A Control Channel Architecture with Collisions Avoidance Strategy for Performance Improvement in WDM Ring Networks

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Abstract: - This study introduces the scalability problem of many WDMA protocols for ring networks. We present a slotted access protocol and a scalable network architecture suitable for WDM ring metropolitan area networks. Each node is equipped with a pair of tunable transceivers to communicate exploiting all the fiber data wavelengths. Also, each node uses a pair of fixed tuned transceivers to exchange control information over a separate control wavelength. The proposed protocol efficiently utilizes the available bandwidth applying a simple access algorithm to avoid both the data channels and the receiver collisions. Performance measures evaluation is provided through analysis. Also, a discrete event simulation model is developed that uses both poisson and pareto traffic sources, giving more realistic performance measures evaluation. Comparative simulation results show that the proposed protocol and network architecture achieve significant performance improvement as compared with the study of [1] which employs nodes with one fixed tuned transmitter.

Key-Words: - Wavelength Division Multiplexing (WDM), WDM ring network, collisions avoidance.

1 Introduction

In WDMA protocols for ring metropolitan area networks (MANs), the phenomena that determine the bandwidth efficiency are the channels collisions and the destination conflicts. Their avoidance is very complicated, since the contention resolution access algorithm has to take into account the propagation delay latency that is much higher than the data packet transmission time.

In literature, many studies assume that a dedicated channel is assigned to each node around the ring for either transmission or reception, aiming to face the channels and the receiver collisions respectively. Particularly, in some WDMA protocols each node uses a fixed tuned transmitter and a tunable receiver (FT-TR) and it has a dedicated channel for transmission to avoid channels collisions [1-2]. On the other hand, in many WDMA protocols each node uses a tunable transmitter and a fixed tuned receiver (TT-FR) and it has a dedicated channel for reception to avoid receiver collisions [3-4]. In these studies, a restriction about the number of nodes is introduced to provide access fairness: the number of nodes (N) is an integer (D) multiple of the number of channels (W), D=N/W. Despite the contention resolution provision, this restriction provides serious scalability problems since in case of a node addition or deactivation the whole network reconfiguration is required.

In this paper, we present a slotted protocol to access the WDM channels of a ring MAN. The proposed protocol uses a separate WDM control channel to exchange control information prior to the data packet transmission to avoid both channels and receiver collisions. Each node uses a pair of tunable transmitter and tunable receiver to access the data channels. Also, each access node uses a pair of fixed tuned transmitter and fixed tuned receiver tuned to the control channel. The proposed protocol provides high scalability since the number of nodes is independent from the number of channels. Thus, the restriction D=N/W is removed.

The maximum throughput per node is analytically derived, while the performance measures evaluation is provided by simulation assuming both poisson and pareto traffic sources. Finally, we compare the proposed protocol with the protocols of [1] which employ nodes with a fixed tuned transmitter and we show the essential performance improvement.

This study is organized as follows: Section 2 gives the network model and the assumptions. The analysis is given in Section 3. Section 4 presents the simulation model and the performance evaluation. Some conclusions are outlined in Section 5.

2 Network Model and Assumptions

A uni-directional single-fiber multi-channel slotted ring MAN that uses W+1 channels is assumed. A
finite number $N$ of nodes is interconnected around the ring, as Fig. 1 shows. The $W$ channels $\lambda_1, \ldots, \lambda_w$ are used for the data packets transmission, and the channel $\lambda_c$ is used for the control communication. Each node is connected to one or more access networks. In the direction from the access networks to the ring, the node stores the incoming packets at a buffer with size $B$ data packets. In the inverse direction, the node terminates the optical signals. The access networks are Local Area Networks (LANs) connected to the nodes by an 1 Gb/s Ethernet link. Each node has optical add-drop capabilities to access the ring. The data packet size is equal to the Ethernet maximum transfer unit size 12 000 bits. Each node uses a fixed transmitter and a fixed receiver tuned at the control channel. Also, each node uses a tunable transmitter and a tunable receiver tuned over all data channels. Thus, the node interface is called FT-FR-TT-TR. We denote as $t_{s-t}$ and $t_{s-r}$ the tuning time of the tunable transmitter and tunable receiver respectively.

At the beginning of a multi-data slot, the control channel carries $W$ mini-control packets one for each data channel. The transmission time of the $W$ mini-control packets is $t_c$. The size of a mini-control packet is $2^n$ bits, $2^{n-1} \leq N < 2^n$ [5]. The $k \in \{1,2,\ldots,W\}$ mini-control packet carries in binary mode the source and the destination address of the data packet transmitted over the $k$ data channel.

A set of $W$ parallel delay lines is assumed at each node, one for each data channel. Each delay line holds up the data packet for time interval equal to $t_c$. The feasibility issue is studied in [6]. When a multi-data slot arrives at a node, the arriving data packets insert to the $W$ delay lines. On the same time, the node follows the following procedure:

1) Reading part of control information: the node receives the $W$ mini-control packets with its fixed tuned receiver for time interval $t_c$ equal to the $W$ mini-control packets transmission time $t_c$, i.e. $t_c = t_c$.

2) Processing part of control information: after the end of time interval $t_c$, the node processes the $W$ mini-control packets for time interval $t_r$. Thus, by the end of time interval $t_r + t_r$ the node is aware of: a) the available data channels for transmission to avoid channel collisions, b) the destination address of the data packets transmitted over the data channels. If the node has a data packet to transmit, it examines the followings: i) the existence of available data channels, and ii) the case where none of the transmitted data packets has the same destination with the node’s data packet. If the above conditions are satisfied, the node chooses randomly one of the available data channels, let’s say $k$ data channel. Also, by the end of the time interval $t_r + t_r$ the node may inspect a data packet destined to it and transmitted over the $m \in \{1,2,\ldots,W\}$ data channel.

3) Tuning part of tunable transceivers: after the end of time interval $t_r + t_r + \max\{t_{s-t}, t_{s-r}\}$, the tunable transceivers are tuned to the appropriate data channels, for possible transmission and/or reception. On the same time, the upstream data packets exit from the nodes delay lines. Thus, it: $t_r = t_r + t_r + \max\{t_{s-t}, t_{s-r}\}$.

4) Transmission and reception part of the data packets: by the end of time interval $t_r$, the node starts: a) the data packet transmission over the $k$ data channel with its tunable transmitter, b) the data packet reception from the $m$ data channel with its tunable receiver. This part lasts for time interval $T$.

5) Transmission part of control information: simultaneously, by the end of time interval $t_r$, the node re-transmits, while modifies, with its fixed tuned transmitter, the fields of the $W$ mini-control packets.
Thus, if it is necessary the node modifies the k mini-control packet, according to the transmission decision. Additionally, it applies the source stripping rule if it is required. In other words, if the node inspects that a data slot that it has transmitted has come back after an entire loop, it deletes the fields of the corresponding mini-control packet. The node re-transmits the remaining mini-control packets without changing their information. Also, the fairness mechanism of [1] is assumed which restricts a node to reuse a data slot that has just been marked empty.

3 Analysis

We define the normalized time $t=1$ as the time duration for a complete ring rotation. Also, we define the normalized time $T_r$ it takes for a data slot, once filled to be made reusable (not emptied). A data slot, upon its return to the source node, cannot be immediately reused and it is released empty to the downstream node. Since it is assumed that the nodes are equally spaced around the ring, the normalized time it takes for a data slot to travel between two adjacent nodes is $1/N$. Thus, it is:

$$T_r = 1 + \frac{1}{N} \tag{1}$$

The maximum throughput per data slot and per data channel $S_{slot}$ is defined as the maximum rate of data packet successful transmissions by a data slot over a data channel, i.e.:

$$S_{slot} = \frac{1}{T_r} = \frac{N}{N+1} \tag{2}$$

We denote as $R_w$ the transmission rate in Gb/s of each data channel. The maximum throughput $S_w$ per data channel is defined as the maximum rate of data packet successful transmissions per data channel and is given by:

$$S_w = S_{slot} \times R_w \tag{3}$$

The maximum throughput $S$ over all data channels is defined as the maximum rate of data packet successful transmissions, i.e.:

$$S = S_w \times W \tag{4}$$

Also, we define the maximum throughput per node $S_{max}$ over all data channels as:

$$S_{max} = \frac{S}{N} \tag{5}$$

Let $R=W \times R_w$ be the data rate in Gb/s over all data channels. From eq. (2)-(5), it is:

$$S_{max} = \frac{R}{N+1} \tag{6}$$

4 Numerical Results

In order to totally investigate the proposed protocol performance measures and not only the maximum throughput per node, we developed a discrete-event network simulator based on C programming. The simulator uses the confidence level 95% and provides additional predictions for the average throughput, the average queuing delay, the average total delay (the sum of queuing and propagation delay), and the average dropping probability per node.

The performance measures evaluation that the network simulator provides strongly depends on the model used to simulate the traffic from the access networks. Common base in several studies [8-9] is that they model the voice and data traffic in LANs with poisson processes and evaluate the performance measures via mathematical analysis. Nevertheless, the high variability and burstiness that the Internet and multimedia traffic in LANs and MANs present can be better modeled by self similar processes [10-11].

In this study, we simulate the traffic from the attached access networks using poisson and pareto traffic sources and we compare the simulation results. The comparative performance evaluation aims to study the effect of the self similar aggregated traffic burstiness on the proposed FT-FR-TT-TR protocol performance. In our simulator, we use the inverse transformation method to generate the poisson traffic [12]. Also, we use aggregated ON-OFF sources of pareto distribution [11] to generate the self similar traffic. The high burstiness of the aggregated traffic is obtained using the Hurst parameter $H=0.8$, as in [11]. Also, the number of ON-OFF traffic sources in each access network is obtained using the log(variance)-log(aggregate level) of the generated load.

In all simulation results, for both poisson and pareto sources, an excellent fairness among all nodes is managed. Thus, the values of the average throughput, average queuing and total delay and average dropping probability per node are very close among all nodes. Numerical results show that the difference between these values is less than 0.6% for the poisson traffic, while it reaches 8% for the self similar traffic. The fairness is managed by the slot reuse scheme according which an empty slot is released for the downstream node after it is marked empty. Thus, the average measures values give a very close estimation of the individual node performance.

In the following figures the performance measures of the proposed FT-FR-TT-TR protocol are compared with those of the two protocols presented in [1]: a) the FT-FR$^4$ protocol in which each node uses four (equal to the number W) fixed tuned receivers avoiding the receiver collisions, and b) the FT-TR protocol in which the fixed tuned receivers have been substituted by a tunable one. Although this substitution intends to improve the scalability, it results to performance deterioration and inefficient bandwidth consumption, since collided at destination packets continuously loop around the ring till their reception. On the
contrary, the proposed FT-FR-TT-TR protocol manages to face the scalability problems, while it achieves to avoid both the data channels and receiver collisions giving essential performance improvement. The improvement is depicted in the following simulation results for both poisson and pareto traffic.

In order to get comparable network conditions, we adopt the network configuration of [1]. In our simulator, the number of nodes N is chosen such that $S_{\text{max}}$ is less than the nodes maximum rate 1 Gb/s. The processing time is assumed $t_p=1 \mu\text{s}$, like in [7]. Based on the rapid technology evolutions, we assume that the tuning times $t_{\text{s-t}}$, $t_{\text{s-r}}$ are small enough and are neglected. Table 1 presents the network parameters.

<table>
<thead>
<tr>
<th>Network Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring length $L_R$</td>
<td>138,240 m</td>
</tr>
<tr>
<td>Light velocity $v$</td>
<td>$2 \times 10^8$ m/s</td>
</tr>
<tr>
<td>Propagation delay latency</td>
<td>691.2 $\mu$s</td>
</tr>
<tr>
<td>Number of data wavelengths $W$</td>
<td>4</td>
</tr>
<tr>
<td>Number of control wavelengths</td>
<td>1</td>
</tr>
<tr>
<td>Data packet size $L$</td>
<td>12,000 bits</td>
</tr>
<tr>
<td>Mini-control packet size $(2 \times n)$</td>
<td>10 bits</td>
</tr>
<tr>
<td>Number of access nodes $N$</td>
<td>20</td>
</tr>
<tr>
<td>Wavelengths data rate $R_w$</td>
<td>2.5 Gb/s</td>
</tr>
<tr>
<td>Rate of data wavelengths on the ring $R$</td>
<td>10 Gb/s</td>
</tr>
<tr>
<td>Data packet transmission time $T$</td>
<td>4.8 $\mu$s</td>
</tr>
<tr>
<td>Mini-control packets transm. time $t_t$</td>
<td>0.016 $\mu$s</td>
</tr>
<tr>
<td>Delay time of each delay line $t_d$</td>
<td>1.016 $\mu$s</td>
</tr>
<tr>
<td>Number of multi-data slots $M$</td>
<td>144</td>
</tr>
</tbody>
</table>

Table 1. Network parameters

The effect of self similar traffic assumption is representatively shown in the following figures, for the proposed FT-FR-TT-TR and the FT-FR4 and FT-TR protocols of [1]. For all protocols, the self similar traffic provides worse performance than the poisson traffic does. This behaviour is more noticeable under heavy offered load conditions. This fact conforms to the nature of poisson traffic whose transmission rate, at high loads, is getting more constant as the packet interarrival duration decreases. In this congestion case, an almost constant packet arrival process is mentioned, while the nodes buffers are kept full of data packets. This fact causes the abrupt increase of the performance measures under high offered load conditions. On the contrary, the burstiness nature of self similar traffic frequently increases the buffers load, providing lower values of average node throughput and higher values of average total delay. Thus, the congestion state under heavy load is reached in a smoother way, giving non abrupt variation of the performance measures values.

Fig. 3 shows the average throughput per node versus the average offered load per node from the access networks for $N=20$ nodes, $W=4$ data channels, and $B=100$ data packets, for poisson and self similar traffic sources. It is shown that the proposed FT-FR-TT-TR protocol essentially ameliorates the system performance as compared with the FT-FR4 and FT-TR protocols of [1] for a wide offered load range. Especially as Fig. 3 presents, the proposed FT-FR-TT-TR protocol provides almost equal average node throughput values to those of the FT-FR4 and FT-TR protocols, for light offered load i.e. lower than 380 Mb/s and 360 Mb/s respectively under poisson traffic (150 Mb/s and 180 Mb/s respectively under self similar traffic). For higher offered load conditions, the proposed FT-FR-TT-TR protocol performs excellent and can serve the offered load without reaching saturation, providing higher average node throughput. On the contrary the FT-FR4 and FT-TR protocols seem to be unable to serve the high offered traffic. This is due to the fact that the proposed FT-FR-TT-TR protocol allows the transmission over all data channels providing lower values of average queuing delay at these heavy load conditions, as Fig. 4 shows. In this case, the data packets at the buffers can be earlier transmitted, providing higher values of $S_{\text{max}}$. This behaviour is illustrated in Fig. 3 where the proposed FT-FR-TT-TR protocol achieves 17% and 23% higher $S_{\text{max}}$ values as compared with the FT-FR4 and FT-TR protocols respectively. This improvement conforms to the theoretical analysis results according to the eq. (6) and the relative formulas of [1]. Also, it is observed that the proposed FT-FR-TT-TR protocol is able to satisfactorily serve very high offered loads from the access networks, almost till the value of 480...
Mb/s for poisson traffic (390 Mb/s under self similar traffic). Above this offered load value, the buffer congestion is getting higher as there are less empty data slots for transmission. On the contrary, the FT-FR\textsuperscript{3} and FT-TR protocols reach buffer congestion at much lower offered load, i.e. at 380 Mb/s and 360 Mb/s respectively under poisson traffic (150 Mb/s and 180 Mb/s respectively under self similar traffic).

The significant performance improvement that the proposed FT-FR-TT-TR protocol provides is shown in Fig. 4 that presents the average queuing delay versus the average offered load per node for N=20, W=4, and B=100, for poisson and self similar traffic. It is observed that for load values lower than 480 Mb/s for poisson traffic (390 Mb/s under self similar traffic) the proposed FT-FR-TT-TR protocol provides almost zero values of average queuing delay. The reason is that in this range, the utilization of the empty data slots is optimum and the total offered load becomes actual node throughput without being dropped at the node buffer. Above this value the average queuing delay increases. On the other hand, the FT-FR\textsuperscript{3} and FT-TR protocols keep low queuing delay values till 380 Mb/s and 360 Mb/s respectively under poisson traffic (150 Mb/s and 180 Mb/s respectively under self similar traffic), while for higher values they abruptly increase reaching extremely high values. This is because in this high offered load range, the FT-FR\textsuperscript{4} and FT-TR protocols can not serve the high traffic demands and reach their throughput upper limit $S_{\text{max}}$, as explained in Fig. 3. This is due to the fact that the FT-FR\textsuperscript{4} and FT-TR protocols restrict the transmission on a specific data channel, although there may exist empty data slots for transmission on the other data channels. This possibility is exploited by the proposed FT-FR-TT-TR protocol that allows the transmission over all data channels. The significant delay reduction is observed, for example, for offered load 300 Mb/s and under self-similar traffic where the reduction reaches 95%.

![Fig. 4. Av. queuing delay vs av. offered load per node for N=20, W=4, B=100 (poisson - self similar).](image)

Fig. 5. Av. packet dropping probability vs av. offered load per node for N=20, W=4, B=100 (self similar).

These remarks are verified in Fig. 5 that shows the average packet dropping probability versus the average offered load per node for N=20, W=4, B=100, for self similar traffic. Indeed, the proposed FT-FR-TT-TR protocol offers almost zero dropping probability values for offered load values lower than 390 Mb/s, while for higher values they significantly increase. On the other hand, the FT-FR\textsuperscript{4} and FT-TR protocols keep low dropping probability values till 150 Mb/s and 180 Mb/s respectively, while above this range they abruptly increase. These results can be estimated in conjunction with the average queuing delay variation. Thus, the essential dropping probability reduction can be observed, for example, for offered load 300 Mb/s, where the reduction reaches 97%. This is due to the fact that in this case, the proposed FT-FR-TT-TR protocol provides 95% lower queuing delay, as previously mentioned. Thus, the buffers are earlier getting empty and are capable of storing more incoming packets and providing fewer dropping events. The same comments can be outlined in case of poisson traffic that is not illustrated for representative reasons.

The overall performance improvement is presented in Fig. 6 which depicts the average total delay versus the average node throughput. Indeed, the proposed FT-FR-TT-TR protocol achieves under high load conditions 15.7% and 23.1% increase of the average node throughput, while it manages 10% and 15.9%
reduction of the average total delay, as compared to the FT-FR and the FT-TR protocols respectively. Also, the proposed FT-FR-TT-TR protocol is able to efficiently operate under very high load conditions, while both the FT-FR and FT-TR protocols reach saturation at considerable light load values.

Fig. 6. Av. total delay vs av. node throughput for N=20, W=4, B=100 (poisson - self similar).

5 Conclusion
In this paper we propose the FT-FR-TT-TR node interface and a slotted WDMA protocol in conjunction with an effective data channels and receiver collisions avoidance algorithm to improve the performance measures in a ring MAN. The use of a separate control channel for control information exchange prior to the data packet transmission is introduced. The proposed FT-FR-TT-TR protocol efficiently exploits the total fiber bandwidth since it utilizes the WDM channels for both transmission and reception. Also, in opposition to other WDMA protocols, the proposed FT-FR-TT-TR protocol provides high scalability since it allows the addition or deactivation of a node without requiring the total network reconfiguration.

In this study, performance evaluation is provided via analysis and via a discrete event simulation model. The comparative simulation results prove that the proposed FT-FR-TT-TR protocol essentially ameliorates the system performance as compared with the protocols of [1] that use a node interface with a fixed tuned transmitter. As the figures show and the numerical results denote the proposed FT-FR-TT-TR protocol achieves significant performance improvement which in many cases reaches to 100%.

References: