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Resource Reservation Techniques in WDM Optical Networks: A Comprehensive Survey

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Abstract— **In WDM optical networks, wavelength is the critical resource for efficient communication of traffic. Hence, suitable protocols are required to allocate and use the wavelengths efficiently. We have studied the protocols already developed and reported in literature, for such networks, and considering the historical development, we have outlined some generalized classification for them. We have also provided comparison of their performances. Finally, on the basis of the previous works, we have discussed some future scopes, which may be explored for further improvement in performance of the protocols.**

***Index Terms*—Optical networks, WDM, aggressiveness, blocking probability, vulnerable period, wavelength reservation protocol,**

I. INTRODUCTION

In distributed WDM optical networks [1]-[4] having no wavelength conversion facility [5], usually a dedicated lightpath is first established between the source node (*source*) and destination node (*destination*), before the actual data transfer starts. A continuous path, having the same wavelength reserved in all the hops of the route, is called a lightpath. Lightpath establishment [1] involves three basic steps: (i) routing, (ii) wavelength selection and (iii) wavelength reservation. In this work, we do not explore routing and consider it to be always fixed shortest path. Requests for lightpath establishment are normally blocked due to non availability of wavelengths due to insufficient network capacity. Non availability of wavelengths may also occur due to wavelength collision, when two or more requests try to reserve the same wavelength without noticing the other free wavelengths. Thus, the method of selection of wavelength is very important to avoid wavelength collision among concurrent requests. It indirectly improves the sharing of wavelengths (a critical resource in WDM networks), and, hence, reduces blocking of requests. Though different methods are used for selection of wavelength for reservation, two conventional methods are: *random-fit* and *first-fit* [5],[8]. Two other notable methods are label prioritization [6] and probabilistic selection using *Markov model* [7].

Once a wavelength is selected, its successful reservation is also very crucial. In a large distributed system like WDM network, information about wavelength availability is difficult to be guaranteed at any particular place and time. So, to handle this issue, several reservation protocols are reported at different points of time. A reservation protocol reserves a wavelength throughout the route before data transfer starts so that uninterrupted data transfer can take place. In general, all the reservation protocols suffer from the major problem of uncertainty of availability of selected wavelength. So a lightpath is established reserving a wavelength for the whole path before transmission of data.

For lightpath establishment, in forward reservation protocols, reservation is initiated from *source*. So reservation is done much before the actual use of the wavelength for data transmission. This leads to *over reservation* because, reservation for longer period of time may cause scarcity of available wavelengths for other concurrent requests. To reduce *over reservation*, backward reservation protocol was proposed [2] where reservation is initiated from *destination* after successful probing from *source* to *destination* (*forward path*). But successful probing does not always guarantee the availability of wavelength during reservation from *destination* to *source* (*backward path*). Probing is done to check the availability of wavelength(s). Now, a particular wavelength, which was available during probing, may not be available, while being attempted for reservation. The selected wavelength may be occupied by some other request within this interval between probing and attempt of reservation. The interval between probing and attempt of reservation is known as *vulnerable period*. The uncertainty in availability of wavelength during reservation increases with increase in *vulnerable period*. To reduce the *vulnerable period*, wavelength(s) may be reserved much earlier in the *forward path*, but that increases the *reservation duration*. The duration for which wavelength is reserved prior to actual data transfer, is called *reservation duration*. If *reservation duration* is increased then wavelength is reserved for a longer period of time which increases *over reservation*. Due to *over reservation* other requests may not get the free wavelengths, and, hence, overall blocking increases. Thus, reservation should be done in such a way that both *vulnerable period* and *reservation duration* are optimised. This is the most important challenge for a reservation scheme. In some schemes, reservation of wavelength is initiated from *intermediate nodes* to balance *reservation duration* and *vulnerable period*. Also, in some protocols, instead of one, a number of wavelengths (denoted by *aggressiveness*) are attempted for reservation so that at least one wavelength can be successfully reserved throughout the route. But *aggressiveness* reserves more

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resource (wavelength) and causes blocking of other concurrent requests. Thus, *aggressiveness* is also needed to be optimized.

In distributed systems, periodical information flooding in the entire network or other form of information exchange among the nodes takes place. Information regarding wavelength availability on some links at any place and time may not be absolutely correct in a distributed system. This occurs because- (i) information regarding wavelength usage status at links is broadcast only periodically and (ii) due to propagation delay the information becomes outdated upon arrival. But the performance of a protocol is very much dependent on the update of the information being used. Hence, utilisation of updated information in a network is another important aspect in any protocol. This challenge is inherent to all the distributed reservation schemes.

The paper is organized as follows. Taxonomy of protocols is discussed in Section II. Working principle of some standard protocols are described and their performances are compared in Section III. In Section IV, modified protocols are presented, and, in Section V, conclusion and future scope of work are outlined.

II. TAXONOMY

Since we have considered fixed shortest path routing, using the remaining two key issues, namely wavelength selection and wavelength reservation, a classification of protocols is done. This attempt of classification may not be fully exhaustive, however, it covers prominent protocols widely used and reported in recent past.

Some important wavelength selection methods are: (i) *first-fit*, (ii) *random-fit*, (iii) *prioritised* and (iv) *probabilistic* (Fig.1).

For the *first-fit* method, all wavelengths are indexed. The wavelength with lowest index is always selected from the available set of wavelengths. Practically, in dynamic traffic situation, *first-fit* method effectively becomes biased towards the lower index [9],[11] which increases the probability of blocking. However, the method is straightforward and simple.

In *random-fit*, from the available set of wavelengths, one wavelength is selected randomly. All wavelengths carry equal probability of being selected, so that wavelength utilisation becomes balanced. Contention problem related to wavelength, is low for random selection method, resulting lower blocking rate. *Random-fit* is widely used, and it performs well [21], [24].

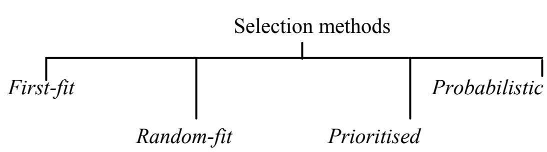

Fig.1: Classification of selection methods

Prioritised method [6] assigns different priorities to the wavelengths to be selected for reservation to each request. Each node maintains three sets of wavelengths : Used Pool (UP), Available Pool (AP) and Flagged Pool (FP). Wavelengths which are currently being used for transmission are kept in UP, free wavelengths are kept in AP and candidates for future reservation are kept in FP. Wavelengths remain in FP for a shorter duration defined by the time required to reserve the wavelengths by the concerned requests. Now, for a request, probing is done in the *forward path* and during the process, wavelengths of AP are labeled as Label selection (LS) and wavelengths at FP are labeled as Flagged Selection (FS). Wavelengths labeled as FS are numbered as, FS(0), FS(1), … , FS(n) for n number of such wavelengths according to their priorities based on appearances in the nodes. Now the *destination* selects a wavelength for reservation from LS, if LS is nonempty. If there is more than one wavelength in LS, then one wavelength is selected randomly. However, if LS is empty, FS(0) is selected. This *prioritization* scheme cannot eliminate blocking, during reservation, but can reduce it.

No systematic prediction for successful reservation of wavelength is done in the above mentioned methods. For example, in case of *random-fit*, no prediction is done for successful reservation of wavelength. So the probability of selection remains equal for all free wavelengths. A prediction is used to achieve more successful reservation in *probabilistic* method. This *probabilistic* method applies Markov method of selection of wavelength [7],[10] using Continuous Time Markov chain for each link. Using this Markov chain, wavelength usage is predicted at some arbitrary point of time, and the wavelength with highest probability of remaining free, is selected. Thus, wavelengths are selected probabilistically.

For wavelength reservation, two important aspects are, (i) position of initiation of reservation and (ii) *aggressiveness* used in reservation.

Since the position of initiation of reservation is an important parameter, to express the position in a general way, here a parameter x is used. The value of x is any real number between and inclusive 0 and 1. If d is assumed as the distance (either in number of hops or in physical length) between *source* and *destination* of a route, then the product ($x*d$) decides the position of initiation of reservation. Depending on the values of x, Reservation Protocols (RP) can be classified into three categories.

- For x=0, reservation is initiated at *source* and such protocol is called Source Initiated Reservation Protocol (SIRP). This is also called Forward Reservation Protocol (FRP) [8], [24].
- For x=1, reservation is initiated from *destination* and such protocol is called Destination Initiated Reservation Protocol (DIRP) which is also reported as Backward Reservation Protocol (BRP) in literature.
- For $0<x<1$, reservation is initiated from any node between *source* and *destination* (*intermediate node*) and such protocol is called Intermediate Node Initiated Reservation Protocol (INIRP) [10],[20],[29],[30],[37],[38].

Depending on how the *intermediate nodes* are selected for reservation, INIRP may again be classified into two ways:

- static and
- dynamic.

Static implies that the initiation of reservation from *intermediate nodes* is done statically. In other words, the initiation of reservation takes place only from some predefined nodes. This is implemented and reported as *Intermediate node* Initiated Reservation Protocol (IIRP) [29],[30].

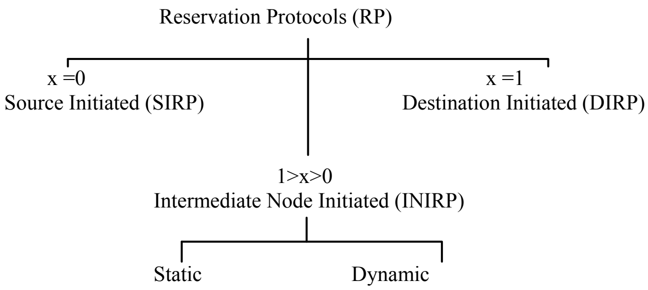

Fig.2: Classification of reservation protocols depending on initiation of reservation.

In dynamic INIRP, the nodes, from where the initiation of reservation takes place, are not predefined, rather decided dynamically. Classification based on initiation of reservation is shown in Fig.2.

Aggressiveness is another important parameter and is used to improve the probability of success of reservation. *Aggressiveness* may vary from most conservative (when only one wavelength is attempted for reservation) to most aggressive (when all the available wavelengths are attempted for reservation). However, in some work, an optimum number of wavelengths (b) are attempted for reservation (multiple wavelengths) instead of considering either conservative or most aggressive. Thus, the use of *aggressiveness* on SIRP and DIRP results in their four variations (Fig.3) as shown below:

- Source Initiated Single wavelength Reservation Protocol (SISRP),
- Source Initiated Multiple wavelength reservation Protocol (SIMRP),
- Destination Initiated Single wavelength Reservation Protocol (DISRP) and
- Destination Initiated Multiple wavelength Reservation Protocol (DIMRP).

These protocols, SISRP, SIMRP, DISRP and DIMRP are developed, compared and reported in different literature [11]-[24].

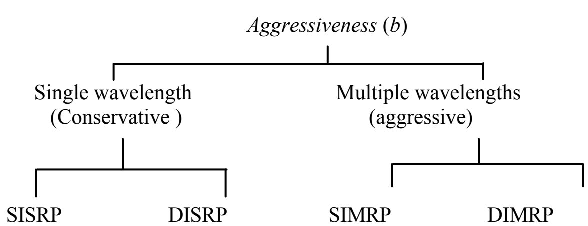

Fig.3: Classification of reservation protocols depending on *aggressiveness*.

Among the different selection methods as shown in Fig.1, *random-fit* and *probabilistic* (Markov selection) are used in some recent works reported in literature. Those are considered in our classification. Now if these two methods of selection are applied on DISRP and dynamic INIRP, following protocols emerge:

- DISRP with random selection (reported as BRP)
- DISRP with Markov selection (reported as MBRP)
- Dynamic INIRP with random selection (reported as Split Reservation Protocol (SRP))
- Dynamic INIRP with Markov selection (reported as Markov based Split Reservation Protocol (MSRP)).

The above mentioned protocols along with modified schemes are proposed in literature, which are discussed here.

III. BASIC PROTOCOLS

The basic protocols SIRP, DIRP and INIRP are discussed in this section. Different control packets are used to describe the schemes. The names and basic functions of such control packets are shown in Table-1. However these control packets are also used with additional tasks as and when required by the modified protocols.

Table-1 : Control packets used to describe the protocols

Name	Description
PROB	moves from *source* towards *destination*, contains probe results.
RES	moves towards *source* or *destination* to reserve wavelength.
RES_FWD	generated after splitting, moves towards *destination* to reserve wavelength.
RES_BKD	generated after splitting, moves towards *source* to reserve wavelength.
ACK	moves towards *source* , caries acknowledgement.
NACK	moves towards *source*, caries not acknowledgement.
REL	moves towards *source* or *destination* to release the reserved wavelength.
NACK_REL	moves towards *source* to release the reserved wavelength, caries not acknowledgement of RES_FWD.
REL_FWD	moves towards *destination* to release the reserved wavelength if RES_BKD fails.
REL_BKD	moves towards *source* to release the wavelength reserved so far if RES_FWD fails, caries not acknowledgement also.
DATA_TRANS	transmits data packet from *source* to *destination*

A. Source Initiated Reservation Protocol (SIRP)

In SIRP, a RES is initiated from the *source* for reservation of wavelength(s). RES moves in the *forward path*. Initially, RES carries a field named as *reserve_set* which contains the set of b (b>0) number of wavelengths selected for reservation. Reservation is attempted for b wavelength(s) by the nodes present in *forward path.* If the value of b is one (conservative), the protocol is SISRP and if b is more than one (aggressive), the scheme becomes SIMRP. However, at any link, if any of the b wavelengths becomes unavailable, the wavelength is excluded from *reserve_set* and the updated set is kept in RES. If RES reaches the *destination*, with a non null *reserve_set*, at least one wavelength throughout the route is guaranteed to be reserved. *Destination* then selects a wavelength from the *reserve_set* and generates an ACK. ACK moves along the *backward path* and releases all the wavelengths except the selected wavelength in the *backward path*. After receiving the ACK, *source* initiates data transmission.

During reservation, if RES fails at any node, i.e., none of the *b* wavelengths remains available in the *next link* (defined as the link, which connects the *present node* and the *next node*) and *reserve_set* becomes empty, the request is blocked. RES is then converted to NACK, which moves back to *source* and carries the information regarding the wavelength(s) to be released. The nodes on the *backward path* releases the wavelength(s) reserved so far, using the information in NACK.

The timing diagrams of the above scheme for successful and failed cases are shown in Fig.4 and Fig.5, respectively. In Fig. 5, *fp* represents the point of failure. In the subsequent figures also *fp* is used to indicate point of failure.

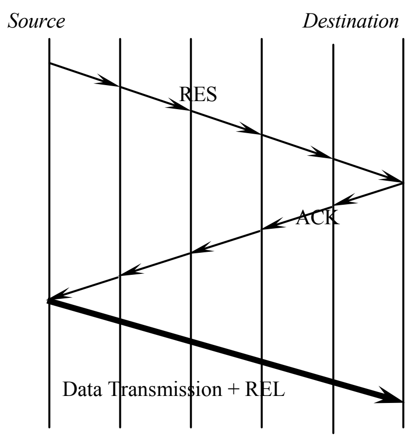

Fig.4: Case of success for SIRP

Blocking probability (*bp*) is one of the most important parameters to measure the efficiency of any protocol [24]-[27] and is defined as the ratio of unsuccessful (i.e., blocked) requests to total requests arriving in a network over a period of time. In SIRP, blocking can occur only in the *forward path*. Such blocking may arise due to (i) insufficient network capacity (when wavelengths are not available, due to scarcity) and (ii) *over reservation* (when more than one wavelengths are reserved in the *forward path*). Performance of SIRP [28], in respect of *bp*, for different values of average request arrival rate (*cr*) is reported. It is found that, with increase of *cr*, *bp* increases up to a certain value, beyond which, it gets saturated. It indicates that as *cr* increases, SIRP suffers from *over reservation* that deprives other requests of getting free wavelengths.

B. *Destination Initiated Reservation Protocol (DIRP)*

The protocol, in which reservation is initiated from *destination* of a route, is called DIRP. In DIRP, *source* of a route initiates PROB which is used to extract information about the availability of wavelength(s) in all the links of the route. PROB contains a field called *prob_set* which carries the set of available wavelengths during probe. The *source* probes the first link of the route and initializes *prob_set* with the available wavelengths in that link and transmits PROB to the *next node*. Each node after receiving the PROB takes the intersection of the set of available wavelength(s) on its *present link* (*present link* is defined as, the link which connects the *previous node* and *present node*) with that of *prob_set*. The *prob_set* is updated with the result of this intersection. Then PROB is transmitted to the *next node*. Thus, the set of wavelengths in the *prob_set*, always indicates the common set of available wavelengths, for the links through which PROB has passed.

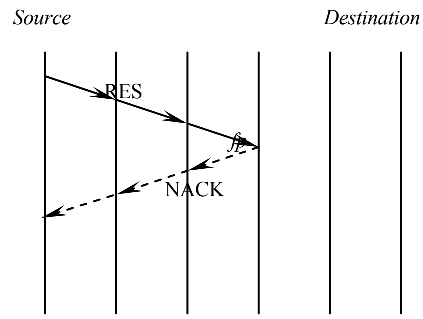

Fig.5: Case of failure for SIRP

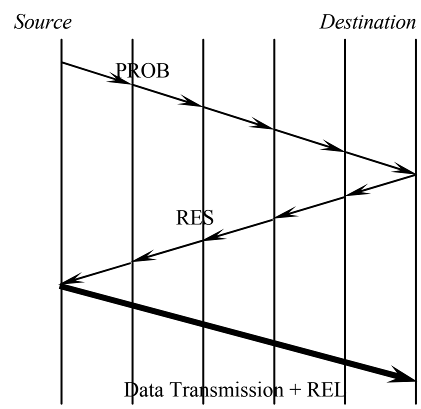

Fig.6: Success for DIRP

Now, if *prob_set* becomes null, anywhere before the PROB reaches the *destination* (indicating that no free wavelength is further available), the request is blocked. Then PROB is converted to NACK, and that moves back to *source*.

On the other hand, if PROB reaches *destination*, *destination* selects one wavelength from *prob_set*. For selection of wavelength any standard method is used. *Destination* then sends a RES towards *source* to reserve the selected wavelength, throughout the route. If RES successfully reaches the *source*, transmission starts. Once the transmission is over, the wavelength reserved for transmission, is released. This is shown in Fig.6.

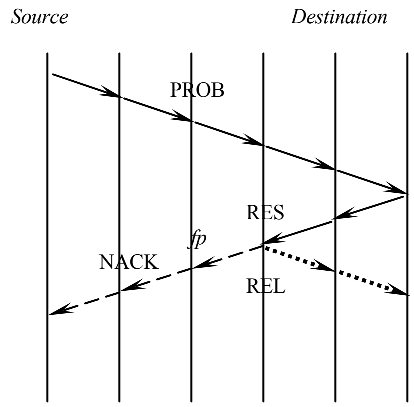

Fig.7: Reservation failure in DIRP

On the way to *source*, if reservation attempt of any node fails to reserve the selected wavelength, a NACK is generated and sent towards *source*. The request is blocked if no retry is attempted. In that case, one REL is also generated and sent towards *destination*, so that the nodes present on its way can release the wavelength(s) reserved so far. Fig.7 represents the timing diagram for this case of failure.

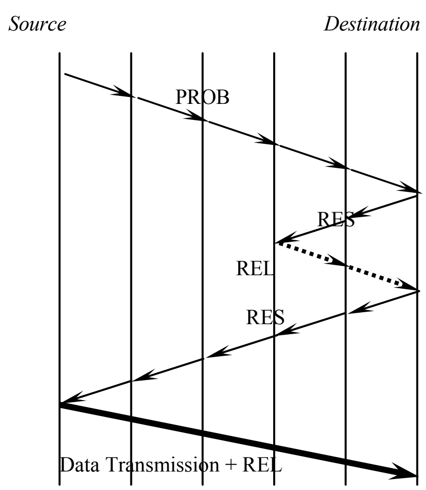

Fig.8: Case of success after one retry in DIRP

In DIRP with retry, for similar situation (if RES fails), RES is converted to REL, which returns to the *destination*, releasing the wavelength reserved so far. *Destination* then sends a fresh RES (retry) towards the *source*, selecting another wavelength from the *prob_set*. This may be repeated for a number of retries till a retry becomes successful, or, until all possible retries are exhausted. If all the retries fail, a NACK is generated and sent to the *source*. A case of success using one retry is shown in Fig.8.

A request may be blocked in DIRP, either in *forward path* (i.e., during probing) or in *backward path* (i.e., during reservation). A PROB may fail due to non-availability of wavelength. Non availability of free wavelength during probing may occur either due to insufficient network capacity or due to collision of wavelengths among the concurrent requests. On the other hand, failure of RES in *backward path* may occur due to non-availability of the selected wavelength. This may happen because, during *vulnerable period*, some other requests may reserve the selected wavelength. However, due to reduced *reservation duration*, DIRP performs better than SIRP for the same network environment.

C. Intermediate Node Initiated Reservation Protocol (INIRP)

DIRP attempts to reserve the selected wavelength in *backward path* after the wavelength is probed in *forward path*. So *vulnerable period* is long for DIRP and that is the limitation of DIRP. On the other hand, the main disadvantage of SIRP is *over reservation* due to longer *reservation duration*. To minimize the effect of both, reservation of wavelength may be initiated from *intermediate node* and such protocols are already mentioned as INIRP.

IIRP is basically static INIRP, which allows the reservation to be initiated by a predefined set of *intermediate nodes*. These predefined *intermediate nodes*, denoted as special nodes, have adequate wavelength usage information of the entire route of a request. When a PROB proceeds in the *forward path* and reaches the first special node, the node initiates a fast RES in the backward direction towards *source*. This RES tries to reserve a particular wavelength (say w_1, selected from *prob_set*) up to *source*. The PROB then proceeds further until it reaches the next special node or the *destination*.

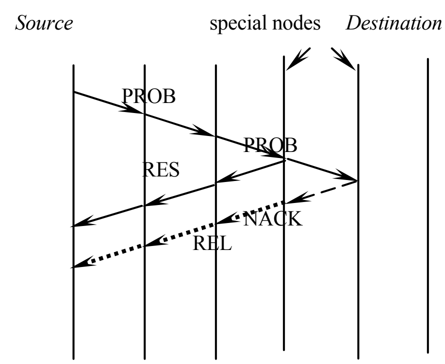

Fig.9: PROB failure after crossing the first special node, in IIRP

In next special node, the node checks the availability of w_1. If it is available, then this special node initiates another RES which moves towards previous special node reserving the same wavelength w_1. However, if w_1 is not available, the node selects another available wavelength (say w_2, selected from *prob_set*) and initiates a new RES, which moves towards *source* and reserves w_2. This new RES also releases w_1 reserved by the previous RES of this request. This is repeated, until the PROB reaches *destination*. The *destination* then initiates the normal RES, to reserve either previously selected wavelength (if that is still available), or a new wavelength, from the *prob_set*. Failure cases may arise due to non-availability of wavelengths during PROB, or during reservation. In such cases, REL is used to release the reserved wavelengths (if any) by this request. Schematic presentation of different cases of IIRP is given in Fig.9 and Fig.10.

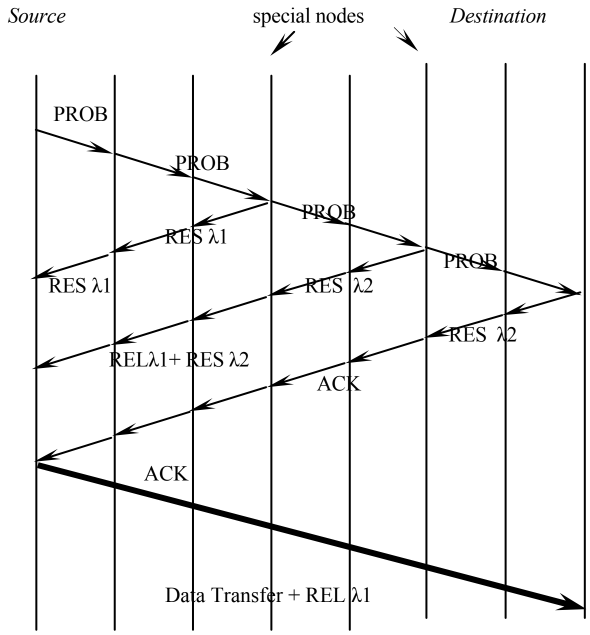

Fig.10: Case of success in IIRP after using two special nodes and successful for second wavelength.

In [29],[31], performance of IIRP is compared with DIRP and SIRP, and reported that IIRP performs better than SIRP and DIRP [Fig.11]. But IIRP suffers from extreme cases, because reservation from an intermediate special node is initiated unconditionally. For example, for a particular request, if a special node exists next to the *source* of the route, it initiates backward reservation after traversing one hop only then the case is almost like SIRP. Hence, it suffers from *over reservation* resulting increase in *bp*. Similarly, if the first special node exists just before *destination*, for a particular route, it initiates the fast RES when only one hop is left and thus probability of getting any free wavelength is reduced due to long *vulnerable period*. This case is close to DIRP.

The study of SIRP, DIRP and IIRP are also supported by the analytical models presented in literature [22]-[23],[26]-[27]. These analytical models explain the characteristics of the schemes. Also, the delay analysis helps to get a futuristic idea for any new protocol to be proposed.

J. Ahmad et. al. have reported [31] the comparisons of different distributed wavelength reservation protocols. In this report, the working principles of SIRP, DIRP and IIRP are considered for comparison on the basis of some important performance parameters, which are *bp, average latency* and *average control overhead*. They have investigated the performance issues and tradeoffs involved in implementation of distributed wavelength reservation schemes. Relative performances of the protocols are presented in their work. Comparative performances shown in Fig.11 are in line with the results reported by them.

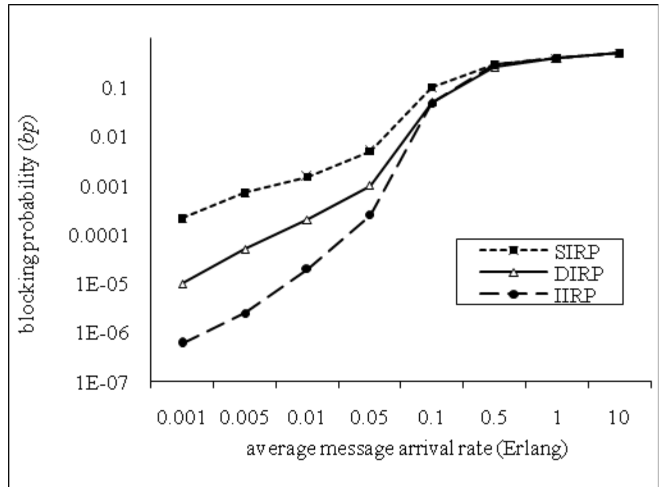

Fig.11: Relative performances of SIRP, DIRP and IIRP

IV. MODIFIED PROTOCOLS

The basic reservation protocols, discussed above, are modified and upgraded with different innovative concepts to improve their performances. Some modified protocols are discussed and compared with their peers (as reported in literature) in this section.

A. Holding and aggressive approach on SIRP

X. Yuan et. al. [32], reported some modified SIRP and DIRP protocols, in which requests may be either held or dropped during lightpath establishment. Also aggressive and conservative policies for reservation of wavelengths are used over the above mentioned schemes. Their schemes are discussed below.

It is already mentioned that, RES is used to reserve the wavelengths while moving in the *forward path* in case of SIRP, and in the *backward path* in case of DIRP. Under the dropping approach, reservation is initiated from *source* like SIRP. During the reservation process, if at any link the desired wavelength is not available, the request is blocked and the wavelength(s) reserved so far is/are released. Under the holding approach, if the required wavelengths are not available further, it keeps the wavelengths on the partial route locked for some period of time, hoping that during this period the wavelengths will be available. If the wavelengths still do not become available, the request is blocked and the wavelengths reserved so far are released.

Under the aggressive reservation approach, as much wavelengths as possible are attempted to establish a connection during the reservation process. Under the conservative reservation, only a minimum number of wavelengths are attempted for reservation. On the basis of these four approaches viz. (aggressive, conservative, dropping and holding), modified SIRP schemes are named as AFH (Aggressive Forward Holding), CFH (Conservative Forward

Reservation), AFD (Aggressive Forward Dropping), and CFD (Conservative Forward Dropping). Similarly DIRP schemes are named as ABD (Aggressive Backward Dropping), CBD (Conservative Backward Dropping), ABH (Aggressive Backward Holding) and CBH (Conservative Backward Holding). Results show that, conservative schemes outperform the aggressive schemes and the backward schemes outperform the forward schemes. One such result for holding schemes is shown in Fig.12.

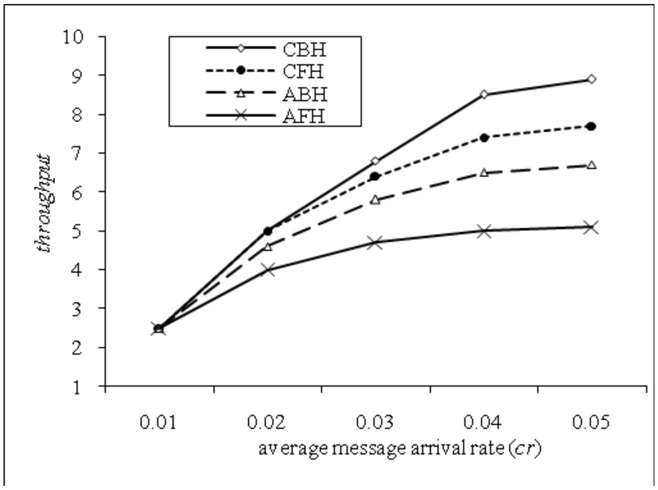

Fig.12: Throughput versus *cr* for CBH, CFH, ABH and AFH

Another comparative study of distributed protocols is reported by D. Saha [24]. The author presented a comparative study of SIRP (reported as Forward Reservation Protocol or FRP) and DIRP (reported as Backward Reservation Protocol or BRP), with and without retries. The author also proposed some modified versions of SIRP, such as exhaustive reservation, Select All With Intermediate Unlocking (SAWIU), and Select N With Intermediate Unlocking (SNWIU). Where N represents the number of wavelengths attempted for reservation, which is basically *aggressiveness*. In exhaustive reservation as well as SAWIU, all available wavelengths are attempted for reservation. But in SAWIU, reserved wavelengths are released, once they are unavailable in the *next links*. SNWIU attempts *N* numbers of wavelengths, for reservation from the available wavelengths but releases reserved wavelengths once they are unavailable in the *next links*. From the comparative study it is concluded that, SIRP is slightly faster (requires less *average latency*) but DIRP outperforms SIRP with respect to *bp*. In SNWIU, it is reported that value of N yielding the best result is 3. A representative result of Protocol Efficiency (PE) for different schemes is shown in Fig.13. PE is defined as reciprocal of probability of blocking.

B. Aggressive and retry approaches on DIRP

Aggressive approach of reservation of wavelength is used on DIRP, and the scheme is reported as DIMRP. It is already mentioned in section III B, that, long *vulnerable period* causes more blocking of requests. In DIMRP, multiple free wavelengths (if available) are attempted for reservation to implement *aggressiveness*. By doing so, chances of getting at least one wavelength throughout the path, is improved considerably and hence *bp* is reduced. However, this concept invites *over reservation* because, too much network resource may be used (through reservation of multiple wavelengths) by one request. In such cases, future requests may be blocked due to non-availability of wavelengths.

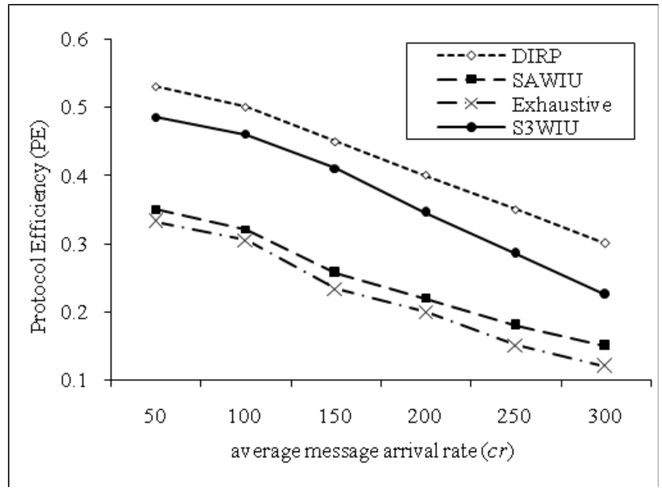

Fig.13: Comparison of PE with variation of *cr*

In DIMRP, when a request arrives, *source* initiates the usual control packet PROB, which moves towards the *destination*. If PROB reaches *destination* successfully, then *destination* checks the availability of wavelength(s) in *prob_set* of PROB. If the number of available wavelengths in *prob_set* is α (say), *destination* randomly selects min (*b*,α), number of wavelengths else selects all α wavelengths. At *destination*, *prob_set* is converted into *reserve_set*. Then RES starts from *destination*, and moves towards *source*, carrying *reserve_set*. RES attempts to reserve wavelength(s) included in *reserve_set,* at every link present on its way. If on the way, at any link, a wavelength is not available, the wavelength is dropped from *reserve_set*. If RES successfully reaches the *source* with nonempty *reserve_set*, then it is a case of success. If the number of wavelengths present in *reserve_set* is *p*, (where $p<=b$, and $p<=\alpha$) then from *p*, *source* selects one wavelength for data transmission. Then RES is converted into DATA_TRANS, which transmits data and also releases the extra reserved wavelength(s) (if any), throughout the route. After completion of data transfer, the wavelength used for data transfer is released. The timing diagram presented in Fig.14, describes this case of success.

Now, during probing, if *prob_set* becomes empty, then PROB is converted into NACK, which moves towards *source*. After the NACK reaches the *source*, the request is blocked.

Again, during reservation, if the *reserve_set* becomes empty due to non-availability of wavelength, at some *intermediate node*, then RES is converted into REL, which moves towards *destination* and releases the reserved wavelengths. Also from that node, a NACK is generated which moves towards *source*, and after reaching the *source*, the request is blocked. This case of failure, during reservation is shown in Fig.15.

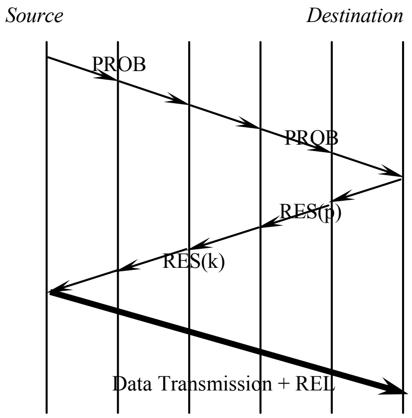

Fig.14: Case of success in DIMRP

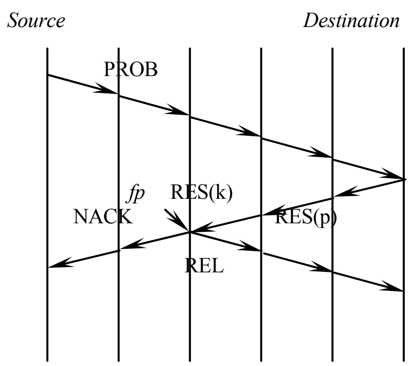

Fig.15: Case of failure during reservation in DIMRP

It may be noted that *aggressiveness* (b) may vary from 1 to n (where n is total number of wavelengths in a link). If b=1, the probability of successful reservation remains low, on other hand, if $b=n$, *over reservation* may spoil the advantage of concurrent reservation. Thus finding an optimum value of b, is a challenging issue. The optimum value of b depends on cr and number of wavelengths present in the network. These optimized values of b are considered to find out performance of the scheme.

Using the simulation results, DIMRP is compared with DISRP. Retry schemes for DISRP are also developed and compared with both DIMRP and DISRP (without retry) to judge the performance for retries and *aggressiveness*. Fig.16 shows variation of bp with different values of cr for wl=75. The figure shows that, DIMRP is a clear outperformer over DISRP. This is because success rate of reservation is improved through aggressive reservation in DIMRP. Now, the following interesting characteristics can be observed, in case of DISRP with retries. First, retries definitely improve the performance of DISRP in respect of bp. In fact, for higher values of cr (greater than 50), both retries perform better than DIMRP. However, for lower values of cr, the performance of DIMRP is at par with the performances of DISRP with retries. This happens because, at lower values of cr, effect of *over reservation* in DIMRP is low because of less demand of wavelengths. But then, for higher values of cr, DISRP with retries suffer from higher *average latency* and *average control overhead*, that make them unsuitable compared to DIMRP.

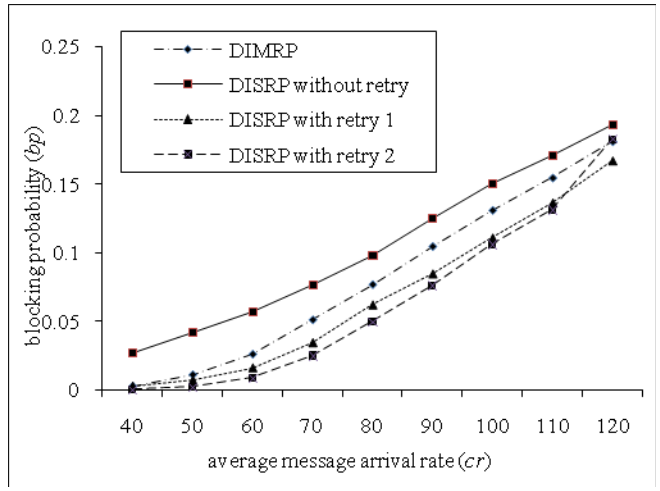

Fig.16: Comparison of bp with cr for DIMRP with other schemes for wl=75

C. Hybrid reservation scheme on DIRP

A scheme which is essentially a combination of SIRP and DIRP was proposed by Guo Yignhua [33]. The proposed scheme is *Source* and *Destination* Cooperative Reservation (SDCR), in which two reservation attempts are initiated by *source* and *destination*, respectively.

In this protocol, a wavelength on a given link can reside in one of the three states: *available*, *busy* and *suggested*. The free wavelengths fall under *available* state whereas wavelengths which are reserved come under *busy* state. When a request comes, *source* decides the route and suggests a wavelength for reservation from *destination* if available and sends a PROB (reported as CAS message) towards *destination*. While PROB moves towards *destination*, *intermediate nodes* set the state of this wavelength as *suggested*, if it is available. However if the wavelength is not available, the request is not blocked as done in SIRP, rather a NACK is sent towards *source* and PROB proceeds further . Once the *destination* receives PROB and it finds that suggested wavelength by *source* is available throughout the path, *destination* sends ACK towards *source*. But if the suggested wavelength is not available, *destination* selects a route and some other wavelength based on information of PROB. If *destination* succeeds, it sends a message to *source* (from this point of view, it is similar to DIRP), otherwise a NACK is sent to *source*.

On the other hand, *source* waits for τ seconds after sending PROB, and then starts transmission if no NACK is received which is similar to SIRP. If any NACK is received, *source* waits for final response from *destination.* Thus, SDCR may be considered as a hybrid scheme of SIRP and DIRP.

The protocol is compared with the SIRP with link state approach [40] and SIRP with distributed-routing approach [41] in respect of bp, using simulation on a mesh network. From the results (Fig.17), it is observed that, under low load situation, all the three candidates perform at par with each other. But, at higher load, *bp* of SDCR is less compared to that of the other protocols.

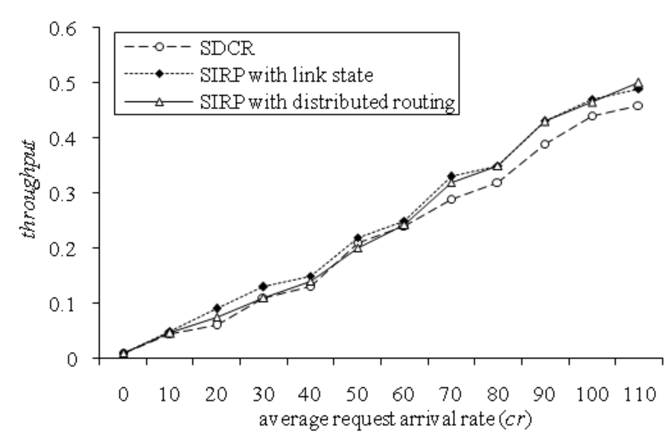

Fig.17: Throughput versus *cr* for SDCR

D. Saha et.al. [34] proposed a new hybrid protocol for WDM optical network. In this scheme when a request comes, the *source* sends a PROB (described as PROB-Th) towards *destination*. This PROB gathers the wavelength usage information along the path and proceeds until the number of free wavelengths on the links remain greater than some pre-selected threshold value, say Th. As the number of available wavelengths becomes equal to Th, the PROB is converted into RES (reported as RESV-Th). This RES reserves all the available wavelengths from that *intermediate node* till *destination*. So, from that *intermediate node* the scheme is similar to the scheme SNWIU (Selective N With Intermediate Unlock) [31]. But *aggressiveness* (here considered as N) of SNWIU is replaced by threshold value (Th) in this scheme and aggressive reservation is initiated from some *intermediate node* depending on the requirement. If this RES reaches the *destination* successfully, the *destination* selects one wavelength from the reserved pool of wavelengths and sends an ACK (described as CONF-Th) towards *source*. This ACK on its way releases the other wavelengths already reserved and also reserves the selected wavelength for the remaining links (for which the reservation is not done). If the ACK reaches *source* successfully, data transfer starts. It may be noted that, for Th=0, the scheme behaves like DIRP, and, if Th=C (i.e., total number of wavelengths present in each link), the scheme behaves like SIMRP.

Simulation results indicate that PE remains constant up to a value of Th (Th=3 for C=5) starting from Th=0, for which PE is almost equal to that of DIRP. If Th is increased beyond that, PE decreases and finally becomes at par with that of SIMRP (Table-2). Regarding *average latency* (referred as *average setup time* (AST) in the paper), it is observed that, for a fixed number of wavelengths, as Th increases from 0 to C, AST decreases. Similarly the *average control overhead* also decreases as the Th increases. Thus, it is concluded in the report that PE of this protocol remains constant at some value equivalent to DIRP until certain threshold is attained. But the *average latency* for this scheme is comparable to that of SIMRP and less than that of DIRP.

Table-2: PE of proposed hybrid protocol with varying Th for C=5

average request arrival rate (/m sec)	Th=0 (equivalent to DIRP)	Th=3	Th=4	Th=5 (equivalent to SIMRP)
50	79.97	76.84	70.00	70.00
100	68.80	64.46	57.59	56.85
150	61.00	55.87	49.16	47.96
200	55.55	50.68	44.15	43.45

D. Parallel reservation scheme

In their work, I. Ogushi et. al., [35] proposed a protocol for OBS (Optical Burst Switching) network, where lightpath for burst transmission is set up by parallel wavelength reservation. In the proposed scheme, the number of wavelengths probed for reservation is dependent on the number of hops present in the route. The basic idea is to limit the number of wavelengths, put into the list for probing in the *forward path.* Here, all wavelengths are not used by all requests for searching a free wavelength in a route. Rather, the total number of wavelengths (n) is divided into S number of groups. When one request comes to a *source*, one group among S, is selected. Then, the usage of the wavelengths within that group, are checked for the *next link,* and a list is updated depending on the availability of wavelengths. As probability of blocking increases with increase of *hop_count*, proportionately more number of wavelengths is allocated in the initial list with the increase in *hop_counts* of that request.

An approximate analysis is carried out, to determine the appropriate number of wavelength used in probing for each request. It is also reported that there exists an optimum number of wavelengths to be used in *prob_set* which yields better results. They have also established that the *bp* of a request having two hops, has more *bp* compared to a request having one hop.

E. Protocols with delayed link state information

In some early studies [2],[14] on routing and wavelength assignment protocols, it was assumed that the current global link state information is available at all nodes. But, in practice this is unrealistic in a distributed environment. Thus, in distributed lightpath establishment, blocking may occur due to *outdated information* of wavelength available at nodes. Probability of establishing a lightpath depends highly on the accuracy of global link state information. In their work, T. Toku et. al., [36] evaluated how the frequency of exchange of link state information affects the probability of establishment of lightpath. They used both SIRP and DIRPs with three different types of network topologies. From the study they have shown that, if frequency of exchange is increased, the protocols perform better in general, and DIRP requires less frequent exchange of link state information to retain the performance [Fig. 18]. In Fig.18, t represents the time interval after which updated link state information are available.

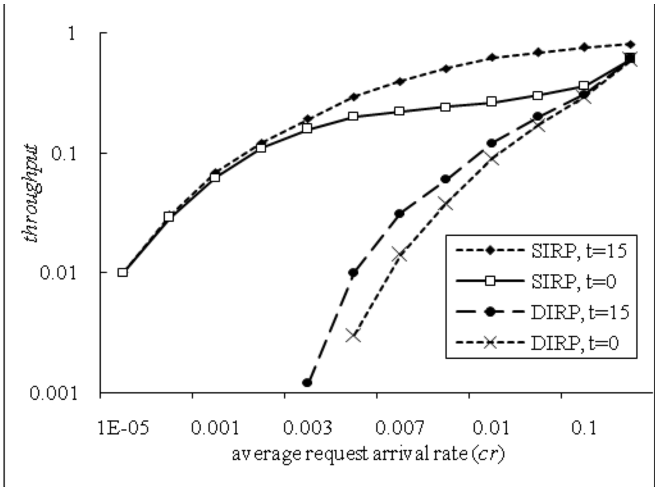

Fig.18: Effect of frequency of exchange of link state information on throughput

F. DIRP using Markov model

To increase the probability of getting the selected wavelength reserved, the concept of broadcasts is used in [7]. The model used by them is reported as *Markov model* and we refer the scheme as MBRP (reported as MBR). In their work, following two types of broadcasts are used: (i) Each node broadcasts its adjoining link usage information at every T seconds. This link usage information is stored at every node. (ii) Link usage information as broadcast above, is not necessarily correct at an arbitrary time between sT and $(s+1)T$. To overcome this uncertainty, a prediction is suggested to select wavelength during these intervals. To take the *probabilistic* method of selection, a C-T Markov chain is used in this work. The required parameters are broadcast at every T' seconds and stored in a table referred as *markov_table* at all nodes. So essentially *markov_table* contains the information of rate of change of states of the wavelength usage for all the wavelengths in all the links. T' is considered to be much longer compared to T. If value of T' is lower than a certain level, it is vulnerable to oscillation which may ultimately lead to poor performance.

In MBRP, When a request comes, the *source* initiates a PROB towards *destination*. While the PROB moves towards *destination*, each node performs two major tasks: (i) detects the *interfering requests* and (ii) selects a *guessed wavelength* for the request.

When a connection request arrives at a node, it is called *current request*. All other ongoing requests that arrived earlier at that node are called *under process requests*. Those under-process requests who have identical *pre_hop_id* or *next_hop_id* as that of *next_hop_id* of the current request are called *interfering requests*. All the *interfering requests* have already guessed some wavelengths, and the *node_table* of that node keeps those as *guessed wavelengths*. The duration of a record in a *node_table* is bounded by *source-destination* round trip time of the concerned connection request.

After receiving a PROB, a node first updates the probe-map field of PROB by marking those wavelengths as busy (if any), which are (i) guessed by *interfering requests* or (ii) being used by other requests for transmission. Then, for each free wavelength (if any), the node uses the *markov_table* to find the maximum probability of getting a wavelength free throughout the path [7]. That wavelength is selected as *guessed wavelength*.

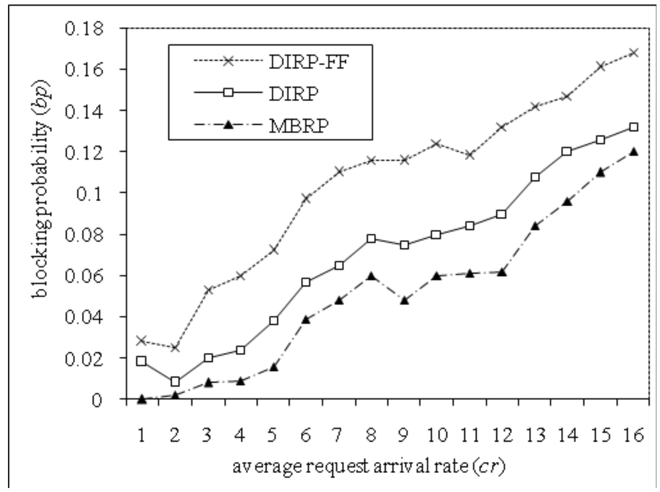

Fig 19: Performance of MBRP over DIMRP and SRP

Using simulated results, they informed that MBRP works best in a small-scale network (Fig. 19). In such networks, the average hop number of a lightpath is small. Backbone networks usually satisfy this topology condition. The performance of MBRP will not improve as the number of wavelength per fiber increases. This is a shortcoming of MBRP compared to DIRP, which uses random selection method (reported as RND) and DIRP-FF, which uses first fit selection method (reported as FFP). However, if the number of wavelengths per fiber is relatively small, then the use of MBRP to decrease reservation confliction is more effective than the use of other algorithms, DIRP and DIRP-FF. They have examined the applicability of the MBRP algorithm to networks where the traffic has Poisson characteristics and self similar characteristics, without temporal or spatial variations. In both cases, the MBRP algorithm has good performance. They also reported that the performance of MBRP requires further research when the traffic pattern may change dynamically. This would require a mechanism to detect when the traffic pattern has changed and a procedure to choose optimal values for the parameters T and T'.

G. Modified INIRP

As discussed earlier, IIRP is static type of INIRP, where reservation is attempted from some predefined *intermediate nodes*, in one direction only (towards *source*). This reduces the uncertainty in getting free wavelength, in *backward path* through reduction in *vulnerable period*. However, reservation can be attempted in both directions (towards *source* and *destination*) as well, thereby reducing the *vulnerable period* and hence reducing the uncertainty of reservation due to *outdated information*. This concept is termed as splitting. However, arbitrary splitting invites certain degree of *over reservation*. Considering this aspect, the position of splitting is to be optimised in order to reduce the effect of *over reservation*. Moreover, decision of splitting is to be taken adaptively to improve the probability of successful reservation in the subsequent links of the route. This is implemented in dynamic INIRP and is reported as SRP [37] and is discussed in Subsection G.1.

If the probability of successful reservation of wavelengths throughout the route can be anticipated using some method, then the decision to select a particular wavelength becomes simple. One such selection method is Markov based selection [7], [10]. The protocol using Markov based selection method with the concept of split embedded in it, is reported as MSRP and is discussed in Subsection G.2.

MSRP is further improved, as reported in [20],[38], using the concept of piggybacking to update link status information in a better way. This scheme is named as Fast Markov based Split Reservation Protocol (FMSRP). FMSRP is presented in Subsection G.3.

MSRP is also improved using multiple splitting [39] and the scheme is reported in Subsection 6.4.

G.1 INIRP using splitting

SRP uses concept of conditional splitting, and both way reservation. In SRP, PROB is split into two reservation packets, to reserve wavelength(s) in both directions (towards *source* and *destination*). Also splitting is done dynamically, depending on some parameters of the network, at that instant of time. If the availability of wavelength during probing, falls below a certain level, and the PROB travels a certain number of hops in the network, reservation is initiated from that *intermediate node* in both directions. This immediate reservation reduces the *vulnerable period*, and thus, blocking is reduced.

When a request comes, *source* initiates a PROB, which moves towards the *destination*. PROB includes *hop_count* and *b* along with other fields. The variable *b* is a predefined positive integer. Basically *b* is the *aggressiveness* of the scheme, which is used for taking decision of splitting. For the first link, *prob_set* is initialised to the wavelengths available in the first link. For the subsequent links, on receiving PROB, a node performs two tasks:

- updates the *prob_set* using the operation,
  prob_set = *prob_set* $\cap$ available wavelength(s) on the *present link* and
- checks the conditions for probable splitting.

SRP dynamically splits probe attempt, into two concurrent (one towards *source* and the other towards *destination*) reservation attempts, at any *intermediate node*. For a request, splitting may occur, if the following two conditions are satisfied:

- *hop_count* $\geq (x * d)$ i.e., whether the PROB has traversed a pre-selected distance $(x * d)$ of a route, where d is total number of hops of the route and x is a positive fraction $(0<x<1)$ and
- number of available wavelengths of *prob_set* $\leq b$, for $b \geq 1$. SRP attempts $(b-1)$ number of retries (if required) for $b>1$.

If conditions of splitting are satisfied, splitting occurs. PROB is converted into two reservation packets: RES_FWD and RES_BKD. The node where PROB splits, is called the splitting point (*sp*). At *sp*, *reserve_set* is copied into both RES_FWD and RES_BKD. RES_BKD selects one wavelength (say w_1) randomly from the *reserve_set* and moves towards *source*, and RES_FWD moves towards *destination*, attempting to reserve all wavelengths of *reserve_set*. However, if the *reserve_set* is empty, request fails and subsequently the request is blocked.

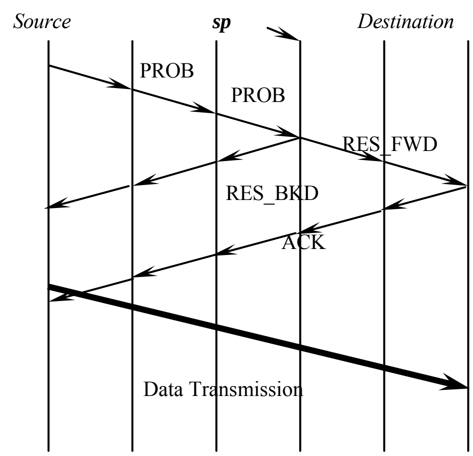

Fig.20: Case of success in SRP

If RES_BKD successfully reaches the *source*, then at *source*, it waits for ACK of RES_FWD. If RES_FWD reaches the *destination*, with nonempty *reserve_set*, then an ACK is sent towards *source* along with the *reserve_set*. ACK, on its way, keeps a copy of the *reserve_set* at *sp*. After receiving the ACK, the *source* checks the matching of the wavelength reserved in forward and backward directions. If those are matched, the data transmission starts (Fig.20). If there be mismatch in wavelength reservation or if RES_BKD fails, then RES_BKD is converted into REL_FWD which moves towards *sp* releasing the reserved wavelength. At *sp*, REL_FWD randomly selects another wavelength from the *reserve_set* for retry, and becomes RES_BKD again. This is repeated (if required) until total number of retries (= *b*-1) is exhausted. Now, if RES_FWD is stuck before *destination*, then it is the case of failure (Fig.21) and it is converted into NACK_REL. The NACK_REL moves from the *intermediate node* to the *source*, and releases the wavelength reserved by both RES_FWD (from the node where failure takes place to *sp*) and RES_BKD (from *sp* to *source*). After receiving the NACK_REL at *source*, the request is blocked.

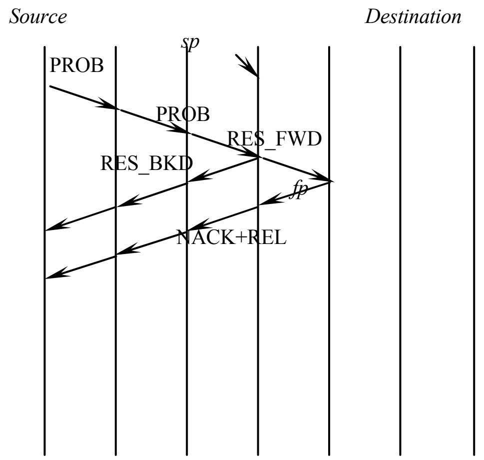

Fig.21: Failure of RES_FWD in SRP

The simulation results (Fig.22) show that SRP outperforms IIRP with respect to *bp*, and *average control overhead*. It is reported that though SRP may have more *average latency*, but considering the betterment in *bp* and *average control overhead* used, the protocol can be considered as better performer.

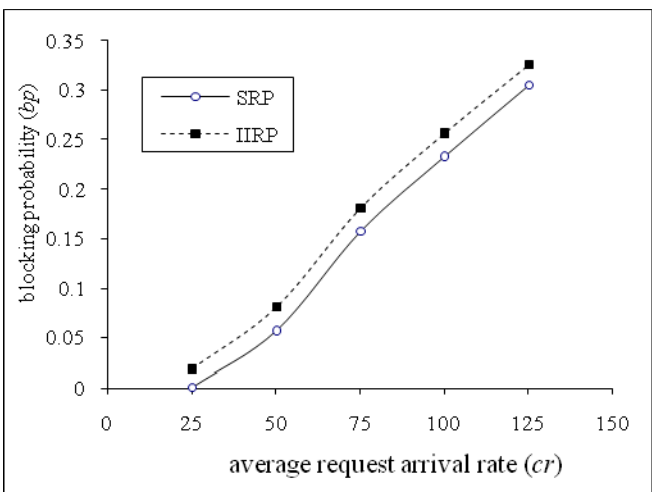

Fig.22: Change of *bp* with *cr* for *wl*=75 in SRP

G.2 INIRP using Markov model

In this scheme, when a request arrives at a node, the node guesses a wavelength based on the link usage information of the *previous link* and the *markov_table*. The wavelength thus guessed has the maximum probability at that time to be reserved successfully. Thus when the *source* initiates a PROB, the PROB moves towards *destination*, and each node after receiving the PROB, performs the following major tasks for the request: (i) detects the wavelengths already guessed by earlier requests and excludes them from *prob_set*, (ii) guesses a wavelength for this request from the remaining free wavelengths and updates PROB, (iii) initiates on-demand splitting (dynamically) if necessary. Conditions of splitting and reservation scheme remain same as that of SRP discussed in section G.1.

Since T_{ratio} (the ratio of T' to T) is an important parameter and affects the performance of the protocol, is studied for different set of values of *cr* and *wl*. It is found that an optimum value of T_{ratio} exists in each case. It is reported that, values of T_{ratio} corresponding to minimum value of *bp* is near 300. Hence, for simulation results, the optimum value of T_{ratio} is kept as 300.

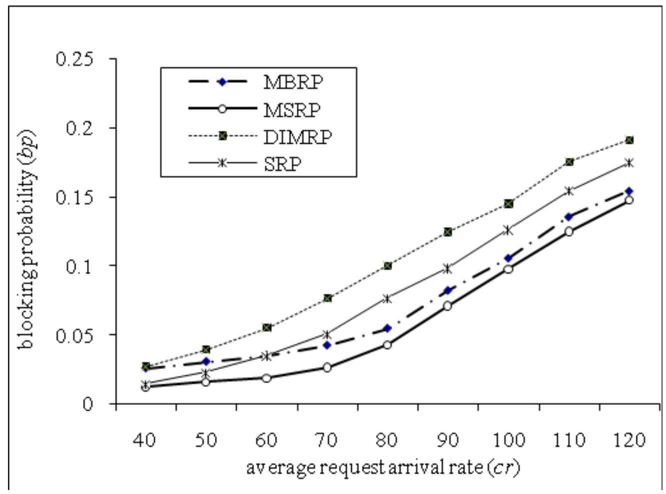

Fig.23: Variation of *bp* with *cr* for *wl*=75 in MSRP

The variation of *bp* with variation of *wl* and *cr* are reported in the study. A result is shown in Fig.23 which represents the variation of *bp* with *cr* for *wl*=75. From the figure, it is found that MSRP always performs better than SRP, DIMRP and MBRP (retry is not used in any protocols for the parity of comparisons). It is also reported that, for moderate values of *cr* (50-80), MSRP performs best. It happens because, in this region of *cr*, the crisis of getting a wavelength is moderate, which leads maximum number of splitting cases to success and relative performance of MSRP improves with increase in *wl*.

From the study it is found that, *average latency* of MSRP is always higher compared to other schemes but *average control overhead* of MSRP is less than SRP. This happens because of better wavelength guessing leading to less number of splitting than SRP.

G.3 INIRP using Fast updating system

It is established that, the success of reservation of a wavelength, highly depends on how much updated information of link usage is used. Also updated information depends on efficient exchange of information. In MSRP, link usage information is broadcast at regular interval *T*. But the information becomes outdated with time till the next broadcast information is received. A new technique, called fast updating system is implemented in FMSRP. In this protocol, two schemes are used for exchange of information: (i) regular broadcast scheme (usual periodic update) and (ii) *piggy_update* scheme. In *piggy_update* scheme, all control packets used otherwise are *piggy_backed* with link usage information of the links, through which the control packets travel. Under this scheme, the nodes update the link usage information while control packets pass through the nodes. Thus, *piggy_update* scheme may allow longer interval of regular broadcasts (*T*), which in effect, lessens the number of control packets required for broadcasts. This reduces broadcast overhead when normal control packets are frequent in the network. The basic protocol, however, remains same as that of MSRP.

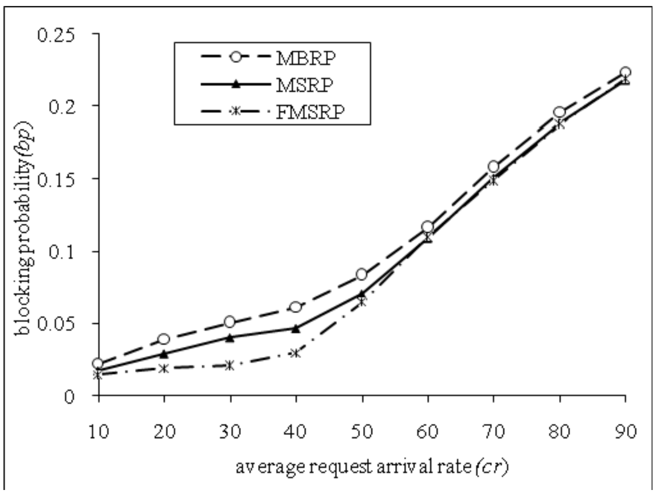

Fig.24: Variation of *bp* with *cr* for *wl*=75 in FMSRP

For the study of FMSRP, T_{ratio} is kept fixed at 300. To judge the performance of the protocol, effect of *cr* on *bp* is studied. One sample result is shown in Fig.24. The figure shows that, FMSRP performs consistently better than MBRP, and it outperforms MSRP for a wide range of *cr*. At very low value of *cr*, (at around *cr*=10), the difference in *bp* between FMSRP and MSRP is less. Basically, in a distributed system, due to nonzero time lag of reaching the updated information, collision with requests to reserve same wavelengths cannot be eliminated completely. But as *cr* increases, the performance of FMSRP improves. After *cr*=40, the betterment of performances reduces. Beyond *cr*=70, FMSRP loses its advantage and behaves at par with MSRP. This happens as at higher load for relatively low number of wavelengths (here *wl*=50), one major cause of blocking is insufficient network capacity. Thus, if other parameters remain unchanged, *bp* can be hardly improved by the use of updated information beyond *cr*=70.

The characteristics of *average latency* and *average control overhead* are also reported. In general, *average latency* decreases with increase in *cr*. This happens because for higher values of *cr*, crisis of *wl* increases. At high crisis of *wl*, probability of lightpath establishment becomes difficult for a request having longer path length. Consequently, at high load, most of the successful requests (which are served) are with shorter path lengths. Also, it is shown that, *average latency* is more in case of FMSRP. This is because, FMSRP performs better (its *bp* is less) compared to the other schemes. This in turn, indicates that for FMSRP, more requests with longer paths are successful compared to other schemes, which contributes to the enhancement of *average latency.* However, for higher values of *cr,* gain of FMSRP in terms of *bp* becomes negligible, so difference in *average latency* also diminishes with high values of *cr*. The change in *average control overhead* is not remarkably noticeable compared to MSRP. This happens because FMSRP does not use any additional control packets compared to MSRP.

G.4 INIRP using multiple splitting

In MMSRP, concept of multiple splitting is implemented to improve the blocking probability further. In this scheme, when a connection request comes, the *source* initiates a PROB towards *destination*. *Source* also computes the probability of success for all available wavelengths for the route using Markov method and selects a set of top p number of wavelengths (subject to availability), say λ1, λ2, λ3…. λp respectively. That wavelength having the maximum probability is selected as guessed wavelength (λ1) and the remaining (p-1) wavelengths are arranged in a list in descending order and are stored in *future-guess-wavelengths* field of the PROB. In this work, p is considered as 2, hence maximum two splitting may occur.

During the process of propagation of PROB at the subsequent nodes of a route, a node checks the availability of already *guessed wavelength*, λ1 in the *next link*. If it is not available, the first candidate (i.e.λ2) of *future-guess-wavelengths* is selected as the new wavelength and this is assigned to *guessed wavelength* and λ2 is excluded from *future-guess-wavelengths.* While the PROB moves towards *destination*, each node selects a *guessed wavelength* for the connection request and updates the *future-guess-wavelengths* field and initiates splitting (dynamic splitting) if necessary.

If splitting does not occur and the PROB successfully reaches the *destination*, *destination* initiates reservation by sending RES towards *source*. Standard DIRP is used for reserving the wavelength. The *intermediate nodes*, on receiving this RES, lock the selected wavelength as busy. If the RES reaches *source* successfully, transmission starts otherwise the connection is blocked.

If splitting occurs (conditions of splitting are similar to that of SRP), the PROB is converted to RES_FWD and a RES_BKD is also generated. The wavelength of *prev_guess_index* field of PROB (say λ2) is assigned to selected wavelength of both RES_FWD and RES_BKD. The RES_BKD moves towards *source* reserving λ2 and deleting the entries of this connection request of the nodes on the way. The RES_FWD moves towards *destination* attempting to reserve λ2. The RES_BKD carries *future-guess-wavelengths* with it for future use.

However if RES_BKD fails at some *intermediate node* due to non-availability of λ2, then it attempts for further splitting. Then the node at *fp*, selects the next candidate (say λ3) of *future-guess-wavelengths* carried by RES_BKD, for the second splitting. If conditions of splitting are satisfied, second splitting takes place and the RES_BKD again splits into two new RES packets, if λ3 is available. These new RES packets are RES_FWD and RES_BKD and they function like previously generated RES packets after the first splitting. These RES packets now attempt to reserve λ3 both in forward and backward direction as well as release all the previously reserved wavelengths. If both RES_FWD and RES_BKD are successful, then data transmission starts after receiving the acknowledgement from *destination*. However if any of the RES packets is stuck at some *intermediate node*, the connection request is blocked and packet is converted into NACK which moves towards *source* and another REL_FWD is generated from that point of failure which moves towards *destination* and releases the wavelengths reserved so far by both RES_FWD and RES_BKD. Again if RES_FWD fails, it is converted into REL-BKD which moves towards *source* and releases the wavelengths reserved so far and also acts as a NACK.

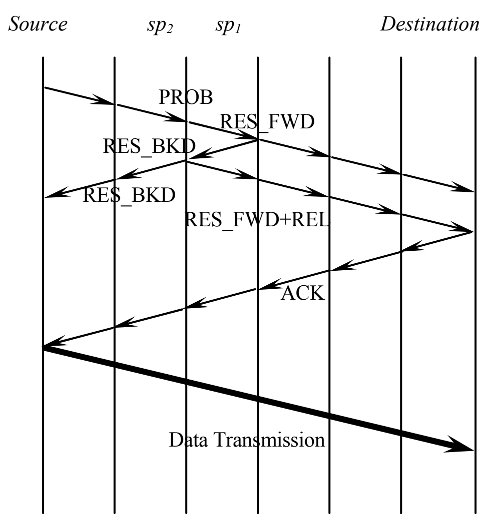

Fig. 25: Case of success in MMSRP.

A timing diagram of MMSRP is presented here. Fig.25 shows a case of success. Sp_1 and Sp_2 used in the figures indicate the two splitting points (nodes) where the first and second splitting respectively occur in a connection request.

The proposed scheme MMSRP is compared with MSRP and MBRP. One representative result for *wl*= 500 is shown in Fig. 26. From the figure, in general it is found that for all the protocols, *bp* increases with increase in *cr*. However MMSRP performs distinctly better than other two. Also it can be observed from the Fig. 26 that with the increment of *cr* the relative performance of MMSRP also improves. This happens because, as *cr* increases, crisis also increases and even after splitting, the rate of failure cases increases. Since MSRP uses splitting only once, it cannot utilize the other wavelengths even if they are free. In contrast MMSRP takes the advantage in such cases, and tries to utilize those free wavelengths, through the process of further splitting.

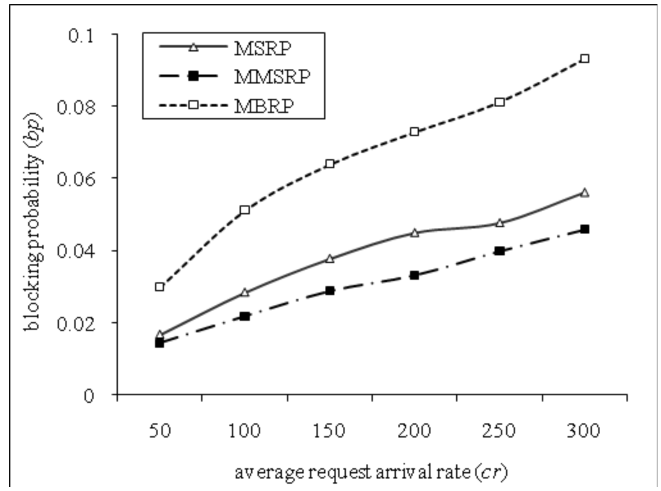

Fig. 26: Variation of *bp* with *cr* for *wl* =500

Variation of *average latency* with *cr* for different fixed values of *wl* is reported in the work. It is found that, *average latency* is slightly higher in case of MMSRP.

Also the *average control overhead* of MMSRP is slightly greater or at par with other two protocols. The increase in the number of average control packet for MMSRP is limited to around 7% only.

Thus it is reported that MMSRP may be considered as an effective protocol for WDM as well as DWDM networks, which performs better than the current best protocols so far blocking probability is concerned, at higher wavelength region, at the cost of increase in average setup time. Thus the protocol can be considered as a better performer, specially in the applications where protocol efficiency is of prime importance and the network uses larger number of wavelengths.

V. CONCLUSION AND FUTURE SCOPE

We have already discussed that two key issues for development of protocols are *vulnerable period* and *reservation duration*. In case of SIRPs, reservation is initiated from *source*, much before the use of it for data transmission. Thus, *reservation duration* is quite high for SIRP. But *vulnerable period* is nil because probing is not done before reservation. For DIRPs, after probing in *forward path*, reservation is initiated from *destination*. Hence, in DIRPs, *reservation duration* is low at the cost of *vulnerable period*.

Now, due to *vulnerable period* success of reservation becomes uncertain and with increase in *vulnerable period*, uncertainty increases. Again, if *reservation duration* is more, more resources (wavelengths) remain unnecessarily occupied. This may cause starvation to other concurrent requests. Thus, ideally to improve throughput, both *reservation duration* and *vulnerable period* are to be minimized. But these two parameters are interlinked and hence both cannot be reduced simultaneously. Hence, optimization is needed and different protocols are developed having moderate *reservation duration* and *vulnerable period*.

Assuming time required to travel the distance between *source* and *destination* as *d/s* (where *d* is the distance between *source* and *destination* and *s* is the transmission speed), we can compute approximate *vulnerable period* and *reservation duration* for different protocols. Considering the best case and worst case, we have computed approximate values of average *vulnerable period* and *reservation duration*, for some notable protocols. The relative positions of different schemes are shown in Fig.27. Here we have assumed that, on an average, four segments are present between *source* and *destination*. In the figure, SIRPs, DIRPs and SRPs mean the schemes whose reservation policies match with SIRP, DIRP and SRP respectively.

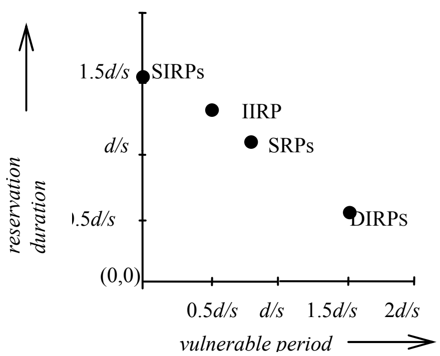

Fig. 27: Comparison of different classes of schemes based on *reservation duration* and *vulnerable period*.

To combat the effects of both higher *reservation duration* and higher *vulnerable period*, several approaches and/or combination of such approaches are used. Few important approaches are, use of *aggressiveness*, dynamic splitting and *probabilistic* selection method of wavelengths. Considering these approaches, different protocols thus proposed, are presented in Fig. 28. Performances of important protocols with respect to different parameters are summerised in Table-3. Using the comparison of the recent protocols, suitability for different situations, as well as, prosperous schemes for future use may be found out.

From the above discussion, it may be noted that DISRP is improved by using *aggressiveness* on it and the scheme is reported as DIMRP. For aggressive schemes, more wavelengths are reserved, so that other requests may face the scarcity of resource. Immediate unlocking system reduces this problem at the cost of excess control packets. Thus DIMRP may further be improved using immediate unlocking.

In SRP, concept of splitting is incorporated. This scheme is further improved to MSRP, where Markov method is used for selection of wavelength. Now, there are some other promising wavelength selection methods, for example priority based selection of wavelengths, which may be used on SRP. In priority based selection, priorities are to be set to every wavelength depending on its history of usage and some other parameters, and wavelength having highest priority is always selected at a given point of time.

Another aspect of SRP is the dynamicity of splitting, which is also used in MSRP and FMSRP. In these schemes, dynamicity is obtained using two parameters, number of hops already traveled and predefined *aggressiveness*. The protocols can further be studied using dynamic splitting for different network parameters. Also, the effective use of *aggressiveness* in selecting wavelengths for reservation may be an area for future study.

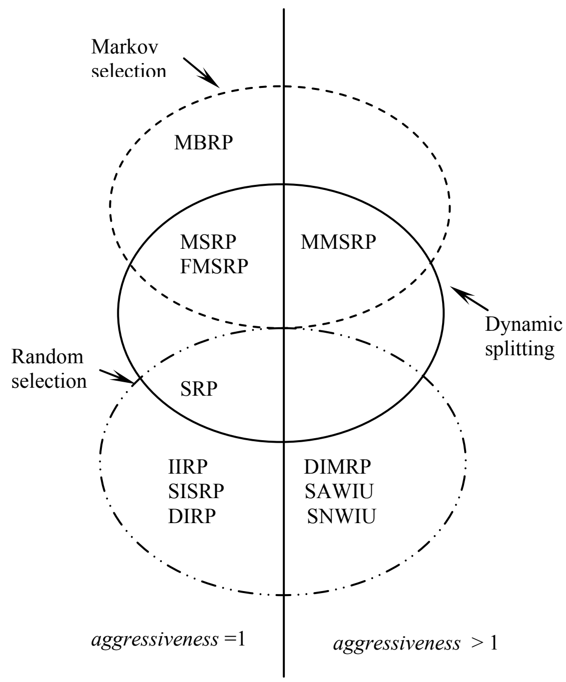

Fig. 28: Some important protocols developed using *aggressiveness*, dynamic splitting and *probabilistic* method of selecting wavelengths

The multiplicity in control packets used in dynamic schemes (e.g., PROB) into two RES packets, may also be used in other reservation protocols. Again, the task of a control packet can be made more versatile and dynamic depending on requirement in the network at the current situation. For example, during failure case of reservation, the release packet can perform more tasks depending on the information available at a node. Also the control packets can be made more informative, so that nodes may take decision and change the tasks of such control packets.

Another important and useful concept of “piggy-back” is used in FMSRP to improve the information update system in a network. This concept is neither biased for some particular scheme nor invites any extra overhead for practical implementation, and hence may be applied on other protocols also.

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Table-3 : Comparison of characteristics of all important protocols

schemes	Ref. no.	Initiation of reservation	Wavelength selection method	*Aggressiveness* (n=total no. of wavelengths per fiber)	*Splitting Static/dynamic*	*reservation duration*	*vulnerable period*	*average control overhead*	*average latency*	*bp*	*Special feature*
SISRP	[8]	*source*	*random-fit*	1	not used	high	0	low	low	high	
SNWIU	[24]	*source*	*random-fit*	1<N<n	not used	high	0	low	low	moderate	Immediate unlocking is used
SAWIU	[24]	*source*	*random-fit*	n	not used	high	0	low	low	moderate	Immediate unlocking is used
SDCR	[33]	*Source* and/or *destination*	*random-fit*	1	not used	moderate	0	moderate	low	moderate	
DISRP (i.e. DIRP)	[24]	*destination*	*random-fit*	1	not used	low	high	low	moderate	moderate	
DIRP_FF	[7]	*destination*	*First-fit*	1	not used	low	high	low	moderate	moderate	
DIMRP	[21]	*destination*	*random-fit*	>1	not used	low	high	low	moderate	moderate	
MBRP	[7]	destination	*Markov method*	1	not used	low	high	low	moderate	low	broadcast is required
IIRP	[29]	*Intermediate node*	*random-fit*	>1	static	high	low	high	moderate	low	
SRP	[37]	*Intermediate node*	*random-fit*	1	dynamic	moderate	moderate	high	moderate	low	
MSRP	[10]	*Intermediate node*	*Markov method*	1	dynamic	moderate	moderate	moderate	moderate	Very low	broadcast is required
FMSRP	[38]	*Intermediate node*	*Markov method*	1	dynamic	moderate	moderate	moderate	high	Very low	wavelength usage information is updated using “piggy backing”
MMSRP	[39]	*Intermediate node*	*Markov method*	>1	dynamic	moderate	moderate	moderate	moderate	Low	Broadcast is required