Multipath Distributed Protocols for Dynamically Reserving Wavelengths in IP-over-WDM Networks

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Abstract—**This work proposes a multipath variation of the conventional Backward Reservation Protocol (BRP) for dynamic lightpath establishment in IP-over-WDM (wavelength division multiplexed) optical networks. It uses simultaneous probing in multiple fixed alternate routes from source to destination. Termed as multipath BRP (i.e., MBRP), it entails significant enhancement in protocol efficiency, when compared with existing protocols, at the cost of a moderate increase in control overhead and setup latency. There are two ways in which we can order the multiple paths during the *reservation* (R) process, namely *sequential* (S) and *temporal* (T). Retries can also be made with MBRP as it is usually done in BRP. Simulation analysis tells us, between SR and TR, which variant should be used under a given network condition. However, from protocol efficiency point of view, in general, SR performs better than TR because TR prefers *breadth* to *depth* in path selection, which results in oscillation between possible paths.**

Index Terms—**IP/WDM, wavelength reservation, protocols, distributed control, alternate routing, simulation, performance analysis.**

I. Introduction

Integrated routing and wavelength assignment, based on generalized multiprotocol label switching (GMPLS) [1],[2], has begun to emerge for the envisioned IP over wavelength division multiplexed (WDM) networks that aim for real-time provisioning of IP-based services by leveraging the distributed control mechanisms implemented in the network [3]-[4]. In the optical Internet, data traffic will be dynamic, and in the extreme case, such as in optical burst switched or virtual-circuit switched networks [1], it is expected that the connection requests will arrive at a very high rate, and that the average duration of each connection will be at least several hundreds of milliseconds [5]. To cope with these new data traffic loads, the development of dynamic lightpath provisioning schemes will become increasingly important in near future [6]-[16].

Distributed signaling protocols have been proposed and standardized within the framework of GMPLS [1],[2]. Candidates include Resource reSerVation Protocol with Traffic Engineering (RSVP-TE) [1],[16] and Constraint-based Routing Label Distribution Protocol (CR-LDP) [1]. In this paper, we focus on RSVP in wavelength management for WDM lightpaths, where wavelength is the premium resource. A wavelength reservation protocol [2]-[5],[13] under the condition of rapidly changing availability of resources in a WDM network, should correctly and efficiently reserve necessary and available wavelengths during lightpath (i.e., connection) set-up time and again release those resources when they are no longer needed. This reservation is normally accomplished with the help of a few control packets exchanged between the source destination pair prior to the start of actual data transfer [7]-[9].

Distributed reservation protocols can be either forward reservation protocols (FRPs) [2],[3],[8]-[13], or backward reservation protocols (BRPs) [2],[3],[8],[9],[15],[17],[19], or intermediate reservation protocols (IRPs) [16]. It is now well-accepted that, if wavelength conversion is unavailable, BRP is superior to FRP in reducing the call blocking probability [3],[15],[18], and IRP is comparable with BRP [16]. However, conventionally, none of FRP, BRP and IRP considers multiple paths; they consider only the first shortest path as per fixed routing. This motivates us to explore in this work the suitability of parallel probing in multiple paths, known as Multipath Backward Reservation Protocol (MBRP). MRBP thrives upon fixed alternate routing and probes more than one shortest path (when available) between the source node and the destination node. Multiple PROB packets along multiple SPs reach the destination with wavelength information on their respective routes. The destination is now better informed to reserve a wavelength as it has information about more than one path. Now, there are two ways in which we can order the RESV packets, namely *sequential* and *temporal* (discussed next). When combined with retries, MBRP proves to be a very efficient protocol till a moderate network load is reached, thereby showing its potential for use in future IP over WDM networks under relaxed delay constraints. It is to be noted that we do not consider wavelength conversion in this work.

The rest of this paper is organized as follows. In Section II, we briefly discuss about the BRPs. In Section III, we present the proposed protocol and discuss its relevant properties. In Section IV, we give a detailed performance comparison of the proposed protocol with respect to current best protocols. Section V concludes the paper.

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II. BACKGROUND

Before describing the new protocol, we first explain BRP briefly for the sake of continuity. We do not discuss FRP here as it is not needed. It can be found in [9]-[12]. For comparing the results, we consider only the best variation of FRP, known as Selective N with Intermediate Unlock (SNWIU) [10]-[12].

A. BRP

In standard BRP (Figure 1), a source node, upon reception of a connection request, first sends a probe (PROB) packet towards the destination. This PROB packet gathers only the current wavelength usage information along the path up to the destination. It does not reserve any wavelength in the process (unlike FRP). Receiving the PROB packet, the destination node decides upon the exact wavelength (from among the available ones as shown by the PROB packet) to reserve and sends back a reservation (RESV) packet, which now locks the wavelength (provided it is still available) along the reverse path towards the source node. If the wavelength is not found available at some intermediate node, the node generates a failure (FAIL) packet to the destination and a NACK packet to the source in order to inform them about the abortion of the process. The FAIL packet, as it goes back, releases the wavelength locked so far in the traversed links, and the NACK packet informs the source about the connection set-up failure.

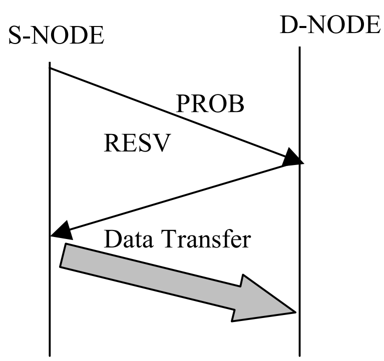

Fig. 1. Successful reservation in BRP

Two major drawbacks of BRP are- (i) *obsolescence* of probed information [19], and (ii) *racing condition* among multiple contemporary RSVP packets for the same wavelength at some common link. The larger the network, the longer the paths between source-destination pairs. The longer the routes, the more outdated the information collected by PROB packets. The higher the obsolescence, the more the probability of failure. On the other hand, in racing, where two contemporary connections, sharing one or more common links, accidentally select the same wavelength (because both of them have found the wavelength available in their respective PROB packets). Here, one of them will be blocked unfortunately, though there may be other free wavelength(s) available for the connection. Hence, there will be an unnecessary blocking which is not logically tolerable. To avoid this problem, the following enhancement [9] of BRP is used.

B. BRP with n reTries (BRP-Tn)

Intuitively, if a connection is blocked accidentally, it should get another chance to start afresh with a new wavelength from the wavelength pool previously created at the destination. So, when a failure is reported back to the destination by a FAIL packet, the destination selects another wavelength from the available pool, and a retry is made to find out whether the second wavelength is still available. This is shown in Figure 2. If this attempt fails too, another retry can be made, provided a third wavelength is available in the pool. The more the number of retries, the less the chance of blocking, and, hence, the better the performance. But retries will obviously turn the wavelength pool more outdated, and introduce some extra delay in the set-up process. Moreover, when the network is already congested at a high load, there will not be too many wavelengths available in the pool itself at the destination. With an aim to get around this problem with BRP, we have planned to introduce parallelism into the probing process, as described next.

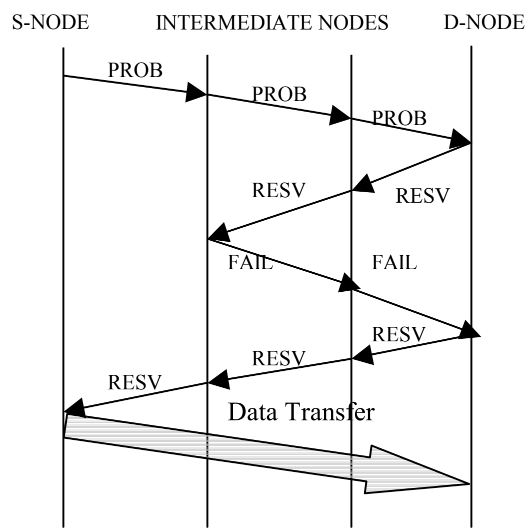

Fig. 2. BRP-T1 (n=1)

III. DESCRIPTION OF MBRP

As illustrated above, in conventional BRP, we probe only the first shortest path (SP) to establish a lightpath. But, in MBRP, we take advantage of fixed alternate routing and simultaneously probe multiple SPs in order to gather more network information simultaneously. The source sends multiple PROB packets (say PROB1, PROB2..., PROBm) on different shortest paths (SP1, SP2..., SPm). They may reach the destination out of order (due to IP routing). But it is more likely that they will reach in sequence because path lengths increase with 'm'. For the time being, let us assume that they reach in order.Retries can also be made with MBRP as it is done in conventional BRP. We use the following notations to explain MBRP operations further:

- RESV i-j: RESV packet corresponding to the j^{th} retry in the i^{th} path, i,j=1,2,3, …...
- FAIL i-j: FAIL packet corresponding to the j^{th} retry in the i^{th} path, i,j=1,2,3, …...
- SR_Sm-Tn**:** Sequential Reservation Scheme with 'm' shortest paths and 'n' retries per path.
- TR_Sm-Tn**:** Temporal Reservation Scheme with 'm' shortest paths and 'n' retries per path.

A. *Sequential Reservation (SR)*

In Sequential Reservation (SR) scheme, the destination, upon receiving PROB1, starts reserving on SP1. If reservation is successful, the source starts data transmission on SP1. On receiving the first data packet, the destination discards all other probe packets. If destination receives FAIL1-1 packet, the destination retries with another wavelength on SP1. This retry process can continue up to a maximum of 'n' times (n is predetermined) before the destination discards PROB1 and starts reservation attempts on SP2 (path corresponding to PROB2). This goes on until all the paths are explored or the destination gets the first data packet from the source. In this way, the reservation process follows the "Depth First" rule as depicted in Figure 3. If all the paths with subsequent retries are checked and no data packet is received at the destination, the connection request is declared as 'blocked'.

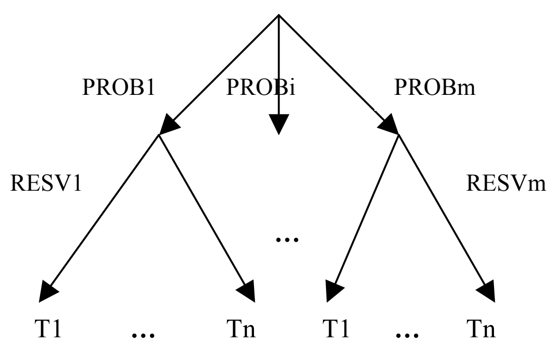

Fig. 3. SR follows Depth-First rule

Consider the case when m=2 and n=2 i.e., SR_S2-T2 (Figures 4 and 5). Here, two paths are simultaneously probed and two retries are allowed on each path, the reservation scheme being sequential. Timing diagrams for two specific instances are shown in Figures 4 and 5.

Now, suppose that the PROB packets reach out of order. Let us assume that PROBi reaches first, PROB1 next, PROBm next, and so on. In this case, the destination, upon receiving PROBi ($1 \leq i \leq m$), starts reserving on SPi. If reservation is successful, the source starts data transmission on SPi. On receiving the first data packet, the destination discards all other probe packets. If reservation remains unsuccessful even after all the retries on SPi, the destination begins to explore SP1. So it is **First Come First Serve** (FCFS) among the PROB packets only and each PROB is handled one-at-a-time till its retries are all exhausted.

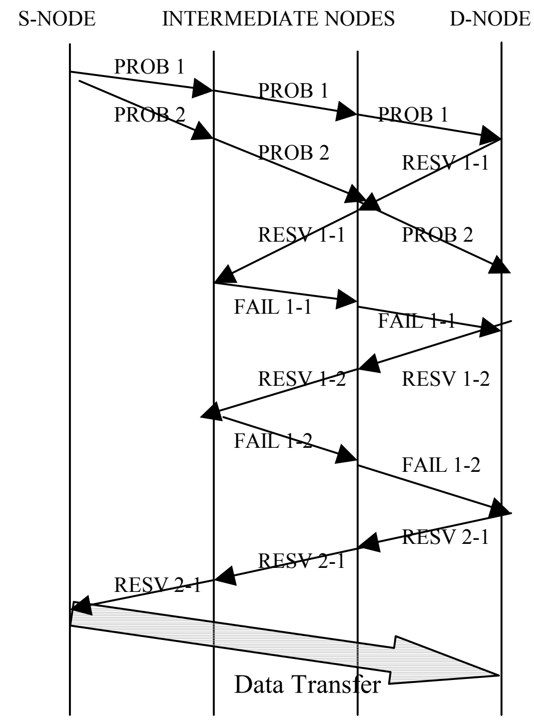

Fig. 4. Reservation in SR_S2-T2 (Reservation with retries in SP1 fails but reservation is successful in SP2)

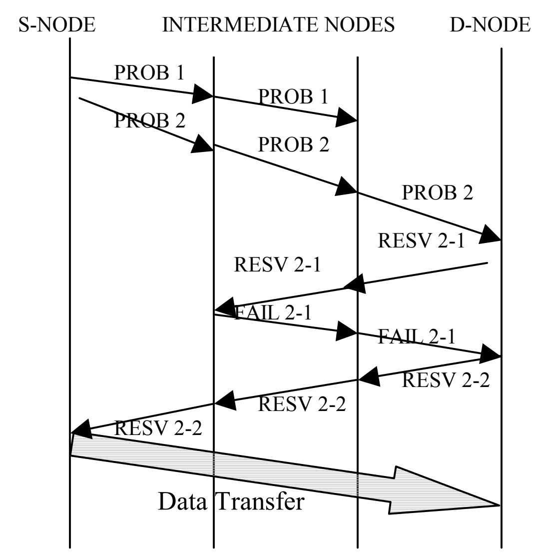

Fig. 5. Reservation in SR_S2-T2 (Probing fails in SP1 but reservation succeeds for second retry in SP2)

B. *Temporal Reservation (TR)*

In Temporal Reservation (TR) scheme, PROB packets are again handled in FCFS manner i.e., if PROBi reaches the destination first, the destination starts reservation on SPi (this event is similar to that in SR). If reservation is successful, the source starts data transmission on SPi. Upon receiving the first data packet, the destination discards all other probe packets. If reservation is unsuccessful on SPi, the destination receives FAILi-1 packet at a later stage. But, unlike SR, after receiving FAILi-1, it will not retry on SPi. Instead it will switch over to PROBk which has probably reached the destination by that time. So TR does not follow *depth first*; rather it follows *breadth first*.

Now let us illustrate TR in some more details. Suppose PROB1 reaches first and PROB2 next. The first attempt on SP1 fails and the destination receives FAIL1-1. Here the protocol will behave differently from SR, depending upon who (between PORB2 and FAIL1-1) reaches destination early. There is always a possibility that PROB2 will reach the destination before FAIL1-1. If PROB2 reaches destination before FAIL1-1, the destination waits until it receives first data packet on SP1 or FAIL1-1. If FAIL1-1 is received, it starts reservation on SP2 (this is different from SR). Otherwise, if FAIL1-1 reaches the destination before PROB2, the destination retries with another wavelength on SP1. As usual, this retry process can continue up to a maximum of 'n' times on each path. TR scheme goes on until all the retries on all the paths are explored or the destination gets the first data packet from the source. So, the reservation process follows the "Breadth First" rule (Figure 3).

If all the paths with subsequent retries are checked and no data packet is received at the destination, reservation is declared unsuccessful after it times out. Thus, TR scheme follows FCFS mechanism not among probing only but among probing plus retrying: *the packet which reaches first at the destination is processed first*. Thus, in TR, we switch between '(j+1)th retry on SPx' and 'fresh reservation on SPy' ($1 \leq x, y \leq m$), depending on whether FAILx-j packet or PROBy packet reaches the destination earlier than the other.

Let us now consider the case when m=2 and n=2 i.e. TR_S2-T2. It is explained in Figures 6 through 8. It is to be noted that, in Figure 7, PROB2 packet reaches the destination before packet FAIL1-1. So the destination sends the RESV2-1 packet before RESV1-2 packet. But in Figure 8, FAIL1-1 reaches destination before PROB2. So the destination sends the RESV1-2 before RESV2-1.

IV. Results and Discussions

We have tested MBRP in a simulation environment. Networks of arbitrary mesh topology are generated randomly with varying number of nodes and links. The number of wavelengths per fiber is assumed to be identical for all links in a network. Propagation delay over a link is assumed to be proportional to the length of the link, and processing delay at intermediate nodes is ignored.

The arrival of connection (call) requests follows Poisson distribution (i.e., call inter-arrival time follows exponential distribution). Call holding time (i.e., connection duration) is assumed to follow exponential distribution. If two requests arrive at the same time, they are processed in random order. Routing is fixed alternate in nature [18]. That is, all SPs for every source-destination pair are calculated in advance and are kept in local database tables. When more than one wavelength is available for assignment, random selection is done at the destination [4].

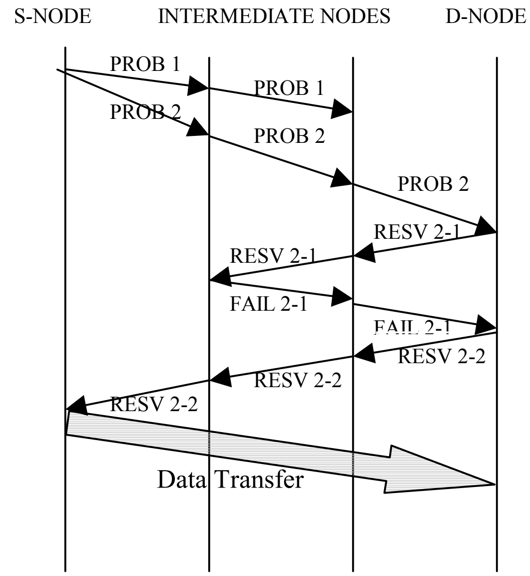

Fig. 6. Reservation in TR_S2-T2 (Probing fails in SP1 and reservation succeeds in second retry in SP2. It happens to be similar to reservation in SR_S2-T2 (Figure 5))

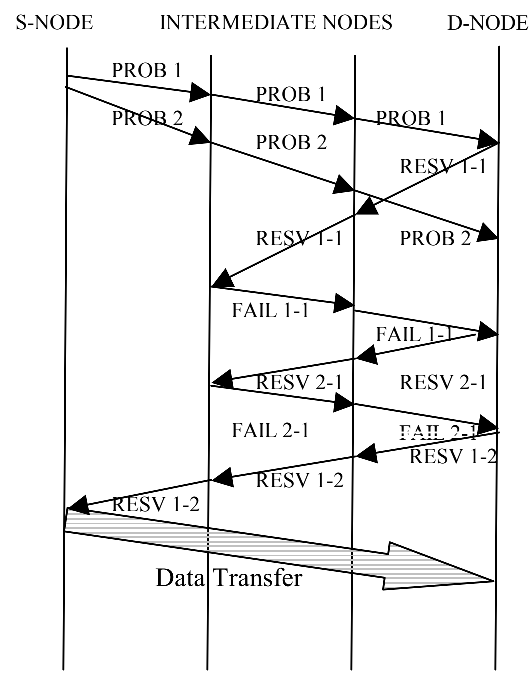

Fig. 7. Reservation in TR_S2-T2 (Reservation fails for the first time in SP1 and SP-2 but successful in second retry in SP1)

Networks of different sizes are tested with varying input conditions. We have varied the arrival rate from 50 (light traffic condition) to 500 (very heavy traffic condition) requests per second for dense networks and from 50 (light traffic condition) to 300 (heavy traffic condition) requests per second for sparse networks. Connection requests are assumed to have a mean service rate of 0.0032 second. Number of wavelengths per fiber is taken to be W=5, 10.

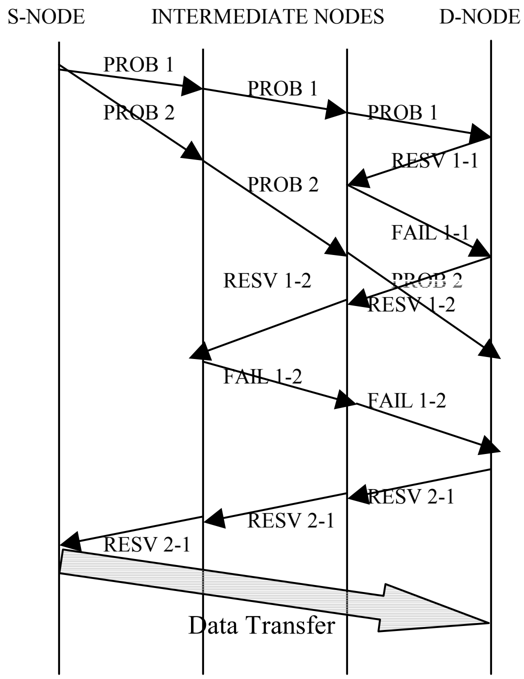

Fig. 8. Reservation in TR_S2-T2 (Reservation fails for all retries in SP1 but successful in SP2)

We use the following notations in presenting the simulation results:

PE: *Protocol Efficiency* (ratio of successful connection establishment attempts to total connection attempts that the network is tested with in an observation period).

ACP: *Average Control Packets* (ratio of total number of control packets in the network to the total number of requests that are tested with the network) per request.

ST: *Set-up Time* (difference between the time a request starts sending data and the time the request entered the network) of a request.

AST: *Average Set-up Time* (ratio of sum of STs of all the requests in the network to the total number of requests that are tested with the network) per request.

W: Number of Wavelengths per fiber.

LAMBDA: *Arrival rate* (Per second)

S3WIU: Selective 3 wavelengths with intermediate unlock protocol (variation of FRP) [10]-[12].

Sm: 'm' Shortest paths are considered.

Tn: 'n' reTries on each path.

It is interesting to note that normal BRP-Tn is the same as MBRP with S1-Tn (since only SP1 is considered, the question of SR or TR does not arise here).

We are primarily interested in comparing the reservation polices in terms of PE, ACP and AST with respect to LAMBDA and W. In all the simulation results presented here, W is taken as 10. If we describe the network as sparse network, it contains 20 nodes and 74 links connecting these nodes. If the network is described as dense, it contains 20 nodes and 152 links connecting these nodes.

TABLE I) P.E., AST AND ACP OF BRP-T3

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	99.19	0.24975	2.58
100	96.54	0.25278	3.03
150	93.29	0.24969	3.37
200	89.71	0.24306	3.69
250	86.17	0.23542	3.94
300	82.73	0.22784	4.16
350	79.17	0.21933	4.37
400	75.73	0.21062	4.56
450	72.33	0.20172	4.72
500	69.07	0.19303	4.86

TABLE II) P.E, AST AND ACP OF SR_S2-T1

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	91.15	0.22858	3.65
100	79.60	0.20299	4.16
150	70.22	0.17790	4.51
200	62.73	0.15849	4.79
250	56.99	0.14375	5.00
300	52.28	0.13174	5.17
350	48.21	0.12103	5.32
400	44.86	0.11165	5.43
450	41.61	0.10346	5.55
500	38.98	0.09621	5.63

TABLE III) P.E, AST AND ACP OF SR_S2-T2

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	99.59	0.25468	3.60
100	97.27	0.26542	4.16
150	93.53	0.26445	4.66
200	88.75	0.25676	5.14
250	83.88	0.24457	5.52
300	78.95	0.23116	5.86
350	73.71	0.21568	6.17
400	69.35	0.20174	6.41
450	65.31	0.19105	6.62
500	61.4	0.17957	6.82

Tables I through VII represent results for the dense network for BRP-T3 and different SR variations. In [10], it is already established that S3WIU performs best in FRP, and, in [3], it is established that BRP-T3 performs even better. We compare these protocols with variations of SR in Figure 9 and find that SR_S3-T3 performs better than BRP-T3 till LAMBDA=500.

TABLE IV) P.E, AST AND ACP OF SR_S2-T3

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	99.99	0.25519	3.59
100	99.59	0.27382	4.11
150	98.47	0.28667	4.60
200	95.69	0.28852	5.11
250	91.85	0.28218	5.55
300	87.39	0.27059	5.9
350	83.16	0.26024	6.26
400	78.86	0.24698	6.52
450	74.22	0.23371	6.82
500	70.47	0.22203	7.11

TABLE V) P.E, AST AND ACP OF SR_S3-T1

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	96.21	0.25722	4.77
100	87.11	0.24665	5.51
150	77.60	0.22334	6.10
200	69.63	0.20222	6.55
250	63.11	0.18186	6.88
300	57.88	0.16766	7.17
350	53.34	0.15397	7.39
400	49.63	0.14403	7.59
450	46.35	0.13471	7.75
500	43.29	0.12492	7.9

TABLE VI) P.E, AST AND ACP OF SR_S3-T2

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	99.97	0.25785	4.60
100	99.21	0.28160	5.23
150	97.08	0.29537	5.87
200	93.09	0.29806	6.59
250	88.24	0.28883	7.18
300	82.84	0.27446	7.67
350	77	0.25539	8.12
400	71.74	0.23855	8.39
450	67.11	0.22273	8.78
500	63.31	0.20924	8.95

PE of S3-T3 increases by more than 50% over S3WIU and more than 8% over BRP-T3 when LAMBDA=200. The percentage increase in PE with respect to BRP-T3 decreases as we increase LAMBDA beyond 250.

Interestingly, from Tables II through VII, we observe that SR_S2-T3 is performing better than others at very high load conditions (at LAMBDA ≥ 350). From Figure 10, we observe that SR_S2-T3 outperforms SR_S3-T3 when LAMBDA > 450 for the dense network. But, in Figure 11, as it is a sparse network, SR_S2-T3 outperforms SR_S3-T3 at LAMBDA > 200. In a sparse network, since the number of links is less, the PE of SR variations decreases qucikly, when compared to the PE of the corresponding variations of the dense network (Figure 11).

TABLE VII) P.E, AST AND ACP OF SR_S3-T3

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	100.00	0.25525	4.59
100	99.97	0.27805	5.12
150	99.60	0.29941	5.66
200	97.59	0.31223	6.32
250	94.31	0.31083	6.98
300	89.35	0.30448	7.49
350	84.29	0.28985	8
400	79.35	0.27461	8.46
450	74.29	0.25794	8.79
500	69.37	0.24206	9.04

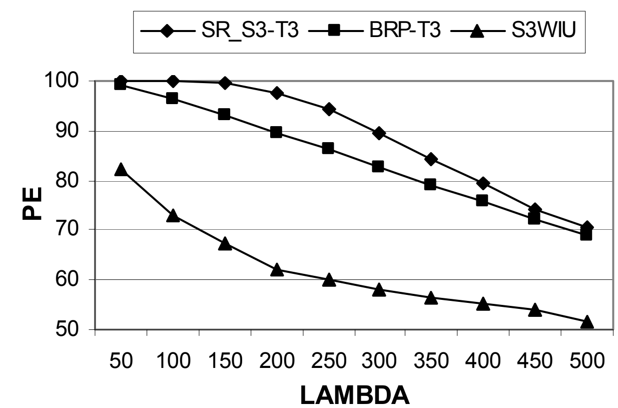

Fig. 9. Comparison of PEs of S3WIU, BRP-T3 and SR variation SR_ S3-T3 *(Nodes=20, W=10, Dense Network)*

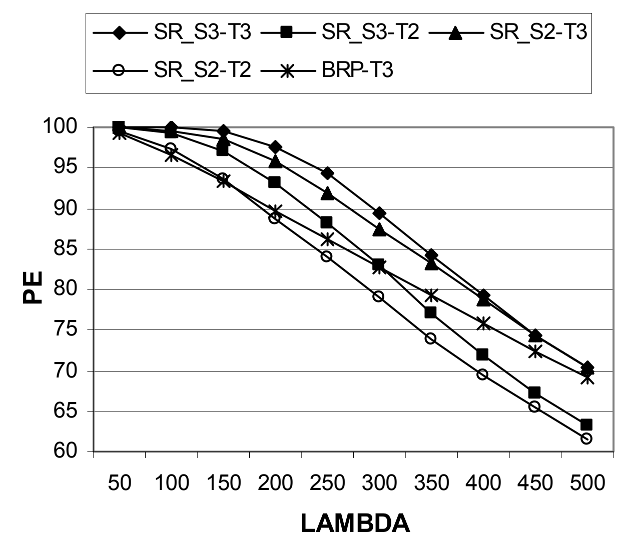

Fig. 10. Comparison of PEs of BRP-T3 and SR variations S2-T2, S2-T3, S3-T2, S3-T3 *(Nodes=20, W=10, Dense Network)*

Now we provide the simulation results (Tables VII through XIV) for TR variations in a dense network. From Figure 12, unlike the trend we have noticed in Figure 10, we observe that

PE of BRP-T3 is higher than other variations at a very high lambda. For lambda ≤ 250, S3-T2 and S3-T3 variations of TR are performing better than BRP-T3. Here, TR_S2-T3 variation outperforms all other protocols. As discussed earlier, in a sparse network, since the number of links connecting the nodes is less, PE of variations in this network decreases expectedly when compared to the corresponding variations in the dense network.

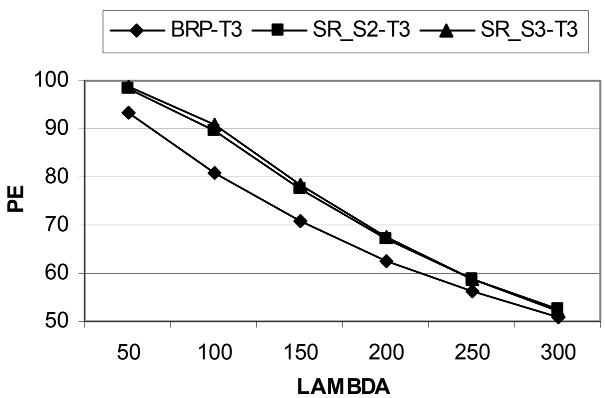

Fig. 11. Comparison of PEs of BRP-T3 and SR variations S2-T3, S3-T3. *(Nodes=20, W=10, Sparse Network)*

TABLE VIII) P.E, AST & ACP OF TR_S2-T1

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	91.21	0.22892	3.65
100	79.65	0.20310	4.16
150	70.27	0.17854	4.51
200	62.65	0.15864	4.79
250	57.00	0.14361	5.00
300	52.11	0.13114	5.18
350	48.3	0.12117	5.31
400	44.83	0.11185	5.43
450	41.6	0.10335	5.54
500	38.95	0.09623	5.63

TABLE IX) P.E, AST AND ACP OF TR_S2-T2

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	99.63	0.26737	3.71
100	97.29	0.28595	4.41
150	93.03	0.28598	5.03
200	88.09	0.27880	5.58
250	82.81	0.26583	6.06
300	77.71	0.25264	6.5
350	72.41	0.23515	6.84
400	68.14	0.22338	7.15
450	63.92	0.21074	7.43
500	60.25	0.19956	7.69

Figure 13 exhibits that TR_S2-T3 is the best among all the TR variations, but BRP-T3 outperforms it at LAMBDA > 200. We do not consider the protocols beyond T3 because it was shown in [12] that retries more than 3 do not pay off much in terms of efficiency.

From the above results, we may conclude that SR_S2-T3 is the best among the SR variations and TR_S2-T3 is the best among TR variations. Now, we will compare these variations with the already existing best variation (i.e., BRP-T3) of BRP and variation with maximum efficiency in FRP (i.e., S3WIU) in a dense network in Figures 14 through 16.

TABLE XI) P.E, AST AND ACP OF TR_S2-T3

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	99.99	0.26993	3.71
100	99.71	0.30332	4.46
150	97.57	0.32031	5.28
200	93.41	0.32080	6.13
250	88.17	0.31314	6.83
300	83.48	0.30084	7.53
350	78.45	0.28656	8.11
400	73.61	0.2728	8.61
450	68.66	0.25737	9.1
500	64.32	0.24348	9.47

TABLE XII) P.E, AST AND ACP OF TR_S3-T1

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	96.30	0.25781	4.76
100	86.96	0.24609	5.52
150	77.66	0.22355	6.09
200	69.70	0.20237	6.54
250	63.16	0.18234	6.87
300	57.66	0.16682	7.17
350	53.47	0.15408	7.38
400	49.57	0.14326	7.59
450	46.46	0.13476	7.75
500	42.87	0.12343	7.92

TABLE XIII) P.E, AST AND ACP OF TR_S3-T2

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	99.98	0.27642	4.76
100	99.25	0.32014	5.69
150	96.57	0.34130	6.63
200	91.94	0.34311	7.59
250	85.95	0.33218	8.49
300	79.73	0.3144	9.31
350	73.13	0.29462	10.09
400	67.47	0.27522	10.62
450	62.59	0.25666	11.04
500	57.89	0.24223	11.42

In Figure 14, we observe that, among MBRP variations, SR_S2-T3 outperforms others, and if we are to rank the MRBPs in terms of decreasing PE, the ranking goes like this: a) SR_S2-T3, b) SR_S3-T3, and c) TR_S2-T3.

We next compare AST and ACP of these variations in Figures 15 and 16. Figure 15 tells us that AST of SR_S3-T3 is the maximum. Also, as ASTs of FRP is much lower than BRP variations, S3WIU has the minimum AST among different protocols under comparison. From Figure 15, if we are to rank MRBPs in terms of increasing AST, the ranking goes like this: a) TR_S2-T3, b) SR_S2-T3, and c) SR_S3-T3.

TABLE XIV) **P.E**, AST AND ACP OF TR_S3-T3

LAMBDA(/sec)	P.E.	AST (mSec)	ACP
50	100.00	0.27654	4.76
100	99.95	0.32767	5.71
150	98.81	0.36667	6.87
200	94.65	0.38139	8.39
250	88.24	0.37737	9.99
300	81.37	0.36159	11.35
350	74.25	0.3407	12.41
400	67.6	0.3179	13.2
450	61.76	0.29671	13.73
500	56.52	0.27578	13.93

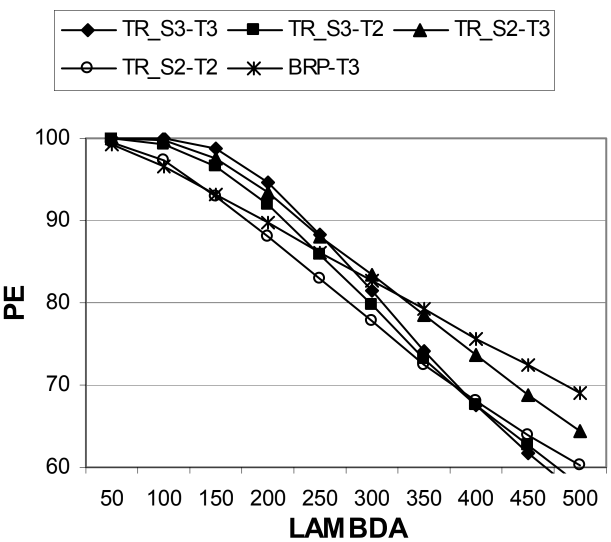

Fig. 12. Comparison of PEs of BRP-T3 and TR variations S2-T2, S2-T3, S3-T2, S3-T3 *(Nodes=20, W=10, Dense Network)*

From Figure 16, we observe that ACP of SR_S3-T3 is the maximum and S3WIU is the least. The reason for the behavior of different protocols in Figure 16 with varying lambda is that, in SR_S3-T3, we are trying at most 9 times (3 retries on 3 paths) to establish a lightpath. This increases the control overhead in the network as, for each retry, we are sending a RESV packet, and, for each failure, we are generating a FAIL packet. Now, as we move to SR_S2-T3 variation, we are trying at most 6 times (3 retries on 2 paths). This further decreases in case of BRP-T3 and, for S3WIU variation of FRP, this is further reduced.

It is interesting to note that BRP-T3 is a steady performer even under a heavy load. This is probably because multipath probing creates too many control packets to congest the network, which is already resource crunched at a high load. But, at moderate load, SR_S2-T3 looks more attractive. So we may think of an adaptive MBRP, where the number of paths to be probed is controlled dynamically with respect to the arrival rate. As the rate increases, 'm' increases and 'n' decreases and vice versa.

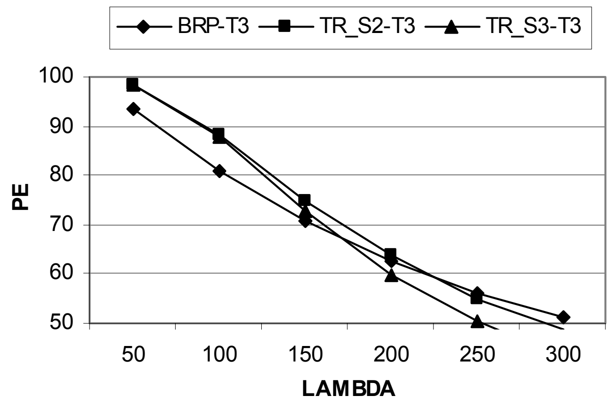

Fig. 13. Comparison of PEs of BRP-T3 and TR variations S2-T3, S3-T3. *(Nodes=20, W=10, Sparse Network)*

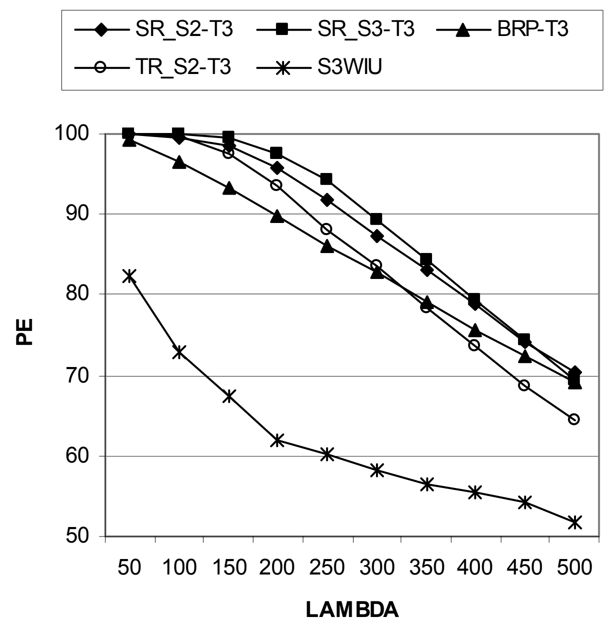

Fig. 14. Comparison of PE of SR_S2-T3, SR_S3-T3, TR_S2-T3, BRP-T3 of BRP and S3WIU of FRP

V. CONCLUSIONS

This work proposes a multipath variation of the conventional Backward Reservation Protocol (BRP) for dynamic lightpath establishment in IP-over-WDM (wavelength division multiplexed) optical networks. It uses simultaneous probing in multiple fixed alternate routes from source to destination. Depending upon the order in which the searching is done, MBRP has two variants, namely SR and TR. In general, SR is performing better than TR because TR prefers breadth to depth, which results in oscillation between paths. This causes TR unnecessarily losing out a potential path at a higher depth because of delayed exploration of the path. Hence, TR also results in better PE. However, the high rate of obsolescence of the information gathered via probing plays a crucial role here in deciding the ultimate success rate (i.e., PE). There may be another reason that, in SR, we are first checking whether we can establish a lightpath in the shortest possible path and then advancing to next shortest path. But, in the case of TR, we are using FCFS mechanism strictly. It may so happen that, while checking for longer paths, the RESV packet may reserve wavelengths for longer time thereby decreasing the PE in TR variations, when compared to SR variations.

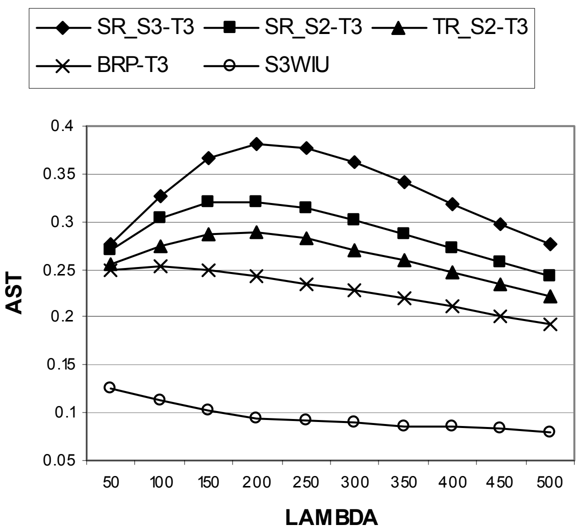

Fig. 15. Comparison of AST of SR_S2-T3, SR_S3-T3, TR_S2-T3, BRP-T3 of BRP and S3WIU of FRP

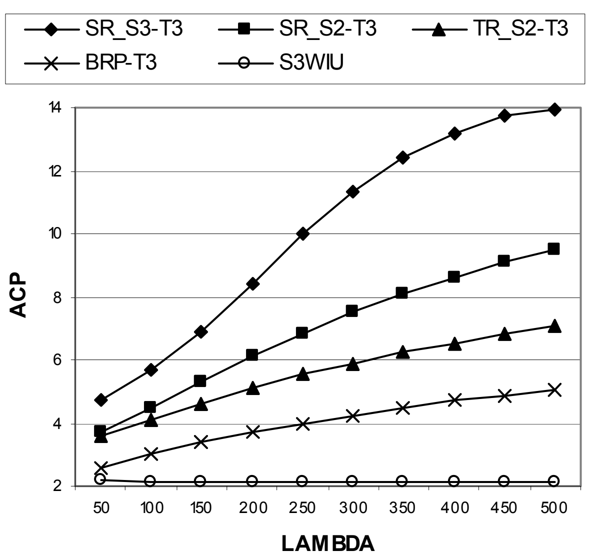

Fig. 16. Comparison of ACP of SR_S2-T3, SR_S3-T3, TR_S2-T3, BRP-T3 of BRP and S3WIU of FRP

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