for transmission.

Note, that the same random seed must be used by all the stations and the central Controller when executing the Packet Selection Algorithm. In this way, all the stations will get the same states of the centralized filters F_k $(k = 1, \ldots, N)$.

3. Performance Analysis

In order to simplify the computation we assume that the network operates under heavy load conditions, thus all the source nodes are always ready to transmit and consequently, exactly N/W packets are transmitted on each wavelength, at each time slot. Furthermore, we assume that the destination node of each newly arriving packet is chosen at random among all nodes.

According to the proposed algorithm, each wavelength λ_i selects a destination node from set $R \cap D_i(t)$. If $R \cap D_i(t) = \emptyset$, then no destination node can be selected. In this case, all the N/W packets which are transmitted on λ_i are blocked by the electrooptic filters and consequently, no successful transmission takes place on λ_i. In any other case, exactly one successful transmission takes place on λ_i.

The blocking probability $P_{BL} = Pr\{R \cap D_i(t) = \emptyset\}$ is equal to the probability that all the destination nodes in $D_i(t)$ have already been selected by other wavelengths. If m is the number of destination nodes which have already been selected by other wavelengths, then:

$$P_{BL} = (m/N)^{N/W} \qquad (1)$$

The probability that a successful transmission will take place on wavelength λ_i is:

$$P_{SUC} = 1 - P_{BL} = 1 - (m/N)^{N/W} \qquad (2)$$

Without loss of generality, lets number the wavelengths according to the (random) order they select their destination nodes. Thus, we call λ_1 the wavelength which selects first, λ_2 the wavelength which selects after λ_1 , etc. Let $P_{b_1 b_2 \ldots b_W}$ with $b_i \in \{0, 1\}$ for $i = 1, 2, \ldots, W$ be the probability of having $b_1, b_2, \ldots, b_W$ successful transmissions on wavelengths $\lambda_1, \lambda_2, \ldots, \lambda_W$ correspondingly. From relations (1) and (2) is derived that:

	Throughput (in packets per data wavelength per slot)	
	ANALYSIS	SIMULATION
N=40 W=20	0.9288	0.9283
N=60 W=20	0.9917	0.9917
N=80 W=20	1.0000	1.0000

Table 1: The throughput of the CPF protocol when operating under heavy load conditions.

$$P_{b_1 b_2 \ldots b_W} = \prod_{i=1}^{W} \left[b_i + (-1)^{b_i} \left(\frac{\sum_{k=1}^{i-1} b_k}{N} \right)^{\frac{N}{W}} \right] \qquad (3)$$

Therefore, the throughput T (in packets per data wavelength per slot) is:

$$T = \sum_{b_1 b_2 \ldots b_W = 10\ldots0}^{11\ldots1} \left[P_{b_1 b_2 \ldots b_W} \times \frac{1}{W} \sum_{j=1}^{W} b_j \right] =$$

$$= \frac{1}{W} \sum_{b_1 b_2 \ldots b_W = 10\ldots0}^{11\ldots1} \left[\left(\prod_{i=1}^{W} \left[b_i + (-1)^{b_i} \left(\frac{\sum_{k=1}^{i-1} b_k}{N} \right)^{\frac{N}{W}} \right] \right) \times \sum_{j=1}^{W} b_j \right] \qquad (4)$$

In any case, 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 presented in Table 1.

4. Simulation Results

In the following, the proposed CPF protocol is compared to TDM: another well-known collision-free protocol, which can be used for sharing each wavelength between more

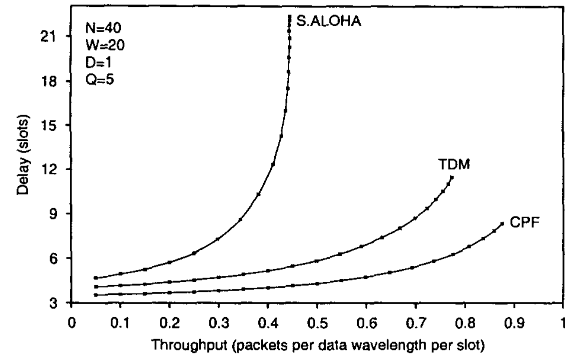

Figure 3: The Delay vs Throughput characteristics of CPF, TDM and S.ALOHA when applied to network N_1.

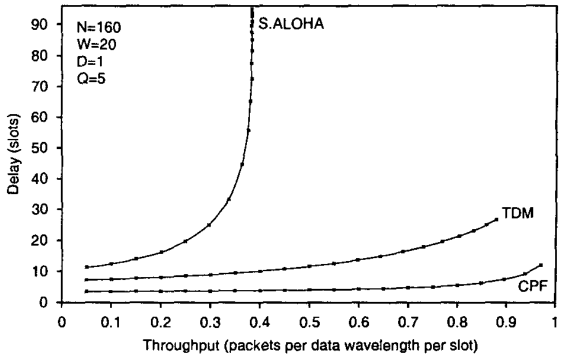

Figure 4: The Delay vs Throughput characteristics of CPF, TDM and S.ALOHA when applied to network N_2.

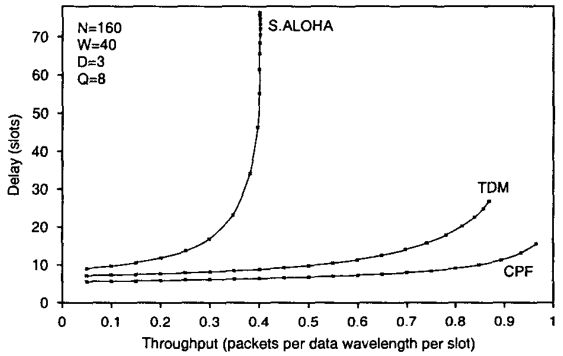

Figure 5: The Delay vs Throughput characteristics of CPF, TDM and S.ALOHA when applied to network N_3.

than one source nodes. According to this protocol, all the source nodes that share a wavelength cyclically grant permission to transmit in a round-robin manner [6],[8]. Due to the absence of collisions, this protocol achieves a high performance. Therefore, its comparison with CPF would be very useful for evaluating the performance of the latter. The protocols which are under comparison were simulated to be applied to three different networks (N_1, N_2 and N_3) of the architectural form described in Section 2. The number of stations N, the number of data wavelengths W, the round-trip propagation delay D and the queue length Q of each simulated network, were taken to be as follows:

a) Network $N_1 : N = 40, W = 20, D = 1, Q = 5$.
b) Network $N_2 : N = 160, W = 20, D = 1, Q = 5$.
c) Network $N_3 : N = 160, W = 40, D = 3, Q = 8$.

We have used the delay versus throughput characteristic as a performance metric in order to compare the two protocols.

The delay versus throughput characteristics of the compared protocols when they are applied to networks $N_1, N_2 and N_3$ are appeared at figures 3, 4 and 5 correspondingly. Each characteristic was constructed by using 20 points, with each point corresponding to a different value of the offered load. The load values were taken to be from 0.05 to 1.00 packets per wavelength per slot.

The following results can be obtained from the above graphs:

1) Under low load conditions, the CPF protocol achieves a lower delay than TDM. Under the these load conditions, according to the CPF protocol, only two slots are required for the successful transmission of a newly arriving packet: one slot for sending the control information and one slot for transmitting the packet. On the other hand, according to the TDM protocol, each source node grants permission to transmit every N/W slots. Thus, a newly arriving packet waits for about N/W slots before being transmitted. Therefore, the mean packet delay of CPF is significantly lower than the one of TDM when both protocols operate under low load conditions. The difference between the two protocols becomes even higher when the ratio N/W is increased.

2) Under high load conditions, the CPF protocol achieves a higher throughput-delay performance than protocol TDM. Under these load conditions, the TDM protocol suffers from a large number of receiver conflicts. Due to the elimination of receiver conflicts, the CPF protocol achieves a significantly higher throughput and a lower delay than TDM.

5. Conclusion

This paper has presented a new protocol for WDM Star Networks. According the proposed CPF protocol, the network hub is embellished with a packet filtering mechanism which controls the passing of the transmitted packets to the Star Coupler. In this way, channel collisions as well as receiver conflicts are prevented so that the network is capable of achieving a high performance under any load conditions. The main advantages and disadvantages of the proposed CPF protocol are summarized below:

Advantages:

a) The CPF protocol achieves a very high throughput-delay performance under both high and low load conditions.

b) The CPF protocol can be applied in already existing WDM Passive Star networks which operate under the DT-WDMA [3] protocol. The only additional hardware is the filter-based mechanism which must be placed at the network hub.

Disadvantages:

a) The use of the tunable filters at the network hub, introduces additional implementation cost. However, the cost increase is limited by the fact that all the filters are placed at the same site and consequently, they can be arrayed in a common device [5].

b) The hub of the network - which represents a single point of failure - is no longer a passive unpowered star coupler as was in the basic DT-WDMA architectural form.

We believe that the idea of placing switching functionality at the network hub as well as at the end users - which is the main idea of the CPF protocol- can be the base of a new family of powerful MAC protocols for WDM Star Networks. We are currently working on this direction.

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