Quality Based Optical Routing Protocol

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ABSTRACT

Optical networking, with its almost unlimited bandwidth, is the only technology that can support communication new applications with high demand for bandwidth such as remote visualization, teleimmersion, collaborative e-science etc. In the optical networks presently deployed, each link is optically isolated by transponders doing O/E/O conversions. But these transponders are quite expensive and lack transparency; hence there is a strong motivation to use large all-optical networks. In all-optical networks, all routes need not have adequate signal quality. To provide reliable and transparent service, there is a strong interest in the industry for routing protocols that take into consideration the impairments of optical layer that degrade quality of the signal. We present a new routing protocol that uses information about the quality of signal to select paths in an all-optical network. Our simulations confirm that this new protocol reaches higher network utilization compared to existing ones.

Keywords: Quality of signal in optical networks, Routing in optical networks, all-optical networks.

1. INTRODUCTION

As the Internet becomes the universal medium of communication, the demand for bandwidth increases exponentially. Communication applications with ferocious demands for bandwidth such as remote visualization, teleimmersion, collaborative e-science, and high-resolution medical image archiving will be in big demand. Optical networking, with its almost unlimited bandwidth, is the only technology that can support such demand for bandwidth. In the optical networks presently deployed, each link is optically isolated by transponders doing O/E/O conversions. They provide regeneration with retiming, re-amplification and reshaping, which eliminates transparency to bit rates and frame formats. These transponders are quite expensive and their lack of transparency also constrains the rapid introduction of new services. Thus there are strong motivators to use large all-optical networks.

Wavelength-routed DWDM networks are attractive candidates for the next generation Internet and beyond. In such networks, the physical topology of the network may be represented as a graph with nodes representing wavelength routers, interconnected by multi-wavelength links. When discussing routing in an all-optical network it is usually assumed that all routes have adequate signal quality. This may be ensured by limiting all-optical networks to subnetworks of limited geographic size that are optically isolated from other parts of the optical layer by transponders. There are, however, strong reasons to consider all-optical networks in which not all routes have adequate signal quality. First, as bit rates increase it is necessary to increase power. This makes impairments caused by nonlinearities more troublesome. Second, from a supply perspective, optical technology is advancing very rapidly, making ever-larger domains possible. We assume that these considerations will lead to the deployment of a domain of transparency that is too large to ensure that all potential routes have adequate signal quality for all circuits. All-optical networks can serve more economically as "express backbones" for longer distances. There is a strong interest in the industry for routing protocols in all-optical networks that take into consideration the impairments of optical layer that degrade quality of the signal.

DWDM networks are sensitive to the effects of dispersion and non-linearities in the fiber. For optimum performance, network parameters must be 'fine-tuned' in the field to give a bit error rate (BER) of less than 10^{-14}. Use of optical performance monitors (plug-in modules measuring Q-factors and eye diagram) is a time-consuming, expensive process requiring days of network down time and so lost revenue. Also, with multiple optical signals just doing a power

measurement is inadequate. In fibers having 80 wavelengths, all that optical performance monitors will be able to measure is aggregate power of the fiber. In the case where we lose one eightieth of that power, the change will be so subtle that establishing whether it's a wavelength lost or a shift in the characteristics of the signal requires a lot of sophistication.

Currently, the quality of a signal received from a fiber optic link is measured either by examining the eye diagram, or by measuring the bit error rate (BER). BER measurements, to be statistically significant, require the accumulation of many errors, which at low bit error rates can require the reception of trillions, even quadrillions of bits. Furthermore, BER measurements require disrupting the data stream to send a lengthy known bit sequence. Eye diagram measurement may be faster and can be performed on real-time data, but requires again the reception of many bits to form a significant sample, requires the conversion of the optical signal to an electronic one. Also, eye diagram measurement accounts only for noise and jitter, not dispersion or attenuation. BER is more meaningful but both processes are excruciatingly slow, taking many minutes to obtain quality data. This is both because of the O/E conversion and the requirement to collect huge numbers of bits. At present the only thing that can be detected instantly is a complete loss of signal.

In this paper we propose a novel network protocol that takes advantage of having available, for the first time, nearly instantaneous information about the quality of optical signal. We propose to take into consideration the overall effects of all such impairments by measuring the quality of signal using our optical correlator. We will take advantage of the quality of signal information made available by the optical correlation device in the design of a new routing protocol. Our routing protocol, when selecting a route, will check that the quality of signal is acceptable. The ultimate goals of our proposal are to allow carriers to quickly and dynamically provision network resources by optimizing the quality of service and network utilizations.

The paper is organized as follows. We start with reviewing the related work in section 2, then describe our routing and control protocol in section 3. We then present simulation and results of quality-based optical routing protocol in section 4 and finally we present some concluding remarks in section 5.

2. RELATED WORK

All-optical networks, especially Wavelength-division multiplexed (WDM) networks, have received an enormous amount of attention, as exemplified by several projects including AON [2], MONET [3] NTON [4], TBONE [5] and various European projects. In such networks, a lightpath is usually established before data is transferred between two communicating nodes, thus eliminating the need for buffering and electronic-to-optical or optical-to-electronic conversions during the data transfer at the intermediate nodes.

Two basic approaches, namely path multiplexing (PM) and link multiplexing (LM) [6], can be used to establish lightpaths in all-optical WDM (or TDM) networks. In PM, a lightpath is established by using the same wavelength that is available on all the links along the path. In LM, different wavelengths that are available on different links along the path can be used provided that all-optical wavelength converters are available at each node. The network control (or signaling) required for establishing a connection may be either centralized or distributed. In large networks, centralized control is not feasible, and hence it is essential to study distributed control protocols.

Choice of a good route-computation algorithm is essential to the performance of these networks. The physical capacity available in transport networks has increased to several Tb/s with optical switching. How much of this available physical capacity can be used for carrying user traffic and the quality of service seen by the users depends on the route-computation algorithm used. Each connection in these networks is capable of carrying 40 Gb/s worth of data. As a consequence, the impact of even a small percent improvement in the usable network capacity, which can be of the order of hundreds of Gb/s, if not Tb/s, in these networks is significant.

The objective of an adaptive route-computation algorithm is to compute paths for arriving connection requests dynamically such that the total number of connections established in the network is optimized. Most of the adaptive route-computation algorithms proposed recently use Dijkstra's shortest-path algorithm [8-15]. In these algorithms, each link of the network is assigned a weight. The total weight of a path is the summation of the weights of all links in it. For

any arriving connection request, a path with minimum total weight is selected. Different algorithms differ in how they define link weights. A description of weight-based algorithms is given here.

Each link L_i is also assigned a weight $W(L_i)$. All of the algorithms described here execute Dijkstra's Shortest-Path algorithm to find a path with minimum total weight. The total weight of a path p, $TW(p)$, is the summation of the weights of all links in it:

$$TW(p) = \sum_{i=1}^{N(p)} W(L_{f(i)})$$

where $N(p)$ is the number of links in path p, and $f(i)$ is the link id corresponding to the ith link in path p.

Availability-based algorithm [9] is an adaptive route computation algorithm in which the weight of a link is defined as

$$W(L_i) = \frac{1}{A(L_i)}$$

where $A(L_i)$ is the number of free channels in Link L_i.

Here, the weight of a link is inversely proportional to the number of free channels in it. The idea is to make a link expensive if it is high in demand, expecting that this link will continue to be high in demand by all future connection requests. But, if for the same set of connection requests the order of connection arrivals is changed so that links high in demand earlier on are rarely needed by later connections, this strategy does not work well. In [8], this algorithm has been referred to as the "total cost-based" algorithm. We use the name "Availability-based algorithm" instead to reflect its definition of link weight

With the emergence of Optical Cross-connects (OXCs) providing dynamic configuration without any o-e-o (optical-electronic-optical) conversion there has been a significant shift in management paradigm from centralized control to distributed control [7]. A few distributed protocols have been proposed either for control or reservation.

We adapt a Fixed Wavelength Assignment scheme [21], which approaches the performance of Packed Assignment scheme. The details are out of scope of this paper and can be obtained from [15, 21, 22]. In this scheme, to find a wavelength assignment, the set of wavelengths are searched in a fixed order.

2.1. Optical Correlator

Fiber optic link quality is conventionally measured using BER or eye diagrams. Both require performing an O-E (optical to electronic) conversion and collecting many, many bits to build up some statistics. In optical correlation, the quality of the bits is determined while keeping everything in the optical domain.

In a companion paper [16] is proposed an optical correlation mechanism for determining the link quality. A '0' and a '1' are transmitted and the received (degraded) signal is correlated with a crisp, clean 0 and 1. The correlation is then done optically in a time of two bit periods. The correlation can be used to detect both the presence of the signal (trivial), and its quality. Figure 1a shows a simple simulation in which an ideal signal is correlated with a signal that suffers only attenuation. Figure 1b shows the effect of dispersion only, where 50% dispersion is defined to mean the point at which half the energy lies outside the original pulse. The correlation peak can be thresholded optically to determine whether the link meets some minimum standard level of quality. At 40Gb/s, the result is obtained in 100ps and without O/E conversion. Noise and jitter must still be measured over many bits; noise produces variation in the peak of the correlation function and jitter produces variation in its position (Figures. 1c,d). Even with a thousand bits the result is obtained in 50 ns at 40Gb/s, as opposed to perhaps minutes using conventional techniques.

An optical correlator consists of a tapped delay line, a set of weights, and a summing element. The key to high-resolution correlation is a large number of taps. The correlator uses a TDL based on the White cell [17], a simple optical device allowing many light beams to circulate between several spherical mirrors. The White cell as adapted to producing time delays is unique because it allows for a very large number of beams (thousands) to circulate between a small number of mirrors (fewer than a dozen) [18,19].
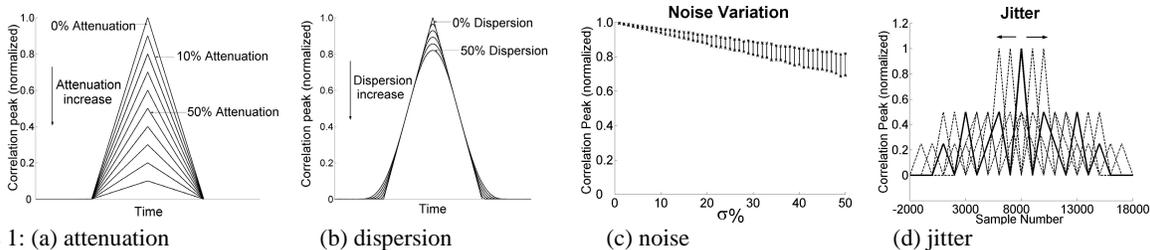
Figure 1: (a) attenuation   (b) dispersion   (c) noise   (d) jitter

In the original White cell, one spherical mirror faces two others. Light beams entering the cell bounce between these three mirrors some fixed number of times, and on each bounce the light is re-imaged to a new spot on one of the mirrors. An important feature is that many beams (hundreds or thousands) can be introduced at the same time, and each traces out a unique, non-overlapping set of spots. If the mirror on which the spots fall is replaced with a fixed array of tiny mirrors, each of which is permanently tipped in an appropriate direction, any beam on any bounce can be directed to go to White cells of different lengths, incurring delay relative to the other beams. An example of five White cells joined by a common micromirror array is shown in Figure 2. Each of the spherical mirrors is at a different distance from the micromirrors, producing delays. One induces a delay of τ, the next a delay of $n\tau$, the next $n^2\tau$, $n^3\tau$, and so on. Each beam is sent to the various mirrors for different numbers of times. In the tapped delay line, the first beam will receive a relative delay of 0, the next a delay of τ, the third beam a delay of 2τ and so on. This design requires ten spherical mirrors and one fixed micromirror array to produce 6550 thousand taps for a 6550 beams in 18 bounces [19]. More taps can be achieved with more bounces. The mirrors will have dielectric high-reflectivity coatings; the total loss (excluding output coupling loss) will be less than 0.1 dB. The lengths can be tuned to 10fs resolution using thin prisms sliding past each other (not shown.)
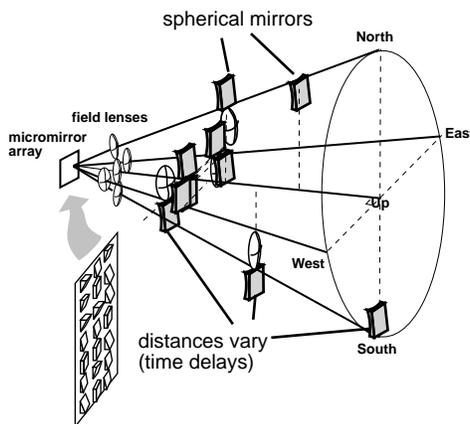

Figure 2: An optical correlator with 10 White cells.

The input to the correlator is an (incoherent) array of spots, one for each intended tap (e.g. a single beam is split into N beams before entering the correlator- ensuring their amplitudes are all the same). These spots are imaged onto an array of amplitude weighting elements, which can consist of simple shutters for fixed 1's and 0's. Actually, the blocked beams do not need to be implemented at all, so for a resolution of R, it requires only $N=R/2$ beams. The weighted spots are then re-imaged to the micromirror array, where they each make their individual bounce patterns, are independently delayed and then summed.

The protocol proposed here is based on the optical link quality obtained by the optical correlator described.

3.   QUALITY-BASED OPTICAL ROUTING PROTOCOL (QORP)

Routing and Wavelength Assignments algorithms are used by the provisioning software in an optical network. Dynamic provisioning in an optical transport network consists of three tasks: computing a path, selecting a wavelength, and reserving the selected wavelength on the computed path. When a connection request arrives, first a path that has at least one free wavelength is computed for it. One wavelength from the set of free wavelengths on this path is then selected for this connection. After a path has been computed and a free wavelength has been selected, an attempt is made to reserve this wavelength on the computed path. Path-computation has the most dominant effect on the total number of connections that can be established in a network [14]. Algorithms for path-computation are called routing or route-computation algorithms. This chapter presents the Quality-Based routing protocol.

The goal of the proposed optical routing protocol is to reduce blocking probability and achieve quality services for customers. The protocol combines intelligent routing with the immediate availability of information about quality of signal provided by the optical correlator. This algorithm is a based on the availability-based algorithm except that it also uses quality information.

We start with a description of network model, information being exchanged between various nodes in the network and present our protocol to achieve routing that satisfies quality requirements.

3.1.   Network Model

An optical transport network is modeled as a connected graph $G = <V, E>$, where V is the set of vertices and E is the set of edges. An example network appears in Figure 4. The edges or links of G are denoted by L_i, where $i=1, 2...N$, and $N = E$. All the links in the network are bi-directional. The maximum capacity of a link L_i is the total number of wavelengths that can be carried on it and is denoted by $f(L_i)$. Each node is equipped with an optical cross-connect (OXC) and a controller. For the purpose of route-computation, it has been assumed that each node has full-wavelength conversion capability. Controllers at each node maintain the status of all links that emanate from it. A signaling channel exists between every pair of nodes, which is used to exchange link state information and for establishing new connections. Every connection request specifies a source (s) and a destination (d). A source node is also sometimes referred to as an ingress node. Similarly, a destination node is sometimes referred to as an egress node. A connection request is presented to its source nodes. Every connection requires one wavelength from s to d. In this paper, connections that are established stay in the network permanently.

3.2.   State Information

The controller for a wavelength-routed switch maintains the state of the connections flowing through the switch in a connection state table (CST). The state information is updated by a connection update procedure. In addition to the CST, the controllers maintain the topology of the network.

In order to set up connections, the nodes must also keep track of the availability of wavelengths on other links in the network, which is done via a Link State update protocol. Every connection is identified by a connection-id that consists of a triplet (originator, destination, sequence number). The connection-id is unique, and is assigned by the originator of the connection. At a switch, a connection may be in a reserved or free state. The connection-id is carried in all control messages related to the connection. Note that the CST accommodates networks with multiple fibers between nodes by assigning different labels to the ports corresponding to the different fibers.

3.3.   Information Exchange

Each node exchanges packets with other nodes in the network and thereby determines its local state information. This state information includes the status of links in the network. Each node advertises its local state information through out the network. Whenever a connection is established, each node involved in the connection broadcasts the change in its link status to all the nodes in the network. The information broadcasted includes the wavelength availability/unavailability information of the link, quality of the link and the new cost of the link.

A link L_{ij} can be uniquely represented by the nodes i and j to which the link is connected to. A node maintains the state information of all the links that are connected to at least one node in the network. The process for calculating the cost of a link C_{Lij} is presented in Section 3.4.

3.4.   Route Determination

The routing and wavelength assignment problem is, given a connection request and the current state of the network, to calculate the shortest path between two nodes that satisfies the quality requirements, and also assign a set of wavelengths along this path. The dynamic route computation algorithm used Djikstra's shortest-path for routing. In this algorithm, each link of the network is assigned two weights. Here, quality and availability are used for link weights. The total weight of a path is the summation of the weights of all links in it. For any arriving connection request, a path with minimum total weight is selected. In the proposed protocol the weights of a link are defined as:

$$W1(Li) = Quality(Li)$$

and

$$W2(Li) = \frac{1}{Availability(Li)} = Cost(Li)$$

The Quality of a path is measured in terms of the quality degradation (QD_{SD}) and is calculated as follows:

$$TW1(p) = QD_{SD} = \sum_{i=1}^{n} QD(Li)$$

where $QD(Li)$ is the quality degradation of link Li, measured by the optical correlator.

The algorithm selects the shortest path that has QD_{SD} below (above) a given threshold QD_{Th}. For instance, a path with QD_{SD} of one would be of perfect quality i.e., there would be no errors because of the channel, but as QD_{SD} decreases then it means the channel is introducing more errors.

The other total weight of the path would be:

$$TW2(p) = \sum_{i=1}^{N(p)} W(Li)$$

The Quality Based protocol uses these two weights to choose the best path. Given a source and destination pair, it finds a path with the minimum total weight $TW2(p)$. It then checks whether the quality of the path (p) is acceptable or not. If the quality is within the given threshold, this path is chosen for connection establishment. If the quality requirement is not satisfied, the next path with minimal total weight $TW2(p)$ is chosen. This process is repeated until a path with acceptable quality is found within k paths between the source and destination. The algorithm is summarized in Figure 3

- **Quality(Li) <- value obtained from the correlator**

- **Cost(Li) <-** $\dfrac{1}{Availablity(Li)}$

- **Compute a minimum cost path, *p1*.**

- **If Total Quality(*p1*) < Threshold choose *p1*.**

- **Else find path *p2* with next minimum cost in a set of *k* paths**

  between source and destination.

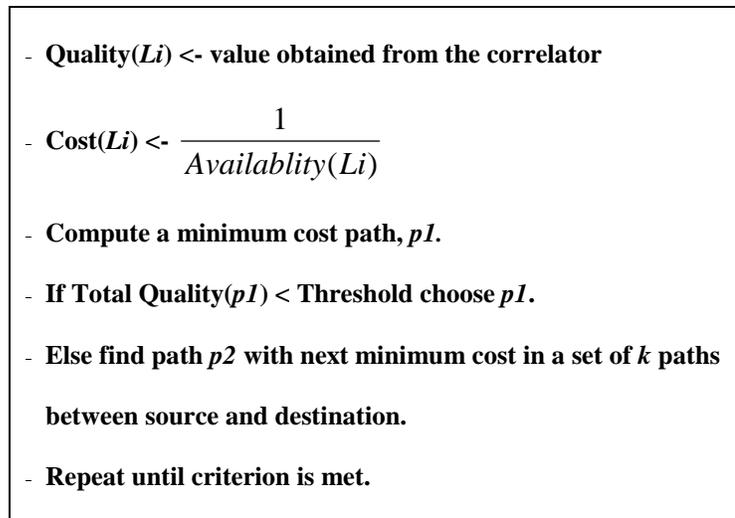- **Repeat until criterion is met.**

Figure 3: Path Computation Algorithm in Quality Based Routing Protocol

3.5. Call Admission/ Connection Establishment

Whenever any edge node receives a connection request from source S to destination D, the source node S computes the cost of each possible path and selects the best path that satisfies the quality requirements. The quality of the path selected is calculated as described in Section 3.4. The whole process is illustrated in Section 3.6. The reservation used is a backward reservation. Source S then sends Path-Probing (PP) packets through the best path. The PP packets are essentially used to check if at least one wavelength is free on all links along the path and to choose one free wavelength. A path-probing packet contains the path that the control packet traverses to reach the destination. This information can be represented as follows:

<node 1><node 2>......<Destination >

A PP packet also has a set of wavelengths that are available on the outgoing link. Each node that receives the PP packet checks the wavelengths in the packet against its available wavelengths to the next node in the path. It then resets the wavelength set in the PP packet to the intersection of the two. This procedure repeats until the PP packet reaches the Destination. When the PP packet reaches the destination, the destination chooses one wavelength from the set in the PP packet & establishes the connection by sending the PP packet with the selected wavelength in the reverse direction. Thus the connection is established when the PP packet traverses the nodes.

3.6. Routing Process Illustration
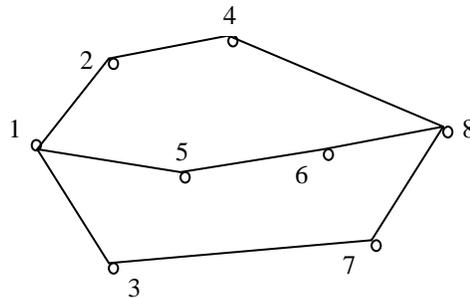
Consider a simple topology as shown in Figure 4,

Figure 4: A simple optical network

When a connection request comes to a source (S) say node-1 requesting for a connection to destination (D) say node 8, S first computes the available paths to D and their details. Let us define the quality degradation threshold ($QD_{Th} = 10$) as the quality degradation of the path above which the path is unacceptable. Let the computed paths between S and D be $p1$<1-3-7-8>($C_{p1} = 4$, $QD_{p1} = 15$), $p2$<1-5-6-8>($C_{p2} = 5$,$QD_{p2} = 2$), $p3$<1-2-4-8>($C_{p3} = 6$, $QD_{p3} = 1$). S finds a path with least cost that is $p1$. S then finds that the quality degradation of this path $p1$ is greater than the given quality degradation threshold. So, S selects the next least cost path that is $p2$. This new path $p2$ satisfies the quality degradation threshold requirement, and hence is chosen. Then the source sends Path Probing packets PP through the path $p2$ that met the quality criteria and minimum cost. The PP packet contains the path chosen $p2$<1,5,6,8> with the wavelength set available for the link between 1,5; say <w1, w2, w3, w4>. Node 5, upon receiving the PP packet checks the wavelength availability for the link 5 – 6 and removes the wavelengths that are not available, for example w2, on this link from the set of wavelengths in the PP packet. It then forwards the PP packet that contains the updated wavelength set, <w1,w3,w4>, to the next node. This process repeats until the PP packet reaches the destination. The destination (D) then chooses a wavelength (w1) from the final wavelength set <w1,w4> and initiates the connection establishment procedure through this path.

4. SIMULATION

The quality-based routing protocol has been implemented in Network Simulator (ns-2) [23]. A comparison of quality-based and availability-based optical routing protocols for the amount of calls established that are of acceptable quality is performed. The National Science Foundation network (NSF Net), shown in Figure 5, has been used as the topology of

the network for simulations. NSF Net consists of 16 nodes, 25 links and 128 wavelengths per link. For quality-based routing simulation, some of these links have degraded quality. Traffic is generated between a random source and destination pair. The number of connections established that satisfy the quality requirements is used as a metric for comparison.

Figure 6 shows the comparison of quality-based and availability-based optical routing protocols when the quality of three links has degraded. The number of connections with acceptable quality degradation is plotted against the total number of connection requests. The results show that the quality-based protocol generates more acceptable connections than that of availability-based. The quality-based protocol takes the information provided by the optical correlator into account and establishes calls that are acceptable, whereas the availability-based protocol, which doesn't account for quality, establishes some calls that are unacceptable.
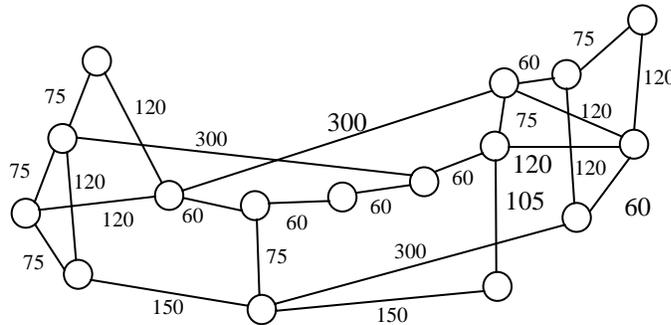

Figure 5: NSF Net

Additional simulations have been performed in which the number of links with degraded quality is varied. In these simulations, the average hop count of connections established is observed to be in the range 3.3 to 3.5, calculated using [20]. The full capacity of the NSF Net with 25 links and 128 links per wavelength is 3200 and is calculated using techniques developed in [20]. Hence the maximum load that can be offered to the network is 941. The load offered to the network in simulations is 100 – 1000 connection requests (10.6% to 106%). Figure 7 and Figure 8 show the comparison of quality-based and availability-based optical routing protocols where the quality of five links and seven links in the network is degraded. From these figures we can see that with the increasing percentage of links with degraded quality, the number of acceptable connections established by quality-based routing protocol is much higher than that of the availability-based routing protocol as it adapts to the quality of links in the network.
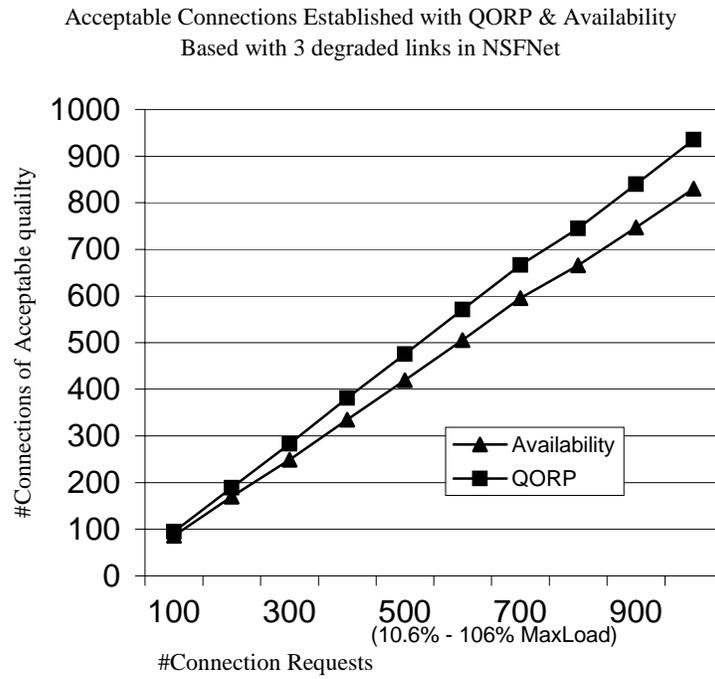
Acceptable Connections Established with QORP & Availability
Based with 3 degraded links in NSFNet

Figure 6: Comparison of Quality Based & Availability Based Protocols with quality of three links degraded

Acceptable Connections Established with QORP & Availability Based
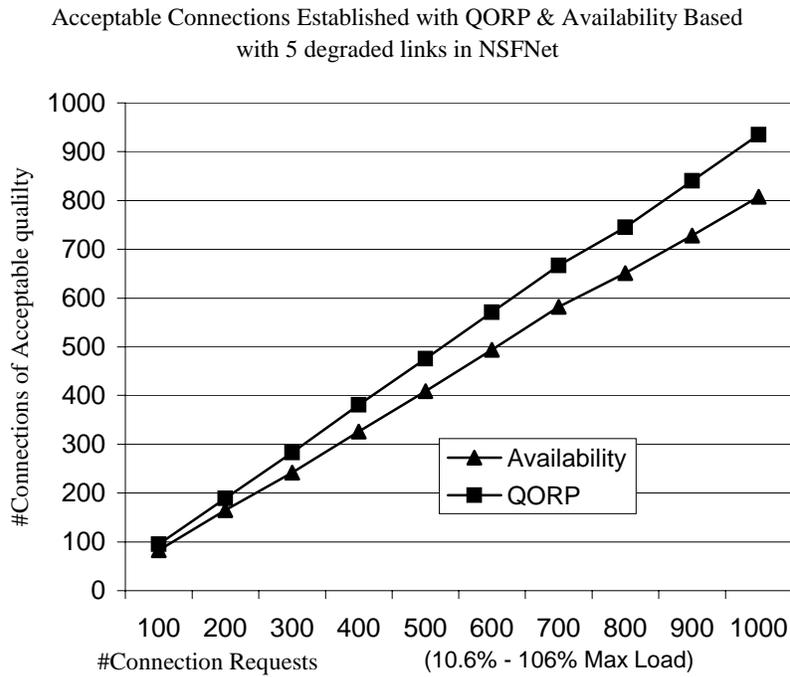with 5 degraded links in NSFNet

Figure 7: Comparison of Quality Based & Availability Based Protocols with quality of five links degraded

Acceptable Connections Established with QORP & Availability
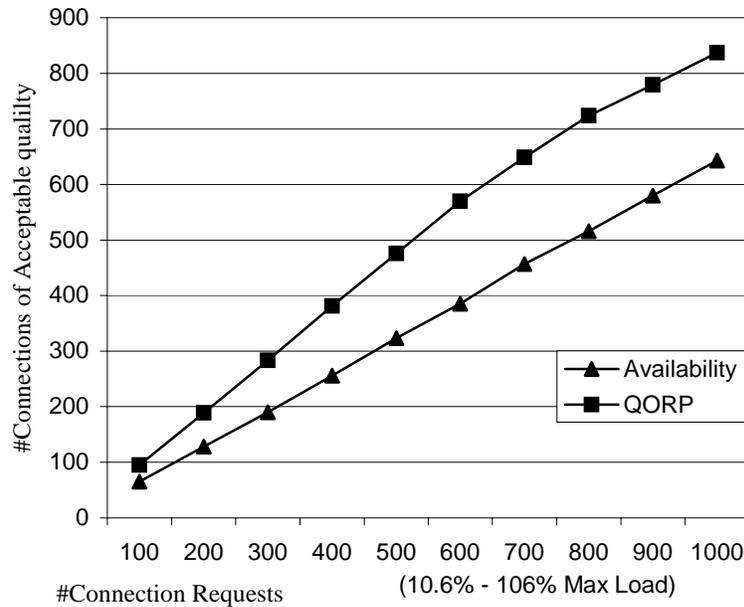Based with 7 degraded links in NSFNet

Figure 8: Comparison of Quality Based & Availability Based Protocols with quality of seven links degraded

5.   CONCLUSIONS

We have proposed a distributed quality-based protocol for routing, setting up, taking down and maintaining the state of connections in wavelength-routed all-optical networks. QORP accounts for physical impairments and minimizes the blocking probability of all-optical wavelength routed networks. The information about quality of the optical signal is made available instantaneously with the help of an optical correlator. In QORP a route is chosen with a quality degradation that is below some threshold. Hence, the protocol eliminates the number of connections with poor quality whereas other protocols, which don't account for quality, establish calls that are of unacceptable quality.

QORP has been implemented in ns-2. Simulation showed that the quality-based routing protocol has a lower blocking probability than the availability-based routing protocol. While other protocols would accept paths with low quality, which the users cannot use, QORP will find paths with acceptable quality.

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