A Systematic Scheme for Guaranteed Deterministic Performance Service on WDM Optical Networks

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Abstract- **A major challenge in design of future generation high-speed networks is to provide guaranteed quality of service for the real-time multimedia applications. In this paper, we study the problem of providing guaranteed deterministic performance service to the real-time and variable length messages in wavelength division multiplexing (WDM) optical networks. In particular, we propose an admission control policy, a traffic regulator and a scheduling algorithm for the single-hop passive star coupled WDM optical networks. All of them are combined to form a systematic scheme to ensure guaranteed performance service. We set up an analytical model to evaluate the deterministic bounded message delay in the specified network base on the max-plus algebra. Our simulation result shows that the delay bound we have set up is valid.**

I. INTRODUCTION

With the proliferation of the world-wide-web (WWW) in all aspects of networking, current local and wide area networks can barely cope with the huge demand for network bandwidth. As a result, there is a world-wide effort in upgrading current networks with high-bandwidth fiber-optic links that can potentially deliver Tera-bits/sec. Wavelength-Division-Multiplexing (WDM) is an effective technique for utilizing the large bandwidth of an optical fiber. This technique, by allowing multiple messages to be transmitted in parallel on a number of channels, has the potential to significantly improve the performance of optical networks. The system can be configured as a broadcast-and-select network in which all of the inputs from various nodes are combined by a WDM passive star coupler, and the mixed optical information is broadcasted to all destinations. Efficient medium access control protocols are needed to allocate and coordinate the system resources optimally, while satisfying the message and the system constraints [1]. The protocols in the single-hop WDM passive star network can be divided into two main classes, namely pre-allocation-based and on-demand adaptive protocols. Most of the on-demand adaptive protocols can only handle fixed length packets for transmissions. Recently, many researchers have relaxed this constraint by allowing their scheduling algorithms to manage variable length messages transmission [9]. The examples of the variable length message traffics can be found in the case of multimedia applications [12].

One of the important issues of high-speed networks, such as WDM optical networks, is to provide guaranteed performance service for real-time applications such as multimedia applications with their QoS requirements.

In this paper, we propose a complete mechanism including an admission control policy, a traffic regulator, and a scheduling algorithm for the reservation-based medium access control protocol in the single-hop passive star coupled WDM optical network to provide guaranteed deterministic performance service to the application streams composed of real-time variable length messages. We have also analytically evaluated the delay bound for the messages delivery in the specified WDM optical network based on the max-plus algebra and the framework proposed in [22] and empirically validated it by simulation experiments.

The remainder of this paper is organized as follows. Section 2 specifies our WDM network environment. Section 3 presents our systematic scheme and Section 4 provides our theoretical analysis on the deterministic delay bound. Section 5 shows the results from simulation experiments. Finally, Section 6 concludes the paper with a summary.

II. SYSTEM MODEL

In this paper, we consider message transmission in a single-hop WDM optical network, whose nodes are connected via a passive star coupler. The star coupler supports $C+1$ channels and N nodes in the network. C data channels are used for message transmission. Another channel is the control channel used to exchange global information among nodes regarding the messages to be transmitted. Each node in the network has two pairs of

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transceivers. One transmitter and one receiver are fixed to the control channel. The other transceivers are tunable to any of the data channels.

The nodes are assumed to connect to the application streams that are composed of aperiodic messages with variable length that can be divided into several equal-sized packets. The basic transmission element is one message rather than one packet. The nodes are divided into two non-disjoint sets of source (transmitting) nodes s_i and destination (receiving) nodes d_j. However, any node can be a source node as well as a destination node at the same time. A message queue exists at each source node s_i.

A Time Division Multiple Access (TDMA) protocol is used to access the control channel. Each node transmits a control packet before data transmission. N control packets make up one control frame on the control channel. Thus, each node has a corresponding control packet in a control frame, during which that node can access the control channel.

Each application stream can be specified by a parameter set with three elements. One of them is the delay allowance of each message, which is to show the time constraint to the application streams. The other parameter is the maximum length of the messages in one application stream. The length of each message can be variable and is bounded by the maximum message length in one application stream. The last one is the traffic intensity that signals the bandwidth which one application stream requires.

We map the specified WDM optical network environment into a simple point-to-point connection oriented message-switched multiplexer with C transmission links so that the problem of providing deterministic bounded delay service to the N application streams in the specified WDM optical network can be feasibly solved. We map each transmission node in our specified WDM optical network as each head of the message queue. We logically map the distributed scheduling algorithm at all transmission nodes as a centralised multiplexer, which has the same function as the original scheduling algorithm at each node for scheduling the message transmission. We map the number of C transmission channels as same number of transmission links outgoing from the logical multiplexer. And we specify that there are N destination nodes to receive the transmitted messages. The configuration of our system model of the specified network is shown in the Fig.1.

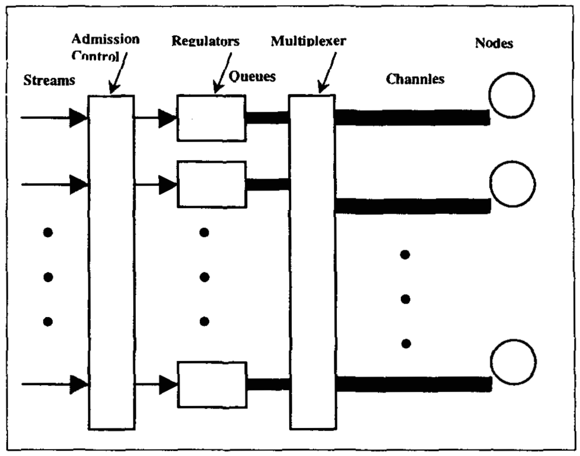

Fig.1. System model of the specified network

III. Systematic Scheme

The network service can be divided into two levels: The upper level is the flow level at which the application streams can be managed and controlled by the network. The lower level is the message level at which individual message is to be scheduled and transmitted. Accordingly, we have an admission control scheme and a traffic regulator to provide flow level service. We have a scheduling algorithm for the multiplexer to provide message level service.

A. Admission Control Scheme

The task of the admission control scheme is to limit the number of application streams entering into the network. We assume that there are n application streams already connected to the network. They can be specified as $S_i=(d_i, m_i, t_i)$ $i=1, 2, \ldots, n$. There are m new application streams requesting guaranteed bounded delay service as $S_j=(d_j, m_j, t_j)$ $j=1, 2, \ldots, m$. The admission control scheme employs transmission bandwidth availability test algorithm to decide whether all of the new application streams can be accepted or rejected or which subset of them can be accepted.

Admission Control Scheme:

m new applications with S_j request service, while n applications with S_i are being served;

Call resources availability test algorithm to consider the $n+m$ applications with S_p, $p=1, 2, \ldots, n+m$;

If the delay bound of the $n+m$ applications can be ensured, accept all of the new applications,

If the delay bound of the $n+k$, $1 \leq k < m$, applications can be ensured, accept the subset of the new applications with number of k;

Otherwise reject all of the new applications.

B. Traffic Characterisation

Besides admission control scheme, traffic policing scheme is another system service to ensure the quality-of-service of the connected application streams. After a connection of the application stream to network is established, the network must monitor the traffics of application streams with traffic policing scheme to ensure that each traffic complies with its traffic characterisation. The traffic policing scheme simply either drops or delays messages when traffic does not conform to the traffic characterisation, avoiding excessive traffics into the network. In our design, we take the policy to delay messages. In this case there are special buffers required to temporarily store the delayed messages.

As the traffic policing scheme is based on the traffic characterisation and it is important to the system to provide guaranteed deterministic performance service, we need to introduce our traffic characterisation, g-regularity, which is dedicated to the traffic with variable length messages.

We use marked point process to model the traffic of an application stream. A marked point process $\Psi = (\tau, l)$ consists of two sequences of variables $\tau = \{\tau(n), n=0, 1, 2, \ldots\}$ and $l = \{l(n), n=0, 1, 2, \ldots\}$, where $\tau(n)$ and $l(n)$ are the arrival time and the packet length of the $n+1^{th}$ packet. Let $L(0)=0$ and $L(n)=\sum L(m)$ is the sum of the packet lengths of first n arrivals and τ is an increasing sequence, l is a nonnegative integer-valued sequence. Under this assumption for l, the sequence $L = \{L(n), n=0, 1, 2, \ldots\}$ is an increasing integer-valued sequence with $L(0)=0$.

Based on above traffic model for the application streams with variable length messages, a new type of traffic characterisation called g-regularity can be introduced. The g-regularity can be defined as following:

Definition: A marked point process $\Psi=(\tau, l)$ is said to be g-regular for some g, if for all $m \leq n$ holds $\tau(n) - \tau(m) \leq g(L(n) - L(m))$, Which is

$$\tau(n)=max_{0 \leq m \leq n} [\tau(m) + g(L(n) - L(m))]. \quad (1)$$

Based on the definition of the g-regularity, we can construct a traffic regulator to proceed traffic shaping so that its output is g-regular.

C. Scheduling Algorithm

We propose a new scheduling algorithm named as Adaptive Round-Robin and Earliest Available Time Scheduling (ARR-EATS) algorithm for the multiplexer to schedule the transmission of variable-length messages in the multiple application streams so that the deterministic delay allowance of each message can be guaranteed.

The first part of the ARR-EATS algorithm is the Adaptive Round-Robin algorithm that determines the message transmission sequence. The basic idea of the Adaptive Round-Robin algorithm is that every application stream admitted to the multiplexer can get the equal opportunity to have its messages to be transmitted.

The second part of the ARR-EATS algorithm is called as Earliest Available Time Scheduling (EATS). It is an efficient channel assignment algorithm for selecting a channel and time slots on that channel to the transmitted messages. The basic idea of EATS algorithm is to assign a message to a data channel that has the earliest available time slot among all other channels.

IV. Delay Bound Analysis

The analytical evaluation of the guaranteed deterministic delay bound for our proposed system service schemes is based on the theory of max-plus algebra in [24]. The analysis on the guaranteed deterministic delay bound for the system service scheme will depend on the analysis on the properties of the g-server.

We have the following theorem on the delay bound of g-server. Consider a g_2 server for a marked point process $\Psi = (\tau, l)$. Let $\Psi' = (\tau', l)$ be the output. Also let $d = \sup[\tau'(n) - \tau(n)]$ be the maximum delay at the server. Suppose that Ψ is g_1-regulator.

1) Maximum delay $d \leq \sup [g_2(n) - g_1(n)]$.

2) Maximum queued service requirements: The total amount of service requirements queued at the server is

bounded above by $g_{u,l}^{-1}(d) + l_{max}$, d is the maximum delay in 1), $g_{u,l}^{-1}$ is the upper inverse function of g_l and l_{max} is the maximum service requirement.

3) Output characterisation: If $\tau' \leq \tau$, then Ψ^n is g_3-regular, where $g_3(0)= 0$ and $g_3(n) = \inf[g_1(m+n)- g_2(m)]$, $n> 0$.

We map each service of the multiplexer to each queue of the application stream as a G/G/1 server with vacation. The service time to each queue is bounded by the maximum message length in that application stream. And the vacation time to the queue of that stream is bounded by the sum of the service time the multiplexer serves to other queues of the application streams. We name the g-server with its deterministic service delay as an O_d server. We map the g-regulator which is to use to characterise the traffic to g-regularity as an O_d server. We map the propagation of either control packet or message transmission as an O_d server too. We also map the waiting time that is the time for a message to wait for a transmission channel available as an O_d server with certain service delay. We notice that all these O_d servers and the G/G/1 server are concatenated so that the evaluation of the bounded-delay to the entire concatenated server is simply to add the bounded delay of each server together according to the theorem of g-server concatenation. We have the following formula to describe the delay bound for each application stream.

$$Bound_i=P+M_i*I_i+M*N/C+\sum_j^N M_j*N_i/C . \qquad (2)$$

where P is the propagation time for the message to propagate in the network; N is the number of application streams admitted into the network; C is the number of the channels; M is the maximum message length from all application streams; and M_i is the maximum message length from the application stream i; I_i is the maximum traffic intensity for admitted application stream i.

V. EXPERIMENTAL RESULTS

We have the following parameters considered in the experiment. The number of application streams admitted is set to 3, and the number of channels is 2. Tuning latency is considered as 10 time units and the propagation delay as another system parameter is set to 100 time units. Message length is a random variable following Exponential distribution with maximum message length as 100 time units. A Poisson message arrival process in each application stream is considered whose intensity changes from 0.14 to 0.32 for each application streams. The total traffic changes from 0.42 to 0.96. Destination nodes for messages are chosen according to a Uniform probability distribution. The message delay allowance is set to the same as the delay bound calculated based on the formula with the current parameters.

In Fig.2, we present the maximum message delay and the delay bound of the ARR-EATS algorithm. The message delay is expressed in the time unit defined in our system model. The figure shows the relationship between the maximum message delay and the total traffic intensity from all the application streams. We can find that the maximum message delay gets increased when the total traffic load increases. The figure also reveals that when the total traffic intensity varies under 1, the maximum message delay can always be kept under the delay bound of this algorithm. When the total traffic intensity approaches to 1, the maximum message delay is close to the delay bound.

VI. CONCLUSION

In this paper, we study the problem of providing guaranteed deterministic bounded-delay service to real-time application streams composed of variable-length messages in a single-hop passive star coupled WDM optical networks. Our main contribution lies in that we have proposed a new admission control policy to make a decision on which application streams can be admitted when more than one new application streams request to enter into the network; We have proposed a new scheduling algorithm dedicated to scheduling the variable-length messages in the specified WDM optical networks; We have formulated a mathematical model to evaluate the delay bound based on

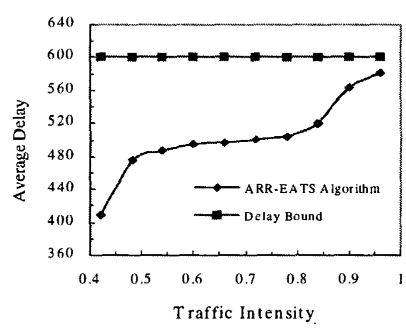

Fig.2. Max delay vs. traffic intensity

the max-plus algebra. We have also conducted extensive simulation experiments to investigate the performance of our network service scheme and validate the analytical results. Both have presented that our network service scheme can provide guaranteed deterministic bounded delay service to the real-time application streams composed of the variable-length messages in the specified WDM optical networks.

REFERENCES

[1] B. Mukherjee, "WDM-based local lightwave networks- part I: single-hop systems," *IEEE Network*, May 1992, pp. 12-27.

[2] B. Mukherjee, "WDM-based local lightwave networks- part II: multi-hop systems," *IEEE Network*, July 1992, pp. 20-32.

[3] K. Bogineni, K.M. Sivalingam, and P.W. Dowd, "Low-complexity multiple access protocols for Wavelength-Division-Multiplexed photonic networks," *IEEE Journal on Selected Areas of Communications*, vol.11, no.4, May 1993, pp. 590-603.

[4] A. Gantz and Y. Gao, "Time-wavelength assignment algorithms for high performance WDM star based systems," *IEEE Transactions on Communications*, vol.42, no.(2-3-4), Feb/Mar/April 1994, pp. 1827-1836.

[5] G.N. Rouskas and M.H. Ammar, "Analysis and optimization of transmission schedules for single-hop WDM networks," *IEEE/ACM Transactions on Networking*, vol.3, no.2, April 1995, pp.211-221.

[6] M.S. Borella, and B. Mukherjee, "Efficient scheduling of nonuniform packet traffic in a WDM/TDM local lightwave network with arbitrary transceiver tuning latencies," *Proceedings of IEEE INFOCOM'95*, April 2- 6,1995, Boston, Massachusettes, USA, pp. 129-137.

[7] K. Bogineni and P.W. Dowd, "A collisionless multiple access protocol for a wavelength division multiplexed star-coupled configuration: architecture and performance analysis," *Journal of Lightwave Technology*, vol.10, no.11, November 1992, pp. 1688-1699.

[8] R. Chipalkatti, Z. Zhang, and A.S. Acampora, "Protocols for optical star-coupler network using WDM: performance and complexity study," *IEEE Journal on Selected Areas of Communications*, vol.11, no.4, May 1993, pp. 579-589.

[9] F. Jia, B. Mukherjee, and J. Iness, "Scheduling variable-length messages in a single-hop multichannel local lightwave network," *IEEE/ACM Transactions on Networking*, vol. 3, no. 4, August 1995, pp. 477-487.

[10] C.S. Li, M.S. Chen, and F.F.K. Tong, "POSMAC: a medium access protocol for packet-switched passive optical networks using WDMA," *Journal of Lightwave Technology*, vol.11, no.5-6, May/June 1993, pp. 1066-1077.

[11] N. Mehravari, "Performance and protocol improvements for very high-speed optical fiber local area networks using a passive star topology," *Journal of Lightwave Technology*, vol.8, no.4, April 1990, pp. 520-530.

[12] D. Le Gall, "MPEG: a video compression standard for multimedia applications," *Commun. ACM*, vol. 34, no. 4, April, 1991, pp. 46-58.

[13] Maode Ma, B. Hamidzadeh and M. Hamdi,"Efficient scheduling algorithms for real-time service on WDM optical networks", *Photonic Network Communications*, Vol.1, No.2, July 1999.

[14] Anlu Yan, Aura Ganz, and C.M.Krishna, "A distributed adaptive protocol providing real-time services on WDM-based LANs", *Journal of Lightwave Technology*, vol.14, no.6, June 1996, pp.1245-1254.

[15] C. C. Yu, and S. Bhattacharya, "Dynamic scheduling of real-time messages over an optical network", in *Proceedings. Sixth International Conference on Computer Communications and Networks*.1997, Los Alamitos, CA, USA, pp. 336-339.

[16] Rene L. Cruz, "A Calculus for Network Delay, Part I: Network Elements in Isolation", *IEEE Transactions on Information Theory*, vol. 37, no. 1, Jan. 1991, pp. 114-131.

[17] Rene L. Cruz, "A Calculus for Network Delay, Part II: Network Analysis", *IEEE Transactions on Information Theory*, vol. 37, no. 1, Jan. 1991, pp. 132-141.

[18] Edward W. Knightly, and Hui Zhang, " Traffic characterization and switch utilization using a deterministic bounding interval dependent traffic model", *Proceedings of IEEE INFOCOM'95*, April 2-6, 1995, Boston, Massachusettes, USA, pp1137-45.

[19] Leonidas Georgiadis, Roch Guerin, Vinod Peris, and Kumar N. Sivarajan, "Efficient network QoS provisioning based on per node traffic shaping", *IEEE/ACM Transactions on Networking*, vol. 4, no. 4, August 1996, pp. 482- 501.

[20] Hui Zhang, "Service disciplines for guaranteed performance service in packet-switching networks", *Proceedings of the IEEE*, vol. 83, no. 10, Oct. 1995, USA, pp. 1374-96.

[21] Jorg Liebeherr, Dallas E. Wregen, and Domenico Ferrari, "Exact admission control for networks with a bounded delay service", *IEEE/ACM Transactions on Networking*, vol. 4, no. 6, Dec. 1996, pp. 885-901.

[22] Cheng Shang Chang, and Yih Haur Lin, " A general framework for deterministic service guarantees in telecommunication networks with variable length packets", *IEEE IWQoS'98*, Napa Valley, California, USA.

[23] Thomas H. Cormen, Charles E. Leiserson, and Ronald L. Rivest, *Introduction to Algorithms*, McGraw-Hill Company, 1990.

[24] F. Baccelli, G. Cohen, G. Oslder, and J. Quadrat, Synchronization and Linearity: An Algebra for Discrete Event Systems, Wiley,1992.