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DESIGN OF SIMULATION SYSTEM FOR PERFORMANCE PREDICTIONS OF WDM SINGLE-HOP NETWORKS

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ABSTRACT

Describes the design, development and use of a software architecture for a simulation environment to examine, validate and predict the performance of piggybacked token passing protocol for a wavelength division multiplexed (WDM) optical network. This simulation environment overcomes many of the limitations found with analytical models. A set of the principal components and their dynamics, which make up the simulation design has been identified. It is shown that this protocol optimises the usage of the bandwidth available in the optical fibre with more than 70% used for data transmission. It is also suggested that the number of channels required to accomplish a single-hop connection within a local environment is small with number of channels to nodes ratio of 1:4. This is comparatively small and requires only limited-tuneable transceivers.

Keywords:** **Performance evaluation, Token-passing, Optical network, WDM, Network simulation.

1.0 INTRODUCTION

Optical fibre is becoming a widespread communication medium in telecommunication and networking. It is capable of providing high transmission speeds with very low error rates. Optical fibre networks are also found suitable for real-time transmission, where guaranteed bound on the waiting time for delay-sensitive messages is needed [1]. However, the speed of the processing devices has not increased to the level of the high speed fibre optic medium. Thus, the communication bottleneck has shifted from transmission medium to the processing medium [2]. To minimise the impact of the speed mismatch, the use of wavelength division multiplexed (WDM) technique has been proposed [3]. Multiple channels are formed on a single fibre using this technique, and the data from different source nodes can be simultaneously transmitted over different wavelengths on the same fibre at the speeds of electronics devices. However, this needs the redesigning of the existing network protocols for effective use of the high speed fibre optic medium capacity. A multiple access environment for the photonic network can be achieved by interconnection topologies such as the bus and star topologies [4, 5, 6].

The nodes are given access to the media using an arbitration scheme, such as random control, centralised control, or distributed control [7]. One of the schemes for media access control (MAC) in the centralised control is the token-passing (TP) protocol [8]. The TP protocol possesses a number of attractive features that contribute to its popularity. It is easy to implement due to its simplicity. It performs reasonably well under a broad spectrum of applications. It is efficient even at high load [9]. There have been many different versions of this protocol reported in the literature. Extensions to the IEEE 802.5 Token Ring protocol are given to realise deterministic communications services [10, 11]. It is shown that the real-time performance of token ring networks could become very satisfactory by choosing a proper message size and a good priority assignment policy [10]. Another protocol for real-time communication in multiple token ring networks is described by Lee and Shen [12]. The protocol attempts to minimise the late messages while maintaining a high channel utilisation. Ciminiera, Mentuschi and Valenzano [13] analysed the behaviour of timed token protocols in a double ring network. Simulation studies of real-time performance of token ring, token bus and slotted ring protocols are presented by Ng and Liu [14]. Even a methodology was proposed for using the timed-token protocol in real-time communication [15]. The timed-token protocol is a TP protocol in which each node receives a guaranteed share of the network bandwidth.

The token-passing protocol on an optical fibre medium with many channels using WDM has been presented by Senior, Cusworth and Ryley [8]. The scheme uses a separate reservation channel to carry the token, while the remaining channels (the data channels) carry only data and acknowledgement packets. In a system with small number of channels and under high load, the bandwidth utilisation is degraded due to the inability of the reservation channel to transmit the data. Ryley, Cusworth and Senior [16] proposed a solution to overcome this limitation in a multichannel piggybacked token-passing protocol suitable for use with the WDM optical fibre LAN. In this, both the data and the token are given access to all the channels. This results in the higher bandwidth utilisation at high traffic loads.

Two different approaches have been proposed for WDM-based networks: multihop and single-hop networks. The multihop network assumes the employment of the fixed-tuned or slowly tuneable component where quasi-static topology is constructed. The key advantage is that each node only needs to access a small number of channels in which high concurrency and scalability can be achieved. However, each packet has to traverse across one or more intermediate stations, where not only extra latency is incurred but also an additional mechanism is required to handle routing and buffering. Various issues associated with the design of multihop networks have been discussed by various authors [17, 18, 19, 20]. On the other hand, the promise of a direct connection among nodes provided by single hop network seems to make it particularly attractive in the local area network environment, which is the main focus of this work.

The MAC protocols may also be classified into three categories based on the way the channels are allocated [21]. They are *random access* protocol, *scheduling based slot assignment* protocol and *pre-transmission coordination* protocol. Based on the requirements, each protocol requires a distinctive configuration of transceivers. Ganz and Koren [22] considered a system with N nodes and W ($1 \leq W \leq N$) wavelengths. Here, each node is assumed to have one tuneable transmitter, a fixed receiver and a tuneable receiver. This protocol is in the random access category. For a TDM scheme [22], a similar transceiver configuration is needed without the additional tuneable receiver, because no feedback from the channel is required at the end of each transmission due to its collisionless nature. Chipalkatti, Zhang and Acampora [23] proposed a protocol which belongs to pre-transmission coordination category. Each node is equipped with a fixed transmitter and receiver pair for accessing the channel, one fixed tuned transmitter to a unique data channel and one tuneable receiver capable of tuning over all of the data channels. Another protocol proposed by Lu and Kleinrock [24] assume that there are W wavelengths available for data transmission which are shared among N nodes ($W < N$), and a separate channel is used as the control channel. Here, each node is equipped with a set of transmitters/receivers, fixed tuned to the control channel, and another pair of tuneable transmitter and receiver which is assumed to be able to tune to all the W wavelengths. However, the token-passing protocol being adapted for study requires only one pair of tuneable transmitter and receiver for each node. This configuration enables each node to be able to transmit and receive data to and/or from any channel.

When designing an optical network, the designer is presented with several design alternatives. There are many operating factors which can affect the performance and validation of the design alternatives. These factors may range from the selection of protocols, the protocol's service scheme and network parameters such as selection of number of channels, node and size of buffers to be associated with the transmitters. Analytical models offer the opportunity to quickly examine a large parameter space to identify a few efficient configurations. However, the results obtained from these models may sometime have large variations in the accuracy. Therefore, selected configurations need to be simulated for a realistic alternative [25].

This paper presents the design and development of a simulation system suitable for validating the performance of an all-optical network system. The simulator considers several input parameters, such as number of nodes, channels, mean inter-arrival rate etc. The system's performance is obtained in terms of measures such as average delay, network throughput and blocking probability. The simulation system is developed in the C language and executed on a Cray supercomputer. Its design consists of defining all the principal components of the simulator. Subsequently, the system dynamics is established, which is based upon the network environment and variables. The system dynamics define how the components behave and interact with each other.

The paper is organised into several sections beginning with the description of the all-optical network under consideration and the protocol's operation. In section III, all the principal components such as entities, queues, events and resources are identified. The scheduler's operation and the simulation algorithm are also presented. In section IV, the performance metrics is defined. The experiments carried out with the simulator and the results obtained are discussed in section V. Conclusions are presented in section VI.

2.0 SYSTEM DESCRIPTION

In the present work, the network interconnection with M nodes with C channels is assumed to be configured as a passive star-coupled network. Any transmission taking place has to pass through the coupler before proceeding to the destination node(s). Each node in a WDM network requires a tuneable transmitter and/or a tuneable receiver. However, a particular configuration is determined by the MAC protocol [3]. The protocol considered here enables each wavelength to be used to transmit and receive the token, as well as data and acknowledgement packets. This imposes a requirement for each node to have both a tuneable transmitter and a tuneable receiver.

In the multichannel piggybacked TP protocol, each channel may be used to transmit the data, token and acknowledgement [16], as mentioned earlier. However in practice, this occurs only at higher traffic loads, when it becomes advantageous to do so. The protocol operates as follows: if two or more channels are available to the node when it transmits, then the data and token packets are sent on separate channels. However, if a second channel is not available for the token, the data packet may be transmitted on the same channel and piggybacked behind the token. Thus, at higher traffic loads, token and data packets are shared over all channels with piggybacked TP MAC protocol, thus increasing bandwidth utilisation. In this scheme the token is being used to grant access to the media by the nodes. To implement TP on a physical star topology, it is passed in a logical sequence over all the nodes using a 'round robin' strategy. Each node has access to the network once in each token rotation time (TRT). Since the token is retransmitted whether or not a data packet is available for transmission, all nodes - both active (i.e. those with a data packet to transmit) and inactive (those without a data packet to transmit) - will contribute to the TRT. Based on the given system description, the simulation model was developed and is discussed in the next section.

3.0 SIMULATION MODEL

A discrete-event simulation model is developed for the performance analysis of the piggybacked TP protocol for a WDM single-hop network. The simulation system is written in C language and is run on a Cray supercomputer. In order to simulate this system, all the principal components such as entities, queues, events and resources are identified. The system dynamics also need to be established. It defines how the components behave and interact with each other.

3.1 Entities

The entities may be active or passive depending on their level of involvement in the system. The entities of this system are nodes, the token and data packets. A node and the token entities are considered the active entities, whereas the packets are passive entities. Each node entity is characterised by its transceivers, which are a tuneable transmitter and a tuneable receiver.

3.2 Queues

The buffer at each node is assumed to have infinite capacity. Any generated packet will be queued in the node's buffer before transmission. The packets are served on a first-come-first-serve (FCFS) basis.

3.3 Events

In any discrete-event simulation model, the events are the primary components. There are 3 events identified based on the system description given earlier. The significant events are packet arrival, packet departure and token arrival.

3.4 Resources

Resources represent passive objects that are used by the entities. The only resource used by the token entity in this system is the channels. The acquisition and release of the channels are handled by the events.

To visualise the dynamics involved in the system, state-transition diagrams are drawn for a typical node and the token. From the system description given above, a state-transition diagram of a typical node is obtained and shown in Fig. 1.

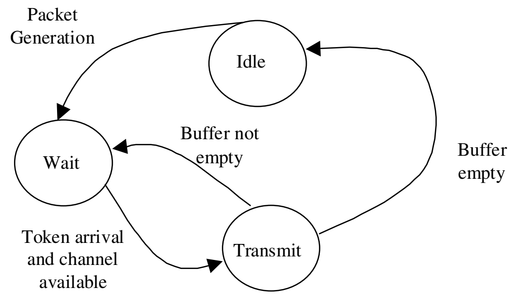

Fig. 1: State-transition diagram of a typical node

3.5 State Transitions

When a packet is generated, the node goes from idle to the wait-state. This transition is represented by pointer from idle state to wait state in Fig. 1. The generated packet is queued in the node's buffer. The node waits until the token arrives before any transmission takes place. The packets are served on FCFS basis with 1-gated transmission approach (where only one packet is transmitted at each token arrival). The token checks for any free channel to transmit the packet. If a free channel is found, it grants access to the packet. This is represented by the transition from wait state to transmit state. Upon transmission, the node will then go either to wait or idle state, depending upon its buffer's content, as shown in Fig. 1. To understand the dynamics of the token, a state-transition diagram is obtained and shown in Fig. 2.

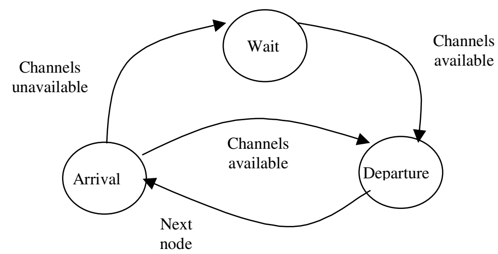

Fig. 2: State-transition diagram of the token

When the token arrives at a node, it checks the node's buffer. If the buffer is not empty, the token prepares the packet for transmission and itself for departure from the node to the next node based upon channel availability. If there is a free channel available, the packet is transmitted to the destination and the token goes to the next node in the logical ring. This is represented by the transition from arrival to departure state in Fig. 2. The arrival at the next node is represented by the transition from departure to arrival state. If no channel is free, the token waits at the node by constantly monitoring the channels. This is represented by the transition from arrival to wait state. If a channel becomes available, the token goes to the next node. In order to activate the different components of the simulation model and maintain the simulation clock, we need a scheduler.

3.6 Scheduler

For any simulation model, the main controller of it is the scheduler. The scheduler maintains the list of events to be executed according to their time stamps and simulation clock. From the types of events given, the packet arrival event has to take place first before any packet departure event is possible. As for the token arrival event, without any packet to serve, there will not be any statistical significance even if it is scheduled first. Therefore, in order to start off the simulation, the first packet arrival events at every nodes are scheduled first at time, $t = 0$. When these events are scheduled, they are inserted to the front of the event-list. The scheduler works as follows:

1) removes the first event in the list and execute it;
2) if the event is a packet arrival event:
   a) a new packet object is created and appended to the node's queue;
   b) it schedules for the next packet arrival based on exponential inter-arrival;
3) if it is a token arrival event:
   a) it checks the buffer contents. If it is not empty it schedules the token and a packet for departure;
   b) if the buffer is empty, the token is scheduled for departure to the next node;
   c) if there is no free channel, the token keeps monitoring at regular interval.
4) if it is a packet departure event:
   a) the queue size is reduced by one;
   b) important statistical information is recorded.

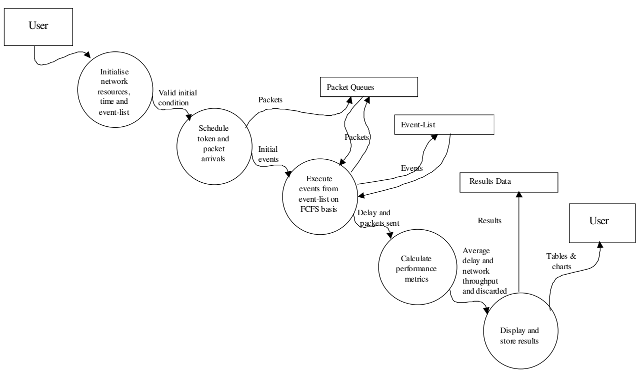

Fig. 3: Level 1 data flow diagram

3.7 Simulation algorithm

From the above discussion, the level 1 data flow diagram (DFD) is drawn and shown in Fig. 3.

Based on the DFD, the algorithm of the whole simulation model operation is given as follows:

i. initialisation of:
   - simulation time variable to keep current time;
   - networks parameters, like number of nodes and channels, station latency, data transmission rate, token transmission time and propagation delay;
   - passive objects, like queues and channels;
   - initial token arrival at a random node;
   - global events' list, which keeps a chronologically-ordered list of all the events to be executed.
ii. schedule for initial arrival of packets at each node;
iii. execution of the following events by the scheduler from the event-list until the a certain criteria is fulfilled (e.g. number of packets departed):
   - packet arrival - after the initial packet arrival, it schedules for the next arrival;
   - token arrival - it checks the node's buffer and schedules any packet for departure. The token arrival is reschedule at every arrival at a node and it follows a logical ring path;
   - packet departure - the node's queue is reduced by one. The performance parameters for analysis are obtained during this event, like number of packets departed and transmission delay.

The simulation model is used to find important performance measures to justify the piggybacked TP MAC protocol's usage in a WDM optical network. The performance metrics being considered are discussed in the next section.

4.0 PERFORMANCE METRICS

The performance metrics analysed using the model described in the previous section, are the average packet delay (D) and network throughput (T). The average packet delay D, is the average time taken from the instant a packet is generated at the source node to the instant it is received at the destination node and its acknowledgement. This includes the waiting time in the queue before transmission, the propagation delay, packet and acknowledgement transmission time. It is given as:

Average delay (D) = (total queuing time + total service time) / number-of-packets-transmitted

The network throughput T, is the measure of the number of packets departed in some interval of time. It is given as:

Throughout (T) = number-of-packets-transmitted / time-interval

The results are discussed in the next section.

5.0 RESULTS AND DISCUSSIONS

The model is evaluated in terms of performance parameters, the average delay (*D*) and the network throughput (*T*) at a node. The input parameters to the model are the number of nodes, number of channels and packet generation rate. Steady state transaction times and throughput are measured, after the system settles down from its transient behaviour after about 10,000 packets are transmitted (about 6 seconds of simulation). Each output value has an associated mean and standard deviation calculated from the sampling distribution, from which 95 per cent confidence intervals are derived. The results from these runs are presented here in graphical form, depicting the nature of the variation in the performance measures. For all the results described in this paper, the propagation delay is fixed at 10μs (2 km-diameter ring). The data, acknowledgement and token packets are 5000, 20 and 50 bits long, respectively. Each channel transmission rate is taken as 100 Mbps.

In Figs. 4 and 5, the results of average delay against packet generation rate are given. For any number of nodes, it can be seen that the average delay increases exponentially as higher load is introduced into the system. From the transmission rate of the channel, the maximum arrival rate that can be supported by the system is 1250 packets/sec. Considerable increment in the average delay is seen, when the arrival rate is at least half of the maximum value. In Fig. 4, at M = 16, the average delay increases only 30% when the arrival rate is changed from 400 to 500 packets/sec. However, when the rate is increased from 700 to 800 packets/sec, the average delay jumps more than 500%. This is probably due to the increased number of packets queued in the buffers at each node. As such, the token is held up at each node contributing to higher delays. Furthermore, there is only one channel for transmission. At any time, there could be only one packet transmission taking place within the fibre. With only one channel in the system, as the number of nodes increases, the average delay also increases.

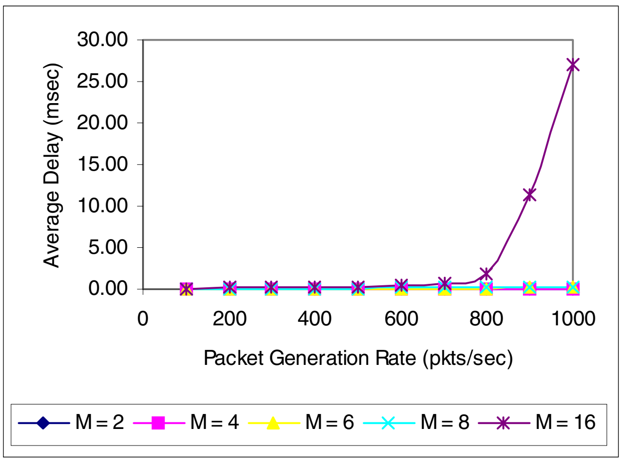

Fig. 4: Average delay vs packet generation rate for number of nodes, M ∈ {2,4,6,8,16} with 1 channel

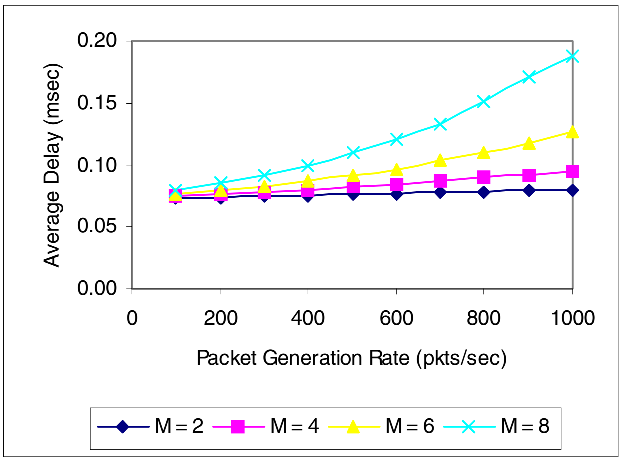

Fig. 5: Average delay vs packet generation rate for number of nodes, M ∈ {2,4,6,8} with 1 channel

In Fig. 6, the results of the network throughput against packet generation rate for various number of nodes are shown. It can be seen that for the curves of M ∈ {2,4,6,8}, the network throughput increases linearly to the increment of arrival rate. However, for the system size of M = 8, the relation is linear only at the lower loads ($\lambda < 800$). At higher loads, the throughput saturates at about 14,000 packets/sec. The throughput is limited by the bandwidth available in the channel. As for the smaller system sizes, the channel may be under-utilised and thus, may result in linear increment in throughput to arrival rate. When the system size is larger and each node is constantly generating packets for transmission, the throughput saturates at the usable bandwidth. At M = 16, network throughput is about 70 Mbps, compared to the transmission capacity of 100 Mbps. It is a 70% utilisation rate. The rest of the bandwidth may be used for token and acknowledgement transmission, and also wasted in propagation delay, processing delay and station latency.

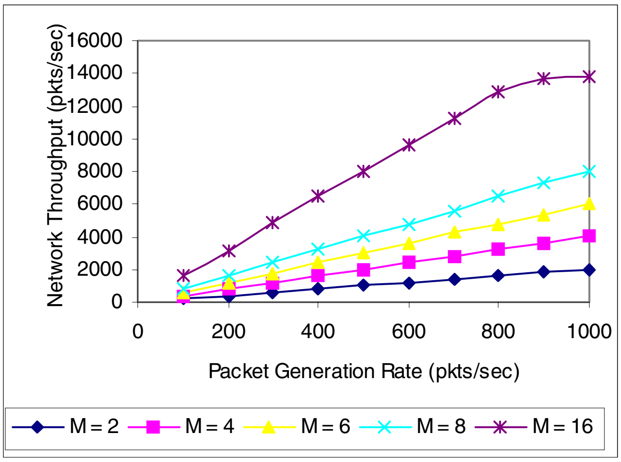

Fig. 6: Network throughput vs packet generation rate for number of nodes, M ∈ {2,4,6,8,16} with 1 channel

In Figs. 7 and 8, the results of average delay against packet generation rate are given for number of nodes, M = 16 and various number of channels. The average delay is seen to reduce as the number of channels is increased. Significant improvement in delay is noticed for packet generation rate, $\lambda > 600$ packet/sec, when C is increased from 1 to 2. At packet generation rate, $\lambda = 400$ packet/sec, when C is increased from 1 to 2, a reduction of only 33% is seen. However at higher rate, $\lambda = 900$ packet/sec, an improvement of almost 98% is obtained. When the number of channels is further increased, improvement is only noticed up to C = 4. Beyond 4 channels, no improvement in delay is noticed. As such, the optimum number of channels for the system size of 16 is 4.

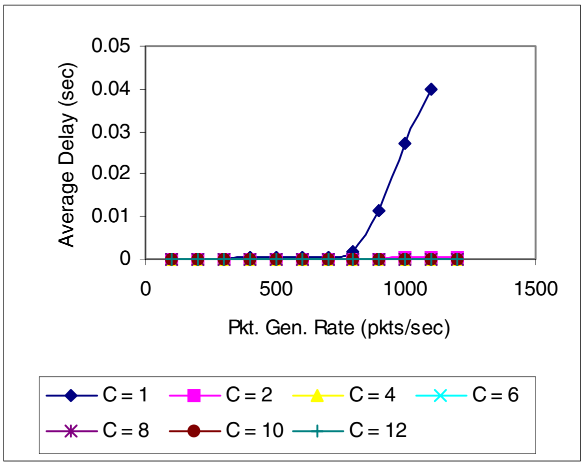

Fig. 7: Average Delay vs packet generation rate for M = 16 nodes and C ∈ {1,2,4,6,8,10,12} channels

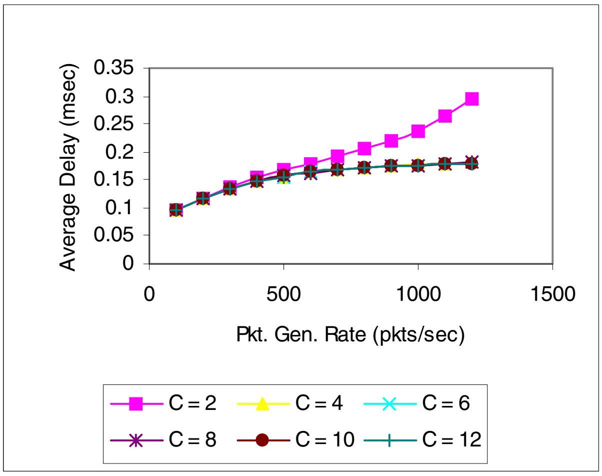

Fig. 8: Average Delay vs packet generation rate for M = 16 nodes and C ∈ {2,4,6,8,10,12} channels

In Fig. 9, the results of the network throughput against packet generation rate for M = 16 nodes and various numbers of channels are shown. It can be seen that for the curves of C ∈ {2,4,6,8,10,12}, the network throughput increases linearly to the increment of arrival rate. It shows that with further increment in packet generation rate, we can obtain higher throughput. It only saturates when number of channel, C = 1. Therefore, this protocol maximises the usage of bandwidth for data transmission and is suitable for the local environment where the network traffic usually is high for intra-communications.

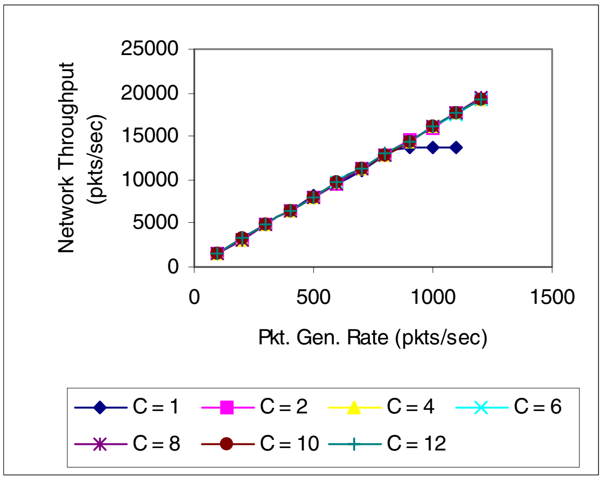

Fig. 9: Network throughput vs packet generation rate for M = 16 nodes and C ∈ {1,2,4,6,8,10,12} channels

6.0 CONCLUSIONS

The paper describes a software architecture for a simulation environment for piggybacked token passing protocol for a WDM all-optical network. The environment provides clearly delineated components to model each aspects of the system. The simulation system is developed using easily portable C language. It is shown that the packets may experience high average delays only when the arrival rate exceeds half of the mean service rate. It is also shown that up to 70% of the available channel bandwidth are used for data transmission. The study has also shown that there is an optimal number of channels for a given system size. The piggybacked TP protocol needs only a ratio of 1:4 in the number of channels to nodes. For further work, we are exploring the extensions of this model for various traffic types.

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BIOGRAPHY

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