DLCR: A New Adaptive Routing Scheme in WDM Mesh Networks*

Xiaowen Chu[1] and Jiangchuan Liu[2]

[1] Department of Computer Science, Hong Kong Baptist University, Hong Kong, China

[2] School of Computing Science, Simon Fraser University, Canada

Abstract – **Rerouting is an effective approach to decrease the blocking probability in legacy circuit-switched networks. In this paper, we consider intentional lightpath rerouting in all-optical WDM mesh networks. We propose a Dynamic Least Congested Routing (DLCR) algorithm which dynamically switches the lightpath between the primary route and alternate route according to the network traffic distribution. Extensive simulation results show that DLCR algorithm can achieve much better blocking performance than traditional routing algorithms, including shortest path routing, fixed-alternate routing, and least congested path routing. We also find that the performance gain is more significant when wavelength conversion is available.**

I. INTRODUCTION

In wavelength routed all-optical WDM networks, a lightpath is setup between the source and destination upon receiving a connect request from the clients [3]. Today, a single lightpath can carry about 40Gbps of data traffic and its holding period is usually very long as compared with the circuit holding time in telephone network. One of the main design goals in WDM networks is to minimize the lightpath connection blocking probability. To achieve this goal, lots of efforts have been tried in the last decade, mainly in two different directions: (1) to make use of wavelength conversion [8, 14, 15, 17, 21]; (2) to design suitable Routing and Wavelength Assignment (RWA) algorithms [4, 5, 7, 11, 13, 16, 22].

Existing research results have shown that adaptive routing algorithms can usually achieve better performance than static routing algorithms [2, 4, 11, 13]. In adaptive routing algorithms, a set of candidate routes are pre-calculated for each source-destination node pair. The focus is to choose the "best" route for the lightpath connection request based on the information of the network status, such as the traffic load distribution. Once the lightpath has been setup, its physical route is usually not allowed to be changed.

Rerouting (or repacking) is a concept originally introduced in the design of circuit-switched telephone networks [1, 6]. It has also been applied to optical WDM networks recently [9, 10, 12, 20]. Rerouting is simply the action of switching an active *circuit* (or *virtual path* in ATM network, *lightpath* in WDM network) from one route to another route without changing the source and destination. A comprehensive survey of rerouting techniques can be found in [18]. An analysis of rerouting in circuit-switched network is given in [19], but it can only apply to symmetrical fully connected networks.

In [9, 10], rerouting is used as an approach to alleviate the effects of wavelength continuity constraint. If a new lightpath cannot be setup directly, the system will try to reroute some existing lightpaths to create a wavelength-continuous route so as to accommodate the new lightpath request. By simulation studies, this rerouting scheme has been shown to reduce the blocking probability by 30% on average. The main concern of their rerouting algorithm is to minimize the lightpath disruption time. In [12], the authors propose a time optimal rerouting algorithm aiming to shorten the disruption time. By simulation experiments, they have also shown that their rerouting algorithm can reduce the blocking probability on the average by 25%.

Both the two aforementioned rerouting algorithms only perform rerouting when a new lightpath request cannot be satisfied directly. We call this *passive rerouting*. In this paper, we propose an *intentional rerouting* scheme in wavelength routed WDM networks. The basic idea is to intentionally reroute existing lightpaths to some vacant routes if better load balancing can be achieved. By applying this idea to the traditionally Least Congested Path Routing (LCR) algorithm [2], we propose a new adaptive routing scheme called Dynamic Least Congested Routing (DLCR) which dynamically switches the existing lightpaths to the least congested route. The blocking performance of DLCR will be evaluated and compared with that of the Shortest Path Routing (SPR), Fixed-Alternate Routing (FAR) [7, 15] and LCR algorithms.

The remainder of this paper is organized as follows. In Section II, we present the DLCR algorithm in detail. Our simulation environment is described in Section III. Simulation results and analysis are given in Section IV. Finally, Section V concludes the paper.

II. DYNAMIC LEAST CONGESTED ROUTING

In this section, we first define the notations of the wavelength-routed WDM network model. We then briefly describe three traditional routing algorithms, i.e. SPR, FAR, and LCR. Finally we present the DLCR algorithm in detail.

An arbitrary WDM mesh network is represented by a graph $G(N, J)$, where N is the set of nodes (i.e., wavelength routers or optical cross-connects) and J is the set of bi-directional

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fiber links. Each link can support W bi-directional wavelength channels denoted by $\{\lambda_1, \lambda_2, \ldots, \lambda_W\}$. A sequence of lightpath connection requests (in terms of source-destination node pairs) arrive to the network randomly. Upon arrival of a connection request, we need to find a physical route (composed by a sequence of consecutive fiber links) and allocate free wavelength channels on all the links along the route. If the WDM network does not support wavelength conversion, same wavelength channels are required to be allocated for one lightpath. This limitation is called wavelength continuity constraint.

A. Existing Routing Algorithms

Shortest Path Routing: For each connection request on node pair (s,d), the shortest route (in terms of hop length) between (s,d) is used to setup the lightpath. If the shortest route has no free wavelength channels, the lightpath connection request is blocked.

Fixed Alternate Routing: For each node pair (s,d), assume $m_{(s,d)}$ number of routes are pre-calculated and denoted by $\{R_{(s,d)}^{(1)}, R_{(s,d)}^{(2)}, \ldots, R_{(s,d)}^{(m_{(s,d)})}\}$. Usually these routes are edge-disjoint $m_{(s,d)}$- shortest routes. We assume they are sorted by hop-length. Upon arrival of a connection request on (s,d), these routes are tried sequentially, until the lightpath can be setup successfully. If all these $m_{(s,d)}$ routes have no free wavelengths, the lightpath connection request is blocked.

Least Congested Routing: For each node pair (s,d), we also assume $m_{(s,d)}$ number of routes are pre-calculated and denoted by $\{R_{(s,d)}^{(1)}, R_{(s,d)}^{(2)}, \ldots, R_{(s,d)}^{(m_{(s,d)})}\}$. Upon arrival of a lightpath request on (s,d), the least congested route (not necessarily the shortest route) is chosen to setup the lightpath. If we define the *residual capacity* of a route as the maximum number of lightpaths that could be setup on that route at the present time, then the least congested route is the one with the largest residual capacity. When there is no wavelength conversion, the residual capacity of a route is equal to the number of common free wavelengths on the route. For networks with wavelength conversion, the residual capacity of a route is equal to the minimum number of free wavelengths among its links.

B. Dynamic Least Congested Routing Algorithm

The advantage of adaptive routing algorithms is the ability of choosing the most suitable route based on the network status. However, in traditional adaptive routing algorithms, once the lightpath has been setup, its physical route will not change. It is possible that, a lightpath is originally setup on a good route; but after a while, this route may not be a good choice anymore. The basic principle of the DLCR algorithm is to dynamically switch the route of a lightpath to the least-congested route. Usually a lightpath will hold for a very long period as compared with the lightpath setup time; therefore it is feasible to reroute existing lightpaths to vacant routes without paying too much traffic overhead. Here we propose the DLCR algorithm as follows:

For each source-destination node pair, a number of edge-disjoint routes are pre-calculated. These routes need to be recalculated if the network topology is changed.

Suppose a lightpath connection request on node pair (s,d) arrives. If all the pre-calculated routes between (s,d) have no free wavelengths, this connection request will be blocked. Otherwise, setup the lightpath on the least-congested route. After the lightpath has been successfully setup, the source node s immediately creates a timer[1] with expiration time of t. The variable t is referred to as *Reroute Time Interval* (RTI). If the timer expires before the release of the lightpath, node s executes the rerouting routine described as follows:

Rerouting Routine

Notations: The old route of the lightpath is denoted as R_o and its residual capacity is $F(R_o)$. The current least congested route between (s,d) is denoted as R_l and its residual capacity is $F(R_l)$ where $F(R_l) \geq F(R_o)$.

There are two different situations:

(1) If $F(R_o) \geq F(R_l) - 1$, it is not worthy to reroute the lightpath to R_l. Therefore in this case we simply create a new timer with expiration time t for this lightpath so as to trigger the next rerouting routine. No rerouting is performed; and R_o is still used to carry the lightpath until the new timer expires.

(2) If $F(R_o) < F(R_l) - 1$, R_l is considered to be more suitable to carry the lightpath. So we reroute the lightpath from R_o to R_l using the following migration process:

1. setup a lightpath between (s,d) on route R_l;
2. switch the optical signal from the original lightpath to the new one on R_l;
3. release the old lightpath on R_o;
4. create a new timer on s with expiration time of t for this lightpath.

Every time a timer expires before the termination of the lightpath, the same rerouting routine has to be run.

The DLCR algorithm has four main advantages: First, it is simple to be implemented since the lightpaths are always rerouted to a vacant route. Rerouting of a lightpath does not affect other existing lightpaths. Second, there is no extra com-

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[1] The timer is associated with the lightpath. So it is possible for a node to have several timers at the same time, each for a different lightpath.

putation requirement. Third, the lightpath disruption time is minimized to the physical limitation of switching the optical signal from one lightpath to another, since the data transmission is preserved on the old lightpath during the setup of the new one. Finally, DLCR algorithm can improve the blocking performance over LCR algorithm significantly, which will be shown in Section IV.

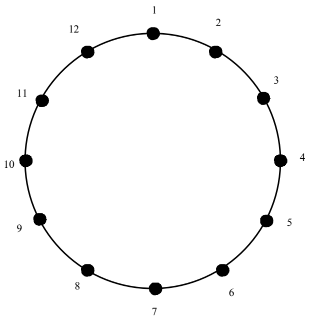

Fig. 1. 12-node ring network

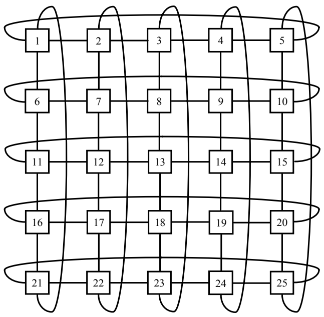

Fig. 2. 25-node mesh-torus network

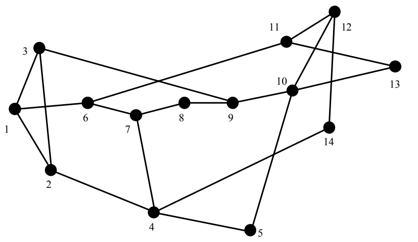

Fig. 3. 14-node NSFNET

III. SIMULATION ENVIRONMENT

The blocking performance of the DLCR algorithm is evaluated by extensive simulation studies on a set of network topologies. Since we are only interested in the steady-state blocking probability, the data of initial transient period in each simulation are discarded. For each data point, 30 independent simulations are conducted and the 95% confidence interval of the blocking probability is estimated. The running time of each simulation is set to be long enough for achieving a small width of confidence interval. For instance, when the blocking probability is at the order of 10^{-5}, about 100 million lightpath requests are generated in just one simulation; while for a higher blocking probability such as 10^{-2}, 1 million lightpath requests per simulation are good enough to generate precise estimations of the blocking probabilities.

In our simulations, the lightpath requests arrive to the network following a Poisson process; and each node pair has the same lightpath request arrival rate. The lightpath holding time is exponentially distributed with a unit time. Each fiber link can support 40 bi-directional wavelength channels.

We will present the simulation results of the following three topologies: 12-node ring (Fig. 1), 25-node mesh-torus (Fig. 2), and 14-node NSFNET (Fig. 3). Four different routing algorithms are investigated: SPR, FAR, LCR, and DLCR. For FAR, LCR, and DLCR, two edge-disjoint shortest paths are pre-calculated for each node pair.

IV. PERFORMANCE EVALUATION

A. Impact of the Reroute Time Interval

The *Reroute Time Interval* (RTI) is a very important parameter in DLCR algorithm. It determines how frequently the lightpath rerouting is performed. Intuitively, a small value of RTI can make the lightpaths more adaptive to the changing of network conditions. On the other hand, with the decrease of RTI, the signaling overhead will increase because the source node needs to refresh the information of network status more frequently.

We assume the average lightpath holding time is one time unit. A set of simulations on NSFNET topology with different values of RTI have been conducted. The results are shown in Fig. 4. The first data point shows the blocking probability of LCR algorithm, i.e., no rerouting at all. It is obvious that, with the decrease of RTI, the blocking probability can be reduced. However, once the RTI is decreased to some small value, the blocking probability will converge to a bound. If RTI is too large, the rerouting process cannot catch up the changing of network status and the performance gain is marginal. However, if RTI is too small, the signaling overhead will increase. Observing that the changing rate of network status depends on the connection arrival rate A, a simple but appropriate approach is to set the RTI as $1/A$. From Fig. 4 (A = 200), we can see that setting RTI as 0.005 is a reasonable tradeoff: the blocking performance cannot be improved further while the signaling overhead is still acceptable. For instance, if the average lightpath holding time is one month, then RTI can be set to 3.6 hours to achieve good performance while keeping the overhead at a very low level.

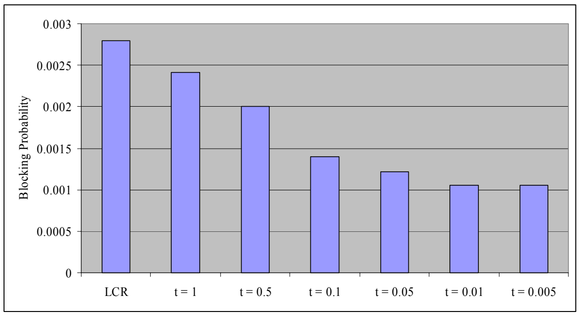

Fig. 4. Blocking probability versus reroute time interval in 14-node NSFNET, without wavelength conversion, W = 40, total traffic load = 200 Erlangs

B. Without Wavelength Conversion

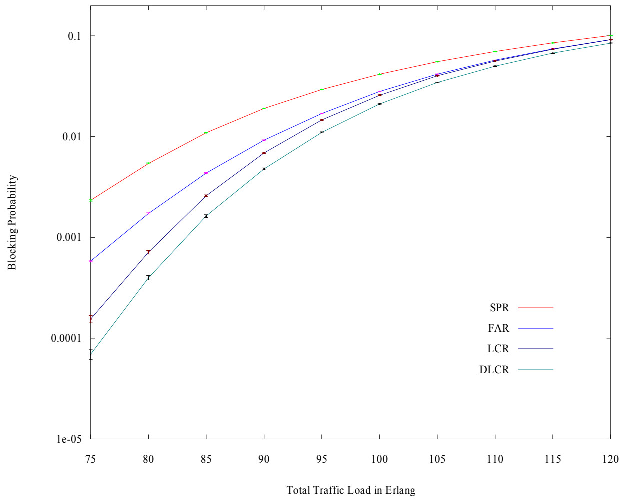

Fig. 5. Blocking probability versus traffic load in 12-node ring network for different routing algorithms, without wavelength conversion, W = 40

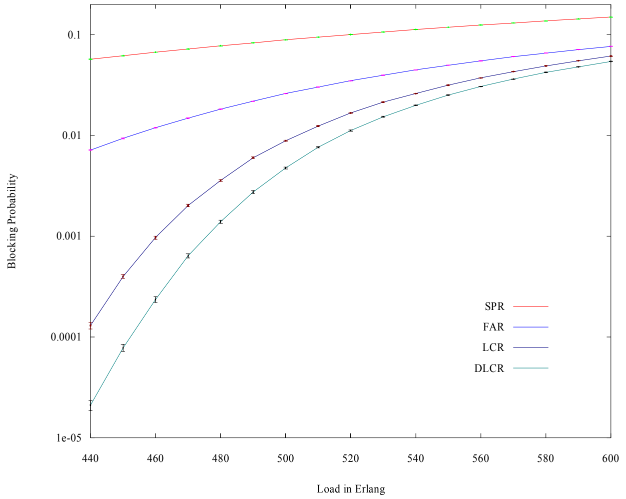

Fig. 6. Blocking probability versus traffic load in 25-node mesh-torus network for different routing algorithms, without wavelength conversion, W = 40

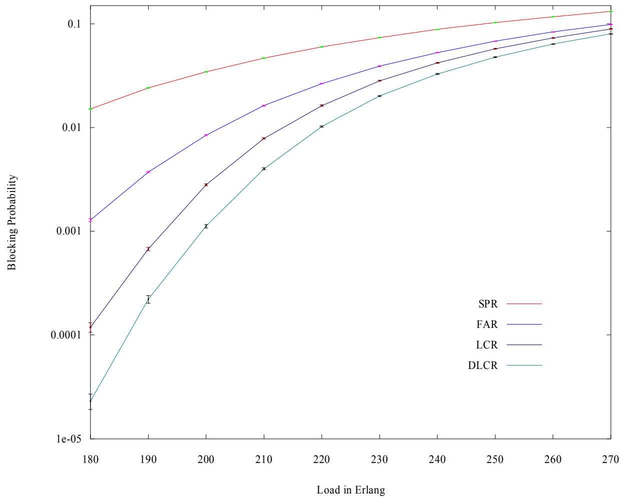

Fig. 7. Blocking probability versus traffic load in 14-node NSFNET for different routing algorithms, without wavelength conversion, W = 40

We first present our simulation results for WDM networks without wavelength conversion. The interval estimations of the blocking probabilities (at 95% confidence level) are shown in Fig. 5, Fig. 6, and Fig. 7, for 14-node ring, 25-node mesh-torus, and 14-node NSFNET, respectively.

In all the three topologies, SPR algorithm has the worst blocking performance. FAR algorithm can improve the performance a lot by providing alternate routes. When the traffic load is low, LCR algorithm can further improve the blocking performance. This is mainly because LCR algorithm prefers least congested route; therefore it can distribute the traffic more evenly and reduce the number of congested links. However, it is possible that during the lightpath holding time, the original least congested route becomes more congested than other candidate routes. By using rerouting technique, DLCR algorithm tries to keep the lightpath on the least congested route throughout its holding period. From the three figures, we can see that DLCR algorithm can improve the performance over LCR by a large margin. The performance gain of DLCR over LCR is comparable with that of LCR over FAR.

C. With Wavelength Conversion

In this subsection, we present the performance of DLCR algorithm for WDM networks with wavelength conversion.

Fig. 8 shows the blocking performance of different routing algorithms in the 12-node ring network. As presented in [4], LCR algorithm does not perform well in ring topology when wavelength conversion is supported. This is again validated by our simulations. Although the performance of DLCR is not as good as that of FAR algorithm when the blocking probability is larger than 0.1%, the difference is very minor; and DLCR can always achieve much better performance than LCR. The design of better rerouting algorithms for ring topology with wavelength conversion is left for future investigation.

DLCR algorithm can achieve tremendous performance gain in mesh-torus network and NSFNET with wavelength conversion. Especially in mesh-torus network, the blocking probability can be reduced by one to two orders of magnitude, as shown in Fig. 9. In NSFNET, the performance of DLCR is also very impressive. When the traffic load is high, the performance gain of DLCR over LCR is even larger than that of LCR over FAR.

V. CONCLUSIONS

In this paper, we propose a new adaptive routing scheme called DLCR algorithm for wavelength-routed WDM networks. It can significantly reduce the blocking probability compared with traditional LCR algorithm by adaptively switching the lightpaths to the least congested routes. DLCR algorithm is simple to be implemented and the lightpath disruptions time is minimized to the physical limitation.

Our future research work is to design a better rerouting scheme for ring topologies when wavelength conversion is available. The rerouting triggering policy is another direction of future investigation.

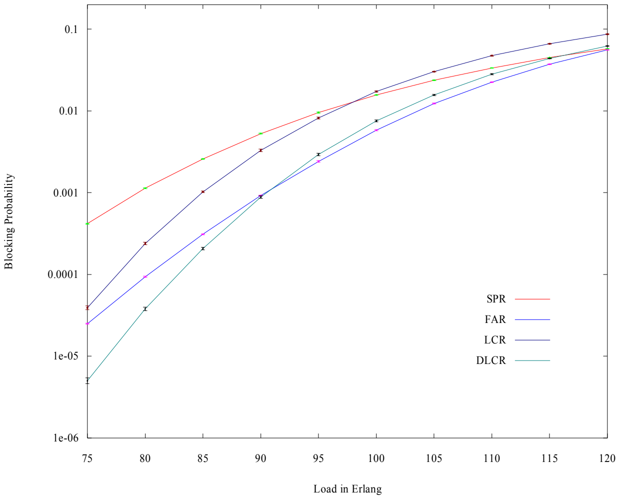

Fig. 8. Blocking probability versus traffic load in 12-node ring network for different routing algorithms, with wavelength conversion, W = 40

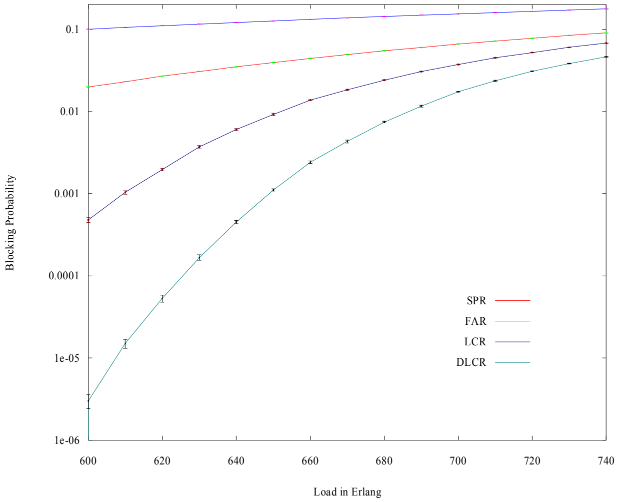

Fig. 9. Blocking probability versus traffic load in 25-node mesh-torus network for different routing algorithms, with wavelength conversion, W = 40

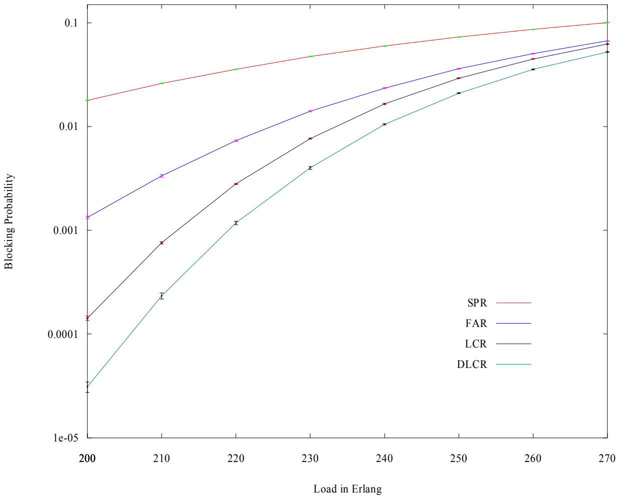

Fig. 10. Blocking probability versus traffic load in 14-node NSFNET for different routing algorithms, with wavelength conversion, W = 40

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