

Centralized Wavelength Conversion Protocols for WDM Broadcast-and-Select Star Networks

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Abstract

WDM broadcast-and-select star networks using fixed lasers and tunable optical filters are favored by the current state-of-the-art in technology over the other WDM star architectural forms. However, networks of this architectural form suffer from low efficiency when the offered traffic is bursty. Under bursty traffic conditions, it is probable that some wavelengths are idle, while some other wavelengths are overloaded. Therefore, the overall network performance is degraded. In this paper, a new MAC protocol which is capable of operating efficiently under bursty traffic conditions is introduced. According to the proposed protocol an array of tunable wavelength converters is placed at the network hub in order to uniformly distribute the incoming packets to the available wavelengths. In this way, the load is balanced between the wavelengths and consequently, the network performance is improved. The performance of the proposed protocol is studied via analytical and simulation results which indicate that a WDM Star network operating under this protocol achieves a high throughput-delay performance under both bursty and non-bursty traffic conditions.

1. Introduction

The emerging single-hop lightwave local and metropolitan area networks [1] are based on Wavelength Division Multiplexing (WDM) in order to achieve gigabit data rates. Due to the limited speed of the stations' electronic circuits, single channel optical networks - such as FDDI, DQDB, Fasnnet, Expressnet, etc - were not proved capable of supporting Gigabit data rates. The WDM technique [2]-[6] solves 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 without the need of optical to electronic translation and vice versa. In this way, the WDM technique allows the implementation of all-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 [2],[7], b) tunable optical transmitters and tunable optical receivers [1],[8]-[11], c) tunable optical transmitters and fixed optical receivers [12]-[17], and d) fixed optical transmitters and tunable optical receivers [2],[18]-[24]. The latter configuration is favored by the current state-of-the art in technology [20]. However, networks of this architectural form suffer from low efficiency when the offered traffic is bursty. Under bursty traffic conditions, it is probable that some wavelengths are idle while some other wavelengths are overloaded. Therefore, the overall network performance is degraded.

In this paper, a new MAC protocol which is capable of operating efficiently under bursty traffic conditions is introduced. According to the proposed protocol an array of tunable wavelength converters is placed at the network hub in order to uniformly distribute the incoming packets to the available wavelengths. In this way, the load is balanced between the wavelengths and consequently, the network performance is improved.

The performance of the proposed protocol is studied via analytical and simulation results which indicate that a WDM Star network operating under this protocol achieves a high throughput-delay performance under both bursty and non-bursty traffic conditions.

The paper is organized as follows: The proposed Centralized Wavelength Conversion (CWC) protocol is presented in Section 2, while its performance benefits are analytically discussed in Section 3. In Section 4, extensive simulation results are presented which indicate the superiority of the CWC protocol over other well-known protocols. Finally, concluding remarks are given in Section 5.

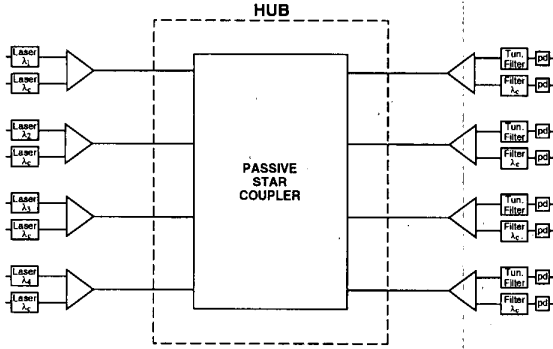


Figure 1: A WDM Broadcast-and-Select Star Network operating under the DT-WDMA protocol.

2. The CWC Protocol

A network using the CWC protocol can be divided into two basic modules which are described below: The Broadcast-and-Select Module and the Centralized Wavelength Conversion Module. The reader can consult figure 2 in order to study an example of a network with four stations and two wavelengths which operates under the CWC protocol.

2.1. The Broadcast-and-Select Module

The Broadcast-and-Select module is based on the well-known DT-WDMA (Dynamic Time-Wavelength Division Multiple Access) [20] architectural form, but differs in that the number of stations is not necessarily equal to the number of 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.

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 $\Lambda = \{\lambda_1, \dots, \lambda_W\}$.

Each source node u_k ($k = 1, \dots, N$) is provided with two fixed-wavelength lasers: one at a data wavelength λ_{i_k} ($i_k = \lceil \frac{kW}{N} \rceil$, thus, $1 \leq i_k \leq W$) 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

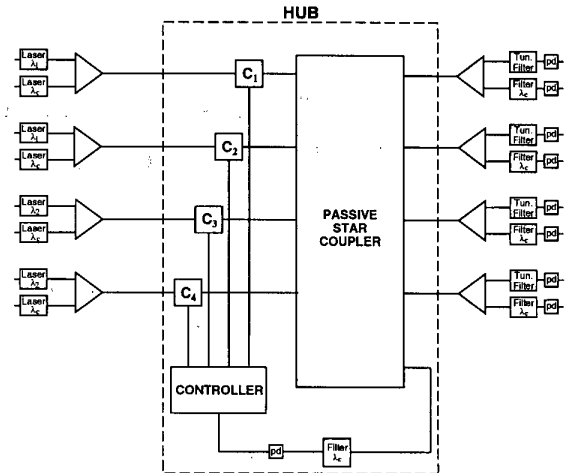


Figure 2: A WDM Broadcast-and-Select Star Network operating under the CWC protocol.

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 wavelength conversion 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 to the corresponding wavelength and receives the incoming packet.

2.2. The Centralized Wavelength Conversion Module

An array of tunable wavelength converters [5], which are capable of converting the wavelengths of the transmitted packets while preserving the control wavelength λ_c (fig.3),

is placed at the network hub. The optical signal of each source node u_k passes through a tunable wavelength converter C_k ($k = 1, \dots, N$). At any time slot t , each wavelength converter C_k can be tuned to convert the fixed incoming wavelength λ_{i_k} to any wavelength $\lambda_{j_k} \in \Lambda$. We denote: $C_k = \lambda_{j_k}$. The wavelength converters can also be tuned to an unused wavelength $\lambda_0 \notin \Lambda$. In this case, the wavelength converter acts as an optical switch which blocks the incoming data signal. The use of λ_0 can be avoided by placing an optical switch after the tunable wavelength converter.

The output port of each converter is connected to an input port of the Star Coupler.

The state of the wavelength converters C_k ($k = 1, \dots, N$) is determined by a Controller according to a Wavelength Conversion Algorithm. The main objectives of this algorithm are the following:

- 1) To minimize the number of idle wavelengths.
- 2) To allow at most one packet per wavelength to pass to the star coupler in order to avoid channel collisions.
- 3) To allow at most one packet per destination node to pass to the star coupler, in order to avoid receiver conflicts.
- 4) To be simple, in order not to introduce a high computational overhead.

Let $X_j(t)$ ($j = 1, \dots, N$) be the set of source nodes which have transmitted a packet destined to node u_j , at time slot t . In order to avoid receiver conflicts, the Wavelength Conversion Algorithm selects one source node $u_x \in X_j(t)$ for each destination node u_j , with $X_j(t) \neq \emptyset$. Then, it distributes the selected source nodes to the available wavelengths and tunes each wavelength converter to the corresponding wavelength.

The algorithmic description of the Wavelength Conversion Algorithm is presented below:

```

PROCEDURE WAVELENGTH_CONVERSION;
BEGIN
  G := ∅
  FOR i := 1 TO N DO Ci := λ0;
  FOR j := 1 TO N DO IF Xj(t) ≠ ∅ THEN
    BEGIN
      Randomly select a source node ux ∈ Xj(t);
      G := G ∪ {ux};
    END;
  R := Λ;
  WHILE G ≠ ∅ AND R ≠ ∅ DO
    BEGIN
      Randomly select a source node uy ∈ G;
      Randomly select a wavelength λz ∈ R;
      G := G - {uy};
      R := R - {λz};
      Set Cy := λz;
    END;
  END;
END;

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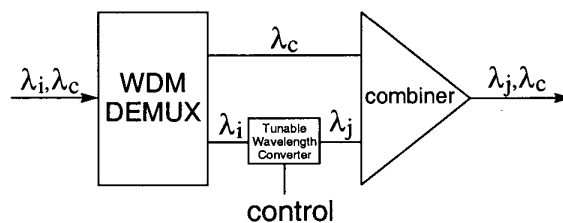


Figure 3: A tunable wavelength converter which converts the data wavelength λ_i , but preserves the control wavelength λ_c .

In order to implement the above algorithm, the Controller must be informed of the source and 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 CWC 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 the data wavelength λ_{i_k} , at the next time slot ($t + 1$). The random transmission strategy was chosen, instead of FIFO transmission strategy, because it achieves a significantly higher performance [25]. 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 Wavelength Conversion Algorithm, in order to determine the state of the wavelength converters C_k ($k = 1, \dots, N$) for the next time slot. The tuning time of the wavelength converters does not affect the network performance, since it is overlapped by the tuning time of the filters of the receiving stations.

After the wavelength conversion, the transmitted packets are broadcasted by the Star Coupler to all the destination nodes.

The same 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 $\lambda_{jk} = C_k$ 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.

Since the same algorithm runs in every station, it might appear that every transmitting station could have the possibility of driving its own wavelength converter instead of having a centralized controller. However, the control information which is necessary for executing this algorithm arrives at the stations after a round-trip propagation delay of D slots, while the packets arrive at the hub after a one-way propagation delay of $D/2$ slots. Thus, the control information is not available at the stations when the packets arrive at the hub. Therefore, the centralized wavelength converters can not be driven by the stations.

3. Performance Benefits of Wavelength Conversion

Assume that m packets are transmitted, at a time slot t . Furthermore, assume that no wavelength converters are used. Let m_i be the number of packets which are transmitted at wavelength λ_i , for $i = 1, \dots, W$. Thus, $m = \sum_{i=1}^W m_i$. In this slot, the mean throughput of the network is limited by the following two bounds:

RECEIVER BOUND: This bound is set by the distribution of the transmitted packets to the N destination-nodes. Since only one packet per destination-node can be received, it follows that the normalized throughput T is limited by the receiver bound B_R as follows:

$$T \leq B_R = \frac{1}{W} \sum_{i=1}^m P_{i,m} \min\{i, W\} \quad (1)$$

where: $P_{i,m}$ is the probability that there are i different destination-nodes, given that m packets are transmitted. The probabilities $P_{i,m}$ for $i = 1, \dots, m$ can be evaluated by setting $P_{1,1} = 1$ and applying the following recursive relation up to the evaluation of $P_{m,m}$:

$$P_{i,m} = P_{i-1,m-1} \left(1 - \frac{i-1}{N}\right) + P_{i,m-1} \left(\frac{i}{N}\right) \quad (2)$$

WAVELENGTH BOUND: This bound is set by the distribution of the transmitted packets to the W wavelengths. Since at most one packet per wavelength can pass through

m_1	m_2	m_3	m_4	m_5	m_6	m_7	m_8	m_9	m_{10}	Var(m_i)	B_w	B_c	$T_{max} (max.)$	T_{CWC}
1	1	1	1	1	1	1	1	1	1	0.0	1.0000	0.9146	0.9146	0.9146
2	2	2	1	1	0	0	0	0	0	0.8	0.6000	0.9146	0.6000	0.9146
2	2	2	2	0	0	0	0	0	0	1.0	0.5000	0.9146	0.5000	0.9146
4	2	0	0	0	0	0	0	0	0	2.6	0.3000	0.9146	0.3000	0.9146
5	0	0	0	0	0	0	0	0	0	4.0	0.2000	0.9146	0.2000	0.9146

Table 1: T_{CWC} vs T_{NWC} for various distributions of the packets to the available wavelengths ($N=50$, $W=10$, $m=10$).

the star coupler, it follows that even when no wavelength collisions are allowed (e.g. protocol CPF [19]) the normalized throughput T is limited by the wavelength bound B_W as follows:

$$T \leq B_W = \frac{1}{W} \sum_{i=1}^W \min\{m_i, 1\} \quad (3)$$

Thus, when no wavelength converters are used, the mean throughput T_{NWC} is limited by both B_R and B_W :

$$T_{NWC} \leq \min\{B_R, B_W\} \quad (4)$$

When the Centralized Wavelength Conversion protocol is used, then the wavelength bound B_W is eliminated, while the mean network throughput T_{CWC} is equal to the receiver bound B_R :

$$T_{CWC} = B_R \quad (5)$$

Thus, the CWC protocol achieves a higher throughput than any protocol which does not use wavelength converters. Furthermore, when the traffic is bursty the variance of the random variables m_i (for $i = 1, \dots, W$) is high. In this case, $B_W \ll B_R$ and consequently, the performance improvement which is due to wavelength conversion (i.e. $T_{CWC} - T_{NWC}$) is also high. A comparison between T_{CWC} and the maximum value of T_{NWC} for various distributions of the packets to the available wavelengths is presented in Table 1.

4. Simulation Results

In the following, the proposed CWC protocol is compared to TDM and CPF; two collision-free protocols for WDM Star Networks using fixed optical transmitters and tunable optical receivers.

Under the TDM protocol [12],[26], all the source nodes that share a wavelength cyclically grant permission to transmit in a round-robin manner.

According to CPF [19], the source nodes transmit their packets in a slotted ALOHA-like fashion and an array of electrooptic tunable filters, which is placed at the network

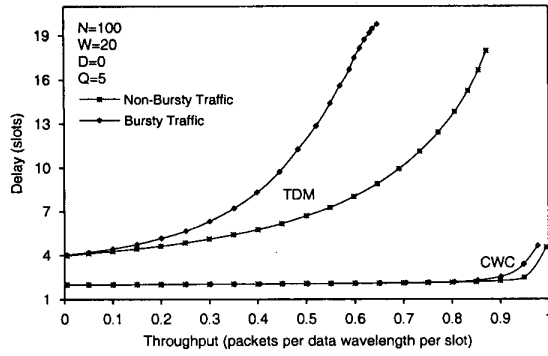


Figure 4: The Delay vs Throughput characteristics of CWC and TDM when applied to network N_1 .

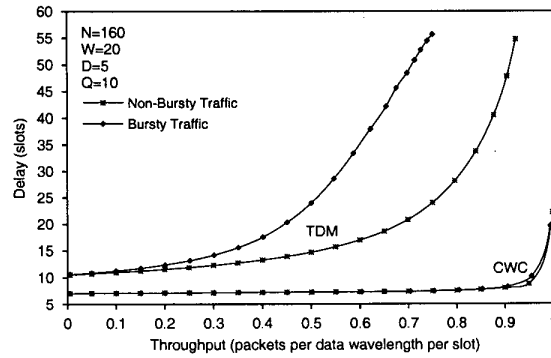


Figure 5: The Delay vs Throughput characteristics of CWC and TDM when applied to network N_2 .

hub, blocks some of the packets in order to avoid channel collisions.

The protocols which are under comparison were simulated to be applied to four different networks (N_1, N_2, N_3 and N_4) of the architectural form described in Section 2, under bursty and non-bursty traffic conditions.

The offered traffic was modelled in a way similar to the one used in [27]. Each source-node can be in one of two states S_0 and S_1 . When a source-node is in state S_i ($i = 0, 1$) then its arrival rate is equal to L_i packets/slot. Given a station is in state S_0 at time slot t , the probability that this station will transit to state S_1 at the next time slot is P_{01} . The transition probability from state S_1 to state S_0 is P_{10} . We selected $P_{01} = P_{10} = 0.01$. If the overall network load is L packets/user/slot, then the bursty traffic was simulated by taking $L_1 = 1.8L$ and $L_0 = 0.2L$. On the other hand, the non-bursty traffic was simulated by taking $L_1 = L_0 = L$.

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:

- Network N_1 : $N = 100, W = 20, D = 0, Q = 5$.
- Network N_2 : $N = 160, W = 20, D = 5, Q = 10$.
- Network N_3 : $N = 80, W = 20, D = 5, Q = 10$.
- Network N_4 : $N = 150, W = 30, D = 10, Q = 15$.

We have used the delay versus throughput characteristic as a performance metric in order to compare the three protocols (figures 4-11). 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 1.00 packets per wavelength per slot.

The following results can be obtained from the above graphs:

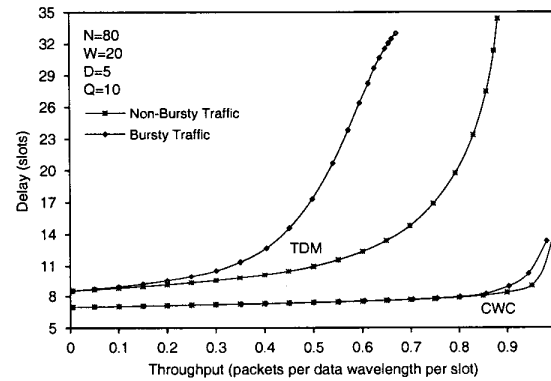


Figure 6: The Delay vs Throughput characteristics of CWC and TDM when applied to network N_3 .

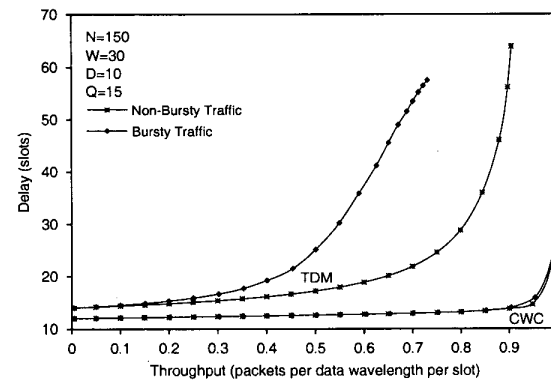


Figure 7: The Delay vs Throughput characteristics of CWC and TDM when applied to network N_4 .

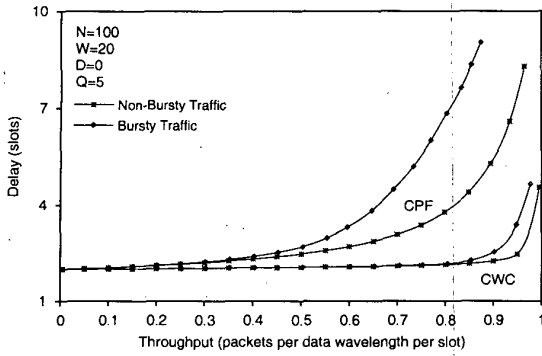


Figure 8: The Delay vs Throughput characteristics of CWC and CPF when applied to network N_1 .

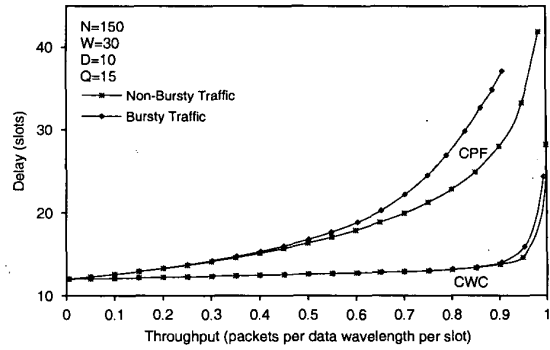


Figure 11: The Delay vs Throughput characteristics of CWC and CPF when applied to network N_4 .

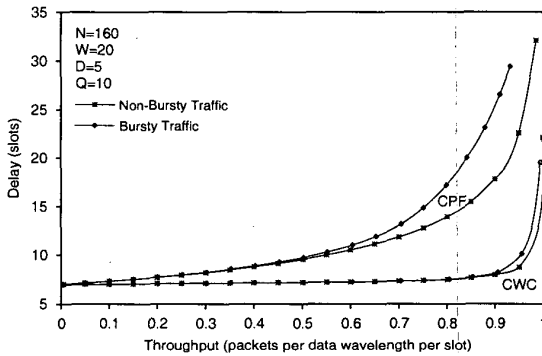


Figure 9: The Delay vs Throughput characteristics of CWC and CPF when applied to network N_2 .

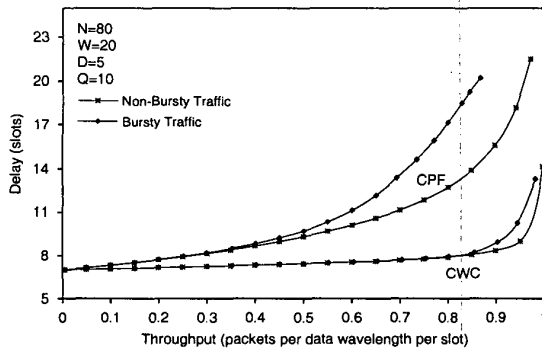


Figure 10: The Delay vs Throughput characteristics of CWC and CPF when applied to network N_3 .

1) The performance of CWC is practically unaffected by the nature of the offered traffic. Under both bursty and non-bursty traffic the protocol CWC achieves a high performance. On the other hand, the performance of TDM and CPF is significantly degraded when the offered traffic is bursty.

2) Even when the offered traffic is not bursty, the CWC protocol achieves a significantly higher performance than TDM and CPF. Even when the traffic is not bursty, there is no guarantee that the load is equally shared between the wavelengths, at each time slot. Therefore, the use of a wavelength conversion mechanism leads to a performance improvement.

5. Conclusion

This paper has presented a new protocol for WDM Star Networks. According the proposed CWC protocol, the network hub is embellished with a wavelength conversion mechanism which converts the wavelength of the transmitted packets before they reach the Star Coupler. In this way, the load is balanced between the wavelengths and consequently, the network is capable of operating efficiently under any traffic conditions.

The main advantages and disadvantages of the proposed CPF protocol are summarized below:

Advantages:

a) The CWC protocol achieves a very high throughput-delay performance under both bursty and non-bursty traffic conditions.

b) It can be applied in already existing WDM Passive Star networks which operate under the DT-WDMA [20] protocol. The only additional hardware is the wavelength conversion mechanism which must be placed at the network hub.

Disadvantages:

a) The use of wavelength converters at the network hub, introduces additional implementation cost. However, the cost increase is limited by the fact that all the wavelength converters are placed at the same site and consequently, they can be arrayed in a common device [21].

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.

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