Performance Evaluation of a Metro WDM Multi-channel Ring Network with Variable-length Packets

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Abstract — In this paper, we discuss and evaluate our two metro wavelength division multiplexing (WDM) ring network architectures for variable-length packet traffic. The paper begins with a brief review of the relevant architectures and protocols in the literature. Subsequently, the network architectures along with their medium access control (MAC) protocols are described. Performance for the two network architectures is studied using both simulation and Markovian modeling approaches with the help of their results for queuing delay, node throughput and proportion of packet dropped. Performance for the network is evaluated under symmetric and asymmetric traffic scenarios with Poisson and self-similar traffic.

Index —Medium access control (MAC) protocol, metropolitan area network (MAN), super-size slot, variable size packet, Wavelength Division Multiplexing (WDM)

I. INTRODUCTION

Data traffic has grown spectacularly over the last few years mainly due to Internet and data-intensive applications such as enterprise resource planner, e-commerce, backup and recovery, data warehousing and mining. This reality generates an insatiable demand for bandwidth as never seen before. Photonic network technologies and WDM have become a technology of choice to increase network bandwidth in recent years and the trend is continuing. Due to its superior characteristics, WDM technology is not only utilized in backbone networks but has also started to be utilized in metropolitan area networks (MANs) [1].

In our previous work, two metro WDM multi-ring network architectures and MAC protocols have been presented [2]. The two metro WDM multi-ring network architectures are designed to accommodate variable length packet traffic, where slots of different sizes circulate along the ring. However, in the previous paper we studied the network performance based on the average results. In this paper, we study the network behavior of each node in details. Furthermore, in addition to symmetric traffic, asymmetric traffic is also considered in order to evaluate the impact of hot-node scenarios, for example where one server acts as a gateway, storage area network (SAN) access point, or as a database server. Performance evaluation under bursty self-similar traffic is also considered.

Following the introduction this paper is organized as follows: Section II discusses metro WDM ring networks which accommodate variable-length packets. Section III presents our node and network architecture, introduces the MAC protocol. The analytical model is explained in Section IV. Performance evaluation results from simulation and analytical modeling are given and discussed in Section V. Finally, the paper is concluded in Section VI.

II. MOTIVATION

A simple WDM ring network architecture intended to serve as a metropolitan access network has been proposed in [3], and is designed to interconnect several access nodes (ANs) on a regional scale. In the proposed architecture, a unidirectional single-fibre multi-channel time-slotted ring is used, with uncomplicated MAC protocol, in which the time is divided into a number of slots. The slots on the ring have a fixed size, which is equal to the Ethernet maximum transfer unit (MTU) frame size, i.e. about 12,000 bits (or 1,500 bytes). An assumption was made that the packet size is always equal to the slot size. Fixed packet size approach is also used in [4-6].

However, in reality the packet size in data communication traffic is not fixed. Based on measurement on the Sprint IP backbone, according to [7] there are mainly five major sizes of packets in the data traffic, i.e. 40, 211, 572, 820 and 1500 bytes. The 40 bytes size is for TCP ACKs, 572 bytes and 1500 bytes are the most common default MTUs. The 211 bytes packets correspond to a content distribution network (CDN) proprietary user datagram protocol (UDP) application that uses an unregistered port and carries a single 211 bytes packet. The packets of around 820 bytes are generated by media streaming applications. Obviously, the fixed slot size architecture is not suitable for this situation, in which a huge number of slot space will be wasted.

III. SYSTEM ARCHITECTURE

In [2], we proposed two novel network architecture to accommodate variable length packet. In this section, the two proposals are discussed in details.

A. Network Architecture

The network is a single-fibre multi-channel slotted ring, which is designed to interconnect access nodes (ANs) on a regional scale (i.e. ring circumference of about 100 km). In
hot-node scenario, this AN can be a network gateway, storage area network access point, or as a database server. Each AN has add-and-drop capabilities to access the ring slots and is used to connect a local area network (or access network) to the ring. Since the vast majority of LANs throughout the world are Ethernet-based, the access networks are connected to the ANs by Gigabit Ethernet (GbE) links operating at 1 Gb/s (Fig. 1).

In the network, the length of the ring is 138 km, which leads to a ring diameter of about 44 km. The number of wavelengths equal to four and each wavelength is considered to have a transmission rate of 2.5 Gb/s (i.e. OC-48). This network is used to interconnect 16 nodes. The network architecture is not limited to 16 nodes, this number is used for demonstration purposes.

For the variable slot (VS) scheme, the slots on the ring have five different sizes, corresponding to the five different sizes of data traffic packets from the access links, which are 40, 211, 572, 820 and 1500 bytes [7]. The total number of slots is 240. The number of slots for each size is 24, 48, 24, 48 and 96, respectively (the numbers are related to the probability distribution of packet size on the access links). The average size for a slot is 6963.5 bits. In the simulation, the different size slots are generated with a fixed sequence. The 240 slots are divided into 24 groups, in each group there are 10 slots with one slot of 40 bytes, two slots of 211 bytes, one slot of 572 bytes, two slots of 820 bytes and four slots of 1500 bytes. This distribution is based on the Internet traffic distribution mentioned in [7].

For the super slot (SS) scheme, the ring is divided into 16 super slots with a size of 13,500 bytes. In the SS case, the length of the ring is 138,240 meters, while in the VS case the length of the ring is slightly changed to 133,240 meters for simplicity.

B. Node Architecture

Every node equipped with one fixed transmitter and four fixed receiver (FT-FR$^4$). The proposed FT-FR$^4$ architecture has been shown to be very flexible and more easily scalable (there can be more nodes than wavelengths) than previous proposals of WDM ring network such as FT-FR$^3$ in [8]. Because in FT-FR$^4$ system, a node can receive packets on any wavelengths, each node is assigned a different sub-carrier multiplexed tone. When a node wishes to transmit to a specific destination, it transmits the packet onto a slot of its assigned transmission wavelength and multiplexes the appropriate sub-carrier tone of the destination. Meanwhile, each node constantly monitors all wavelengths in parallel in order to detect its own sub-carrier tone, which will notify it that it is the intended destination of the corresponding packet. The feasibility of such a mechanism for a slotted ring has already been demonstrated in the HORNET [9] network project.

![Fig. 1. Network architecture](image)

Each wavelength is shared both for transmission and reception since there are fewer wavelengths than nodes in the network. In the VS scheme, each node has five First-In-First-Out (FIFO) buffers for transmission to store packets with five different sizes. A maximum of 20 packets can be stored in each buffer.

In both architectures, newly arriving packets are discarded when the buffer is full. It is expected that higher layer (e.g. IP) will do the recovering task.

The network parameters used in the simulation and modeling are summarized in Table 1.

### Table 1. Network parameters

<table>
<thead>
<tr>
<th>Architecture</th>
<th>Variable Slot (VS)</th>
<th>Super Slot (SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength rate: $R_w$</td>
<td>2.5 Gb/s</td>
<td></td>
</tr>
<tr>
<td>Number of wavelengths per fibre: $\omega$</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Total network rate: $R_0 = R_w \times N_w$</td>
<td>10 Gb/s</td>
<td></td>
</tr>
<tr>
<td>Number of access nodes: $N_v$</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Light velocity in fibre: $V$</td>
<td>$2 \times 10^8$ m/s</td>
<td>$2 \times 10^7$ m/s</td>
</tr>
<tr>
<td>Bandwidth-delay product: $B_{bw} = R_w \times D$</td>
<td>1,665,480 bits</td>
<td>1,728,000 bits</td>
</tr>
<tr>
<td>Average slot size: $S$</td>
<td>6,939.5 bits</td>
<td>108,000 bits</td>
</tr>
<tr>
<td>Slots per wavelength: $S_w = B_{bw} / S$</td>
<td>240 slots</td>
<td>16 slots</td>
</tr>
<tr>
<td>Slots duration: $\sigma_i = D / S_w$</td>
<td>2.776 $\mu$s</td>
<td>43.2 $\mu$s</td>
</tr>
</tbody>
</table>

C. MAC Protocol

In order to transmit and receive packets, for the VS scheme, each node continuously inspects the activity of all the wavelengths and probes the destination ID for each packet arriving at the slot. The packet is received from the ring if it the destination ID is matched with the ID of this node, and the slot is marked empty (destination-stripping). This empty slot can be used by the same node if the node has a packet to send with length matching the size of the slot.

For the SS scheme, the transmission is quite different. The transmitter always inspects the free slot space (the capacity of the slot minus the current load of the slot) of the current slot. While the free space of a slot is larger than the size of the current packet in the buffer, the current packet will be transferred into
the slot. Thus, the SS scheme can convey a number of packets from current nodes while it has enough space. In this case, the slot is able to make good use of the free space to carry all kinds of packets, and do not have to consider the size of the packets.

IV. ANALYTICAL MODELING

We now describe an analytical model of the WDM ring network. In our model, we assume the mean slot size for the variable slot (VS) architecture, and therefore, the model described here applies to both the VS and the super slot (SS) architectures.

We model each of the $i$-th node in the network as a queue with a fixed-size buffer. The packets in the queue arrive with Poisson distribution at the mean rate, $\eta_i$. The mean arrival rate is composed of the arrivals of five packet types, collected in five different buffers, each packet type forming a Poisson arrival stream. The collective queue at the $i$-th node needs access to the ring network -- the amount of access time required is independently and identically distributed with mean, $\mu_i$. The node experiences periods of unavailability of slots on the ring network due to the traffic generated by the upstream nodes on the network. We consider that the upstream traffic for the $i$-th node is also Poisson distributed with the mean packet arrival rate, $\xi_i$. The upstream traffic requires access to the network which is independently and identically distributed with mean, $\mu_i$. The access time required by the upstream traffic and the $i$-th node, $\mu_i$ and $\mu_p$, equals the slot duration $\sigma$, which are given in Table 1 (for VS and SS architectures).

The model parameters are derived as follows. The behavior of the upstream nodes, as experienced by the $i$-th node, is determined by their cumulative traffic; it is calculated as:

$$\xi_i = \sum \eta_p P_{(p,q)} \quad (p,q) \in A_i,$$  \hspace{1cm} (1)

for all $p \leq p < n, p \neq i$, and where, $A_i$ and $P_{(p,q)}$ are defined as follows. The set $A_i$ consists of all the (sender, receiver) pairs of nodes which require access to the slot at the $i$-th node. The wavelength used for the $i$-th node is represented in the equation as $\lambda_i \leftarrow i \mod \omega$ (see Table 1).

$$A_i \leftarrow \begin{cases} 0 \leq i, p, q < n , \ i \neq p \\ \lambda_p = \lambda_i \\ p > i \ & \& \ q > i \ & \& \ p > q \\ p < i \ & \& \ (q > i \ & \& \ q > p) \ | (q < i \ & \& \ p > q) \end{cases} \hspace{1cm} (2)$$

The probability that node $p$ transmits a packet addressed for node $q$ is given by $P_{(p,q)}$. For the asymmetric traffic case (see Section V), $a = 0.6/(n-2), b = 0.4, c = 1/(n-1)$ . For the symmetric traffic case, $a = b = c$. The probability $a$ is assigned to $P_{(p,q)}$ when the receiving node is the SAN node, while the probability value $b$ is assigned when the receiving node is not a SAN node; if the sending node is the SAN node than it transmits packets to all the nodes with equal probability $c$. The probability values $a$ and $b$ default to $c$ for the symmetric case.

$$P_{(p,q)} \leftarrow \begin{cases} 0 \leq p,q < n, p \neq q \\ a \quad q = SAN \\ b \quad q \neq SAN \\ c \quad p = SAN \\ 0 \quad p = q \end{cases} \hspace{1cm} (3)$$

Considering that the model consists of two non-preemptive priority classes of traffic, where the traffic from the upstream nodes enjoys a higher priority over the traffic from the $i$-th node, and that the service of a packet from a node, once begun, cannot be preempted, the queuing delay at the $i$-th node, $D_{(i)}$, is given by:

$$D_{(i)} = \frac{\xi_i \mu_{i2} + \eta_i \mu_{i2} - \eta_i \mu_{i2}}{2(1-\xi_i \mu_i)(1-\xi_i \mu_B - \eta_i \mu_B)} \hspace{1cm} (4)$$

where $\mu_{i2}$ and $\mu_{i2}$ are the second moments for $\mu_i$ and $\mu_B$. $D_{(i)}$ consists of the time for the ring to serve all the upcoming traffic at the node $i$, the time to transmit all the previous packets in the buffer at the node $i$, and the residual upload time of the packet. Using this, the total waiting time at the $i$-th node to transmit a packet to its destination can be calculated by adding the buffer queuing time and the mean transmission time:

$$W_{i} = D_{(i)} + \gamma_i, \quad \gamma_i = \sum_{q=1}^{n} \frac{q}{n} P_{(i,q)} \hspace{1cm} (5)$$

where $\gamma_i$ is the total mean transmission time of a packet for the $i$-th node, including the packet upload time.

V. PERFORMANCE EVALUATION

Poisson traffic generator is used to simulate the traffic received from the GbE access link. Poisson traffic has been widely used to simulate independent inter-arrival traffic. Performance evaluation under self-similar traffic is also considered. The self-similar traffic sources were simulated using aggregated ON–OFF sources using Pareto distributions. The Hurst parameter of the aggregated traffic is $H=0.8$ which represents a high degree of burstiness. Network performance in terms of node throughput, packet queuing delay in the transmission buffer, and proportion of packet dropped for both architectures was assessed under symmetric and asymmetric traffic. In case of symmetric traffic, all source nodes generate statistically the same amount of traffic to all other destination nodes. A node cannot transfer traffic to itself. On the other hand, under asymmetric traffic, one node generates more traffic compare to all other nodes. One hot-node
scenario is considered (node 0), i.e. one node receives 0.4 of the total network traffic.

Each simulation is characterized by two parameters: the normalized network load and traffic distribution model. The normalized network load, denoted by $L$, is used to study the performance of the network against varying level of traffic volumes, ranging between zero and one, i.e. null traffic to 1 Gb/s. Since there are a total of 16 nodes in the network, the total traffic generated for the ring network with $L = 1$ will be 16 Gb/s. Note that the total bandwidth capacity of the WDM ring is 10 Gb/s ($2.5$ Gb/s $\times 4$) and therefore the normalized load of 1 will create more traffic on the ring than the total carrying capacity of the WDM ring network.

This section shows the results of discrete-event simulations and analytical modeling. The same traffic was applied to the VS slot and SS slot schemes.

A. Symmetric traffic

Fig. 2 shows delay for each node from analytical results for VS architecture. Simulation results show similar graphs. From the figure we can see that there is a sharp increase in delay when $L = 1$ which reach 75 $\mu$s.

![Fig. 2 Delay per node under symmetric traffic](image)

Fig. 2 Delay per node under symmetric traffic

Fig. 3 shows the throughput of each node. We can see that all nodes able to send packets fairly. No fairness issue here. Node throughput able to reach maximum throughput of 1 Gb/s when $L$ equals to 1.

B. Asymmetric traffic

Fig. 4 shows the delay for each node for VS. Delay is increased significantly when $L > 0.9$, especially for node 13 to node 15. This is understandable as many nodes want to send packets to node 0. Due to the ring symmetry and destination-stripping policy implemented, each node has a better-than-average access to the channels leading to certain destination nodes and a worse-than-average access to channels leading to other destinations [10]. Therefore, the closer a node to node 0 (in clockwise direction) the more difficult to find empty slots in the ring. In climax, delay for node 13 to node 15 increased sharply when network load is very high ($L > 0.9$).

Throughput per node for VS is shown in Fig. 6. Here we notice that the throughput of three nodes leading to node 0 (SAN) is declining when network load is very high ($L > 0.8$). This is mainly due to packet dropped as the buffer being full as packet interarrival duration decreases. In Fig. 8 and Fig. 9 we can see the proportion of packet drop of the network. When the network load is very high ($L > 0.9$), nodes leading to node 0 (clockwise), i.e. node 13, 14, and 15, drop packets significantly.
As shown in Fig. 8 and Fig. 9, the analytical model is also precisely depicts the trend in the proportion of packet dropping, especially when $L \leq 0.9$. Although the analysis underestimate the packet drop probability for $L > 0.9$ (Fig. 8).

The use of self-similar traffic sources slightly reduces the achievable throughput when compared with the case where Poisson traffic is used (Fig. 7). This is expected, as the burstiness nature of the self-similar traffic may filling up the buffer at any time, causing packets to be dropped.

In general, for the queuing delay (Fig. 10-11), the use of self-similar traffic also gives worse performance than with Poisson traffic.

Compared to SS, VS performs slightly better in terms of throughput (Fig. 6 and Fig. 12) and delay (Fig. 4 and Fig. 10). In Fig. 12, we can observe that more nodes are having difficulties to find empty slots in SS compared to VS (see Fig. 6).

Furthermore, from Fig. 8 and Fig 13 we notice that the proportion of packet drop for SS is relatively higher than for VS.
VI. CONCLUSION

The paper analyzed our two metro WDM ring network architectures to accommodate variable length packet traffic, i.e., the variable-size slot network architecture and the super-size slot network architecture, through stochastic modeling. Compared with the simulation results, the stochastic modeling achieved roughly similar results.

Compared with the super-size slot architecture, the variable-size slot architecture achieved slightly better performance, especially under asymmetric traffic. This is shown in both analytical and simulation results.

However, as super-size slot network architecture not based on the already known packet length distribution of certain traffic, the architecture is more suitable for general IP traffic with unknown packet length distribution.

The effect of bursty self-similar traffic was also presented and discussed. Due to the nature of its burstiness, the network performance under self-similar traffic is generally worse than under Poisson traffic.

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