Stochastic Preplanned Restoration Algorithms

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Abstract

The ability of overcoming service interruptions, i.e., resilience, has always been an irremissible requirement for communication networks. Resilient schemes can either reserve in advance network spare resources (*protection schemes*) or found them upon failure occurrence (*restoration schemes*). While fixed protection schemes have been extensively used thus far in the telephone industry, the envisioned dynamic Optical Layer (OL) and the lack of flexibility proper of protection schemes are driving network designer to resort to restoration schemes.

By dynamically looking for backup paths of spare wavelengths upon failure occurrence, restoration schemes have the potential to yield efficient and flexible resource reservation. However restoration schemes, generally, present long failure recovery time (i.e., the time required to restore the disrupted connections). This is mainly due to the heavy signaling that originates upon failure occurrence. In high capacity WDM networks, the presence of many connections concurrently seeking restoration exacerbates the above problem as, in existing restoration schemes, coordination among restoration attempts may further slow down the process completion.

To exploit the flexibility of restoration schemes and decrease their failure recovery time and resource contention, the authors propose a class of fast and efficient path restoration schemes called Stochastic Preplanned Restoration (SPR) schemes. In the SPR schemes each active connection is associated with an agent resident at the connection master node. Communication between agents is not allowed. This permits to reduce the coordination required during the failure recovery process. Distinct restoration paths are precomputed at the connection master node at the time the connection is set up. Upon failure of the connection working path, one of the preplanned paths is randomly selected as restoration path depending on specific probabilities calculated by the connection agent. The proposed schemes require limited signaling upon failure occurrence as coordination among the agents involved in the restoration process is not required. Therefore, the schemes are fast and scalable in terms of number of network nodes, link or fiber capacity, and number of connections. Yet, presented results show that the SPR schemes may considerably decrease the blocking probability of the restoration attempts when compared to other distributed restoration schemes, such as alternate routing, and perform closely to centralized schemes based on ILP solutions.

I. Introduction

The continuous increase of data-centric traffic is — although not unanimously in terms of growth rate — recognized worldwide [1], [2]. To circumvent the rapid depletion of today's telecommunication network resources and reduce the existing multi-layer architectural complexity, Wavelength Division Multiplexing (WDM) networks that directly supports the Internet Protocol (IP) — the so called IP over WDM architecture — represent an appealing solution that may yield contained network costs and management burdens.

Wavelength Division Multiplexing (WDM) harnesses the Optical Layer (OL) fiber bandwidth with a number of parallel channels that increases yearly, thus providing the necessary capacity growth at acceptable

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costs. In addition, solutions for automatically controlling the optical network layer that substitute the present slow and manual optical network control with an integrated management solution spanning across the IP and the WDM layer are gaining increasing interests [3], [4], [5], [6]. The envisioned solutions based on Generalized Multi-Protocol Label Switching (GMPLS) [7], [8] permit the Optical Layer to dynamically adapt its configuration to better accommodate traffic and topology changes.

From a practical perspective, due to the heterogeneous and enormous amount of data carried along the network lines, a mandatory feature of the IP over WDM architecture is the ability to guarantee network resilience to unexpected component failure at the WDM layer. In general, a network is referred to as *resilient* if it provides some ability to restore ongoing connections in the event of a catastrophic failure of a network component, such as a fiber cut. The design of resilient networks is achieved generally by exploiting protection and/or restoration schemes that guarantee network resilience in presence of such network failures. *Protection schemes* reserve in advance dedicated backup resources that are readily available upon occurrence of a network failure. *Restoration schemes*, on the contrary, dynamically look for backup paths of spare capacity upon failure occurrence. Both schemes can be implemented in the IP-GMPLS control plane that

1. offers the required signaling [3] and
2. represents a solution compatible with the existing IP/MPLS resilient techniques [9].

Protection schemes have been extensively utilized in the telephone industry as they provide fast reaction to faults. However, because spare resources are statically provisioned during the netowk planning phase, protection schemes do not have the necessary flexibility to be applied in a scenario in which connections are dynamically set up and torn down. Recently, solutions for the dynamic provisioning of resilient connections have been proposed [10], [11], [12], [13], [14], [15], [16]. In these schemes upon arrival of a request for setting up (tearing down) a connection, both a working and a protection paths are established (torn down) and resources along the network are reserved (released). The efficiency of the scheme (e.g., maximization of resource sharing, low connection request blocking) critically depends on the signaling protocol convergence time. In particular the convergence time of the network status information at the nodes must be faster than the connection interarrival time. In addition because the resources reserved are strictly related to the considered failure scenario the schemes are not flexible.

Restoration schemes suach as the ones proposed in [17], [18], [19], have the potential to yield more efficient and flexible resource reservation than the former protection schemes. Restoration schemes can be divided in two classes: *centralized* restoration and *distributed* restoration.

In centralized restoration the decision of how to reroute disrupted connections is made at a centralized controller. After the failure the controller locates the fault (from the messages sent by the network nodes), decides what rerouting to apply, and implement the decision by downloading the rerouting instructions to the network nodes. Centralized restoration has the advantage of the simplicity of a centralized controller and the capability of obtaining an optimal solution by solving the Integer Multicommodity Maximum Flow (MCMF) that models the rerouting of the failed connections along the residual network capacity. One drawback of this approach is represented by the cost of making reliable both centralized controller and its communication network with the other nodes. Furthermore this approach has been proven to be relatively slow with conventional signalling and messaging protocols [18], [19] and the real time optimal solution of the Integer MCMF problem, an NP-hard problem [19], is rarely practical.

To overcome the centralized restoration drawbacks, distributed restoration [19], [20] has been proposed. In this case network nodes run a distributed protocol not only for failure location [17] but also for alternative route discovery, and connection rerouting [18], [19]. Distributed restoration therefore, by eliminating the need for a centralized controller to manage reconfiguration, can provide high restorability and capacity efficiency, and it is potentially faster than centralized restoration as the signalling can be carried out in the physical layer using a dedicated signalling and locally to the failure location. However it presents the inherent complexity of designing a correct distributed fault tolerant protocol that, to be efficient, must be able to solve or approximate the Integer MCMF problem. In addition distributed restoration may experience a high degree of message contention and resource competition increasing the protocol blocking probability.

Both centralized and distributed restoration techniques can be further divided in *real-time* and *pre-planned* [18].

Real-time restoration techniques can provide high restorability [1] because they perform restoration upon failure occurrence and are, therefore, aware of the most up-to-date network resources. However the failure recovery time is slow and resource contention can be high. On the contrary, pre-planned techniques have faster failure recovery time because they utilize the processing power and the time available during operational periods to minimize system 'panic' when failure occurs. However they cannot guarantee high restorability should network state change significantly and plans become out of date. Moreover to obtain low resource contention network nodes need to store pre-optimized restoration configurations requiring a large amount of memory and fast access to pre-planned configurations.

In this paper the authors propose a novel class of restoration schemes, called Stochastic Preplanned Restoration schemes or SPR for short, whose objective is to provide fast and efficient allocation of spare resources at the occurrence of a network fault. SPR schemes can be classified as pre-planned distributed restoration schemes. In the SPR schemes each active connection is assigned an *agent* resident at the connections master node (e.g., the source node). A the occurrence of a network fault each agent associated with a connection involved in the failure chooses among the precomputed paths the restoration path. The novelty of the SPR schemes is the stochastic nature of the selection process. Indeed the choice of the restoration path is based on probabilities that are computed at the moment of the fault occurrence and assigned to the restoration paths. The probabilities take into account the available resources in the network at the moment of the failure and the likelihood that such resources will be chosen by some agents during the restoration process. By using these probabilities, each agent performs a stochastic choice that will result in a balanced routing of the disrupted connections over the network available resources. Blocking probability of the restoration attempts due to resource contention is therefore reduced.

A key property of the proposed scheme is the total absence of coordination between agents while restoration is taking place, i.e., each agent chooses its restoration path independently from the others. Thus, only path activation messaging is required once the agent at the master node has selected the restoration path.

[1] Restorability is defined as the ratio between the number of recovered conneections and the number of disrupted connections.

Consequently, the SPR schemes are potentially faster than other dynamic rerouting restoration schemes that require some degree of coordination between nodes.

The agent choice depends on the correctness of the network status information and thus on the convergence time of the advertisement protocol. However, differently from schemes for dynamic provisioning of reliable connections, the time allowed for the flooding protocol to converge is the Mean Time Between Failure (MTBF) that is usually bigger than the connection request interarrival time.

Moreover, the SPR schemes scale well with the increasing number of connections and wavelengths in the networks since with a large number of connections being restored, the actual distribution of the chosen restoration paths will asymptotically approach the desired probability-based distribution that reduces the blocking probability of the overall restoration attempts. Last but not least, the node databases, where network resource information and pre-calculated paths are stored, depend only on the network dimensions (number of nodes and links) and the number of pre-calculated paths.

The SPR schemes proposed in this work are based on three different algorithms for calculating the choice probability of a restoratiion path. In the first scheme each precomputed path is assigned a uniform choice probability. In the second the choice probability depends on the ratio between the network resource available after failure and the potential resources utilized by restoraiton lightpaths. In the third scheme the choice probability calculation is based on a ball and urn model. In the following sections the SRP schemes are described in more details and applied at the optical layer (OL) to restore lightpaths disrupted by a fiber cut (i.e., link failure). Results obtained using a benchmark network reveal that in spite of the lack of signaling and coordination between the agents, the SPR schemes significantly reduce the blocking probability of the restoration attempts when compared to other restoration schemes, such as alternate routing, and perform closely to centralized schemes based on ILP solution.

II. Previous work

Thus far many solutions have been proposed in the literature to implement restoration algorithms. The solutions differently combine the four types of restoration depicted in Figure 1 to efficiently exploit the qualities of each of them.

In [17] a hybrid restoration technique is proposed. This technique, called NETSPAR, separates the phase of failure location and restoration activation from the problem of designing a network reconfiguration for the failure. Response to a failure is accomplished by a distributed protocol executed at the network nodes. Surviving network nodes converge to an agreement on the surviving topology and based on the agreed topology and on a precomputed plan for that topology reconfigure themselves to restore the disrupted connections. The precomputed plan consists of a rerouting policy and configuration that are determined in a centralized location. For each covered failure new routes for the connections disconnected by that failure are precalculated and downloaded (prior to the failure) to all nodes. The new routes are calculated using the spare capacity on the surviving links and the capacity previously used and released by disrupted connection (stub release), without rerouting connections not involved in the failure. NETSPAR reduces the reliability requirements of the controller and its communication network by removing the centralized controller from the immediate failure response. It works for any failure that can be detected and classified. However, for each covered failure, each node is required to store a different configuration table. This implies high storage requirement, proportional to network traffic, number of covered failures, and memory required for each configuration table. In addition, restoration configurations are limited to the finite number of covered failures and precomputed restoration plans must change if traffic pattern changes. In the end failure recovery time is proportional to the required time for the most distant node to find out about a failure and the time for that node to load the corresponding configuration table.

In [18] another hybrid approach called Multilayer Restoration Strategy (MRS) is proposed. In this case both pre-planned and real-time distributed restoration are implemented. Pre-planned restoration attempts to restore disrupted connections along one preferred path. This is to guarantee extremely fast, low contention, and pre-optimized restoration. Real-time restoration supplements this to ensure high restorability when the pre-planned route does not succeed in establishing a connection. The pre-planned restoration path is calculated by a distributed background route finder at each node that, during normal network operation, look for alternative routes (not necessarily link disjoint from the working one) corresponding to failure of all the resources connected to it. Upon failure pre-planned and real-time restoration processes are simultaneously activated. If the pre-planned path is successfully established the real-time result is discarded. Instead, if pre-planned path is not valid, a back-track undo procedure for the pre-planned path permits the real-time process to take-over the restoration. By combining pre-planned and real-time restoration the proposed method offers restoration time faster than conventional restoration algorithms and ensures high restorability to link, path, and node failure. However pre-planning requires storage at the node proportional to the network size and the number of channels along the links connected to the node. Furthermore completion time of the distributed background route finder must be lower than Mean Time Between Failure (MTBF) of the network (that, however, as of today, can be assumed high) and coordination between the two schemes is required.

In [19] the aim is to implement a Distributed Restoration Algorithm (DRA) that incorporates a relatively simple heuristic algorithm to approximate the solution to the Integer MCMF that models the failure scenario. The proposed DRA is able to find all the required information in the network itself at the time of failure without requiring any database of either restoration path or network topology either centrally or at every node. However the DRA still presents slow failure recovery time. To improve the failure recovery time a Distributed Pre-Planning (DPP) technique that decouples the real-time phase of restoration from the slower path-set finding phase performed ahead of the fault by the DRA, is also proposed. The DPP, by continually executing the DRA in the background, utilizes it as an autonomous prefailure distributed preplanning process. This way each network node updates and continually adapts to the actual network status a local table that contains only the minimum of information required for restoration in each possible failure scenario. However, while this scheme eliminates the need for a centralized database and any computational dependency from it, it presents a finite interval of vulnerability between any network status update and the recalculation of the DPP node tables. In fact the time required to build the restoration tables at each node is proportional to the number of network failures scenarios (e.g., number of single link failures) and the DRA execution time. Therefore an optimal decision on the connection rerouting cannot be mode before the DRA completion.

III. The Stochastic Preplanned Restoration Schemes

The Stochastic Preplanned Restoration (SPR) schemes are characterized by the following two phases:

- the off-line phase prior to the fault occurrence for
  - preplanning of the restoration paths
  - broadcast of network status information
- the on-line phase upon failure occurrence for
  - assignment of choice probability to restoration paths
  - choice of the restoration path
  - activation of the restoration lightpath.

Each scheme differs from the others on the required node databases, on the calculation of the restoration path choice probability, and the broadcast network status information. In the remainder of the paper the term *path* is used to indicate a possible ordered set of links along which a connection may be routed. The term *lightpath* is used to indicate the path chosen to carry the connection.

A. Network Model

To describe the different SPR schemes the following quantities are defined.

- $G(\mathbf{N}, \mathbf{L})$, the graph consisting of N nodes and L unidirectional links representing the OL network;
- $\mathbf{P_{s,d}} = \{p^1_{s,d}, \cdots, p^k_{s,d}\}$, the set of k paths between s and d.
- $\mathbf{L_{p^i_{s,d}}} = \{l_0, l_1, \cdots, l_j\}$, the set of links l_j, $0 \leq j \leq L-1$, in path $p^i_{s,d}$;
- $\delta^l_{p^i_{s,d}}$, a binary variable assuming value 1 if link $l \in \mathbf{L_{p^i_{s,d}}}$ and 0 otherwise;
- $\mathbf{W_{s,d}} = \{p^{i_1}_{s,d}, \cdots, p^{i_v}_{s,d}\}$, the set of paths chosen to carry working lightpaths for pair (s, d);

- $\mathbf{R^i_{s,d}} = \mathbf{P_{s,d}} \setminus p^i_{s,d} = \{p^{j_1}_{s,d}, \cdots, p^{j_t}_{s,d}\}$, the set of paths available for restoration of lightpaths routed along path $p^i_{s,d} \in \mathbf{W_{s,d}}$;
- $\mathbf{D_{p^i_{s,d}}} = \{d^{1,i}_{s,d}, \cdots, d^{k,i}_{s,d}, \cdots, d^{D,i}_{s,d}\}$, the set of lightpaths from s to d routed along path $p^i_{s,d}$;
- $D_{p^i_{s,d}} = |\mathbf{D_{p^i_{s,d}}}|$, the number of lightpaths from s to d routed along path $p^i_{s,d}$;
- $D_{s,d} = \sum_{p^i_{s,d} \in \mathbf{W_{s,d}}} D_{p^i_{s,d}}$, the total number of lightpaths between s and d.

The multiple paths in the set $\mathbf{P_{s,d}}$ can be computed using either a k *link-disjoint shortest path* or a k *link and node-disjoint shortest path* algorithm to overcome either single link or single link and single node failure, respectively. The path computation algorithms are applied to the network topology built at the node by exploiting link state routing protocol (e.g., OSPF [21]) information. During the off-line phase for each newly generated connection request for pair (s, d), one of the k paths is chosen to be the working lightpath and it is setup by reserving bandwidth (i.e., one wavelength) along each link of the path by means of GMPLS signaling protocols (e.g., CR-LDP) [22]. The other paths are the potential restoration paths. During this phase the routing protocol broadcasts information regarding the network status to each network node. The broadcast information depends on the specific SPR scheme implemented.

During the on-line phase each agent associated with the disrupted lightpath assigns to each restoration path the probability to be activated as restoration lightpath upon network failure[2]. The agent readily chooses a restoration path for its disrupted working lightpath. This choice is stochastic and based on the computed probabilities. During this phase, signaling is limited to the notification of the failed link and to the setting up of the Optical Crossconnects (OXCs) along the routes followed by the restoration lightpaths. In case a selected restoration lightpath is unsuccessful (blocked) a notification message is sent back to the connection agent.

[2]The calculation of this probability varies depending on the SPR scheme considered.

B. *Stochastic Preplanned Restoration scheme with Uniform path choice — SPR-U*

The Stochastic Preplanned Restoration scheme with Uniform path choice, *SPR-U* for short, is the simplest among the SPR class schemes. The only network status information maintained at each network node is represented by network topology graph $G(\mathbf{N}, \mathbf{L})$ and the set of paths $\mathbf{P_{s,d}}$ computed during the off-line phase for each destination d actively connected by at least one working lightpath.

During the on-line phase, each agent associated with a connection routed along a path $p^i_{s,d} \in \mathbf{W_{s,d}}$ disrupted by the failure of a link $\bar{l}$ assigns to each available restoration path $p^j_{s,d} \in \mathbf{R^i_{s,d}}$ a uniform probability to be chosen as restoration lightpath

$$Pr^{\bar{l}}_{p^j_{s,d}} = 1/|\mathbf{R^i_{s,d}}|. \tag{1}$$

The chosen restoration path is then activated.

With respect to a simple Alternate Routing (AR) scheme in which the disrupted connections can exploit only one restoration path, the SPR-U offers the advantage of choosing among multiple restoration paths. This leads to the uniform balancing of the disrupted connections among the available restoration paths. However the choice is not based on either any network status information (except for a link being functioning or not) or forecast resource contention among restoration paths.

C. *Stochastic Preplanned Restoration scheme with Proportional Weighted path choice — SPR-PW*

In the Stochastic Preplanned Restoration scheme with Proportional Weighted path choice (SPR-PW), the node database includes, in addition to the network topology and the list of computed paths, a more detailed network status information. The network status information regarding each network link $l \in L$ consists of the following quantities:

- c_l, the total capacity of link l;
- μ_l, the utilized working capacity along link l;
- $\lambda^{\bar{l}}_l$, the potential capacity required by restoration lightpaths on link l upon failure of link $\bar{l} \in L$,

where c_l and μ_l are a scalar values while $\lambda_l^{\bar{l}}$ is a vector of $|L|$ elements.

The values of c_l, μ_l, and $\lambda_l^{\bar{l}}$ when the set of paths, $\mathbf{P_{s,d}}$, calculated by each source node consists of the k link-disjoint shortest paths between the node pair (s,d) can be expressed as follows. While the value of c_l is fixed once each network link capacity is assigned, the values of μ_l, and $\lambda_l^{\bar{l}}$ are given by the following equations

$$\mu_l = \sum_{s,d} \sum_{p^i_{s,d} \in \mathbf{W_{s,d}}} D_{p^i_{s,d}} \delta^l_{p^i_{s,d}} \tag{2}$$

$$\lambda_l^{\bar{l}} = \sum_{s,d} \sum_{p^i_{s,d} \in \mathbf{W_{s,d}}} \sum_{p^j_{s,d} \in \mathbf{R^i_{s,d}}} D_{p^i_{s,d}} \delta^{\bar{l}}_{p^i_{s,d}} \delta^l_{p^j_{s,d}} \tag{3}$$

The network status information is built at each node during the off-line phase by means of proposed extensions to routing and signaling protocols such as OSPF-TE and CR-LDP [23].

In SPR-PW, during the on-line phase, based on the former quantities c_l, μ_l, and $\lambda_l^{\bar{l}}$, each agent associated with a connection routed along a path $p^i_{s,d}$ passing through the failed link $\bar{l}$, independently assigns a weight $w_l^{\bar{l}}$, to each network link belonging to the set of available restoration paths $\mathbf{R^i_{s,d}}$

$$w_l^{\bar{l}} = \frac{c_l - \mu_l}{\lambda_l^{\bar{l}}}, \forall\, l \in \mathbf{L_{p^j_{s,d}}}, p^j_{s,d} \in \mathbf{R^i_{s,d}}. \tag{4}$$

The weight indicates the likelihood of the link l, to be used for restoration upon the failure of another link $\bar{l}$ (or more in general of a network element).

A weight $w^{\bar{l}}_{p^j_{s,d}}$ is then associated with each restoration path $p^j_{s,d} \in \mathbf{R^i_{s,d}}$. The weight is computed as follows

$$w^{\bar{l}}_{p^j_{s,d}} = \min_{l \in \mathbf{L_{p^j_{s,d}}}} w_l^{\bar{l}}. \tag{5}$$

From the weight values, every agent computes the probability of success (i.e., no resource contention) in attempting to establish each of its restoration paths. The probability of choosing path $p^j_{s,d}$ to carry a restoration lightpath given the failure of link $\bar{l}$ is computed using the following formula

$$Pr^{\bar{l}}_{p^j_{s,d}} = \frac{w^{\bar{l}}_{p^j_{s,d}}}{\sum_{p^j_{s,d} \in \mathbf{R^i_{s,d}}} w^{\bar{l}}_{p^j_{s,d}}}. \quad (6)$$

It is worth to notice that agents associated with disrupted connections between the same (s, d) pair independently calculates the same values of $Pr^{\bar{l}}_{p^j_{s,d}}$. Then the agents chooses the restoration path based on the calculated probabilities $Pr^{\bar{l}}_{p^j_{s,d}}$ and it activates the chosen one.

D. Stochastic Preplanned Restoration scheme with Binomial Weighted path choice

The Stochastic Preplanned Restoration scheme with Binomial Weighted path choice (SPR-BW) is based on either a *global* or *local ball-and-urn (BU) model* [24]. The BU model is used for the assignment to each available restoration path $p^j_{s,d}$ of the probability $Pr^{\bar{l}}_{p^j_{s,d}}$ of being activated as a restoration lightpath.

The main elements of either model are:

- $b^{k,i,\bar{l}}_{s,d}$, ball representing the k-th connection $d^{k,i}_{s,d}$ between pair (s, d) routed along working path $p^i_{s,d}$ disrupted by the failure of link $\bar{l}$;
- $u_{\hat{l}^{\bar{l}}_{j,s,d}}$, urn representing, through *bottleneck link* $\hat{l}^{\bar{l}}_{j,s,d}$, one available restoration path $p^j_{s,d}$ for connections between the pair (s, d) disrupted by the failure of link $\bar{l}$.

The bottleneck link $\hat{l}^{\bar{l}}_{j,s,d}$ is defined as the link l belonging to the path $p^j_{s,d}$ whose weight $w^{\bar{l}}_l$ is minimum

$$\hat{l}^{\bar{l}}_{j,s,d} = l : \min_{l \in \mathbf{L_{p^j_{s,d}}}} w^{\bar{l}}_l; \quad (7)$$

D.1 Model construction

For consistency with the previous algorithms, it is assumed that the failure scenario consists of a single link failure, e.g. link $\bar{l}$, and the paths in the set $\mathbf{P_{s,d}}$ are the k-link disjoint shortest paths between s and d. Either BU model construction is characterized by the following phases:

- *Ball calculation* (phase $\mathcal{B}$)
- *Urn definition* (phase $\mathcal{U}$)
- *Linking of balls to urns* (phase $\mathcal{L}$)

The main difference in the construction of the two BU models consists in the implementation of the three phases (namely $\mathcal{B}, \mathcal{U}$, and $\mathcal{L}$) and in the network status information available at the nodes.

The *global BU model* construction can be conducted either at a central controller node (centralized implementation) or, independently, at each network node (distributed implementation). In either implementation the necessary network status information consists of all the precomputed paths $\mathbf{P_{s,d}}$ and of all the working connections $\mathbf{D_{p^i_{s,d}}}$ routed along any working path $p^i_{s,d} \in \mathbf{W_{s,d}}$ for any (s,d) pair. For simplicity purposes the centralized global BU model implementation is described. The distributed global BU model implementation consists of the same construction phases of the centralized global BU model replicated at each network node.

Upon notification of a network failure, e.g., the failure of link $\bar{l}$, the central node starts the global BU model construction. During phase $\mathcal{B}$ the central node identifies, for any (s,d) pair, which paths $p^i_{s,d} \in \mathbf{W_{s,d}}$ carrying working connections $d^{k,i}_{s,d}$ are affected by the failure. The central node defines the following variables

- $\mathbf{\Phi^{\bar{l}}_{s,d}}$, the set of paths between node pair (s,d) disrupted by the failure of link $\bar{l}$ [3]

$$\mathbf{\Phi^{\bar{l}}_{s,d}} = \{p^i_{s,d} \in \mathbf{W_{s,d}} : \bar{l} \in \mathbf{L_{p^i_{s,d}}}\}; \tag{8}$$

- $\mathbf{\Phi^{\bar{l}}}$, the set of all the paths between any pair (s,d) disrupted by the failure of link $\bar{l}$

[3] In case the set of precomputed paths $\mathbf{P_{s,d}}$ for pair (s,d) is link-disjoint, one and only one path $p^i_{s,d} \in \mathbf{W_{s,d}}$ is affected by the failure of link $\bar{l}$.

$$\mathbf{\Phi^{\bar{l}}} = \bigcup_{s,d} \mathbf{\Phi^{\bar{l}}_{s,d}}; \tag{9}$$

From the sets of equations 8 and 9 the central node then computes

- $\mathbf{B^{\bar{l}}_{s,d}}$, the set of balls representing failed connections between the pair (s, d)

$$\mathbf{B^{\bar{l}}_{s,d}} = \{b^{k,i,\bar{l}}_{s,d} : d^{k,i}_{s,d} \in \mathbf{D_{p^i_{s,d}}}, p^i_{s,d} \in \mathbf{\Phi^{\bar{l}}_{s,d}}\}. \tag{10}$$

- $\mathbf{B^{\bar{l}}}$, the set of all the balls representing connections disrupted by the failure of link $\bar{l}$

$$\mathbf{B^{\bar{l}}} = \bigcup_{s,d} \mathbf{B^{\bar{l}}_{s,d}} \tag{11}$$

During phase $\mathcal{U}$ the central node identifies which restoration paths $p^j_{s,d} \in \mathbf{R^i_{s,d}}$ are available for any disrupted connection. The following variables are defined

- $\mathbf{\Psi^{\bar{l}}_{s,d}}$, the set of paths available for the restoration of any disrupted connection $d^{k,i}_{s,d}$ between the pair (s, d) routed along any working lightpath $p^i_{s,d} \in \mathbf{\Phi^{\bar{l}}_{s,d}}$

$$\mathbf{\Psi^{\bar{l}}_{s,d}} = \mathbf{P_{s,d}} \setminus \mathbf{\Phi^{\bar{l}}_{s,d}} \tag{12}$$

- $\mathbf{\Psi^{\bar{l}}}$, the set of all the restoration paths for any (s, d) pair

$$\mathbf{\Psi^{\bar{l}}} = \bigcup_{s,d} \mathbf{\Psi^{\bar{l}}_{s,d}}. \tag{13}$$

To define the urns involved in the model the central node first defines the set of bottleneck links of all the available restoration paths $p^j_{s,d} \in \mathbf{\Psi^{\bar{l}}_{s,d}}$ for the pair (s, d)

$$\mathbf{\hat{L}^{\bar{l}}_{s,d}} = \{\hat{l}^{\bar{l}}_{j,s,d} : p^j_{s,d} \in \mathbf{\Psi^{\bar{l}}_{s,d}}\} \tag{14}$$

Because of the one to one correspondence between bottleneck links and urns the set of urns to which all the balls $b_{s,d}^{k,i,\bar{l}}$ representing disrupted connections between the pair (s,d) can be assigned is

$$\mathbf{U}_{\mathbf{s,d}}^{\bar{\mathbf{l}}} = \{u_{\hat{l}_{j,s,d}^{\bar{l}}} : \hat{l}_{j,s,d}^{\bar{l}} \in \hat{\mathbf{L}}_{\mathbf{s,d}}^{\bar{\mathbf{l}}}\} \tag{15}$$

However bottleneck links of restoration paths belonging to different source destination pairs may coincide (e.g., link (3,7) in Fig. 2)

$$\hat{l}_m^{\bar{l}} = \hat{l}_{j,s,d}^{\bar{l}} = \cdots = \hat{l}_{q,o,e}^{\bar{l}} \tag{16}$$

and, therefore, the intersection of the sets of bottleneck links of restoration paths available between different source-destination pairs may not be the empty set

$$\hat{\mathbf{L}}_{\mathbf{s,d}}^{\bar{\mathbf{l}}} \cap \cdots \cap \hat{\mathbf{L}}_{\mathbf{o,e}}^{\bar{\mathbf{l}}} \neq \emptyset. \tag{17}$$

Similarly for sets of urns belonging to different (s,d) pairs

$$\mathbf{U}_{\mathbf{s,d}}^{\bar{\mathbf{l}}} \cap \cdots \cap \mathbf{U}_{\mathbf{o,e}}^{\bar{\mathbf{l}}} \neq \emptyset \tag{18}$$

Therefore the set of urns present in the global BU model upon failure of link $\bar{l}$ is

$$\mathbf{U}^{\bar{\mathbf{l}}} = \left\{u_{\hat{l}_1^{\bar{l}}}, \cdots, u_{\hat{l}_m^{\bar{l}}}\right\} \tag{19}$$

where

$$|\mathbf{U}^{\bar{\mathbf{l}}}| \leq \sum_{s,d} |\mathbf{U}_{\mathbf{s,d}}^{\bar{\mathbf{l}}}|. \tag{20}$$

The capacity $c_{u_{\hat{l}_m^{\bar{l}}}}$ of each urn (i.e., the number of balls the urn can contain) is the capacity of the correspondent bottleneck link

$$c_{u_{\hat{l}_m^{\bar{l}}}} = c_{\hat{l}_m^{\bar{l}}}. \tag{21}$$

During phase $\mathcal{L}$ the central node links the balls in the set $\mathbf{B}^{\bar{\mathbf{l}}}$ to the urns in the set $\mathbf{U}^{\bar{\mathbf{l}}}$. Under the assumption of single link failure all the balls $b_{s,d}^{k,i,\bar{l}}$ belonging to a (s,d) pair are linked through link $\rho_{\hat{l}^{\bar{l}}_{j,s,d}}^{k,i,s,d,\bar{l}}$ to all the urns in the set $\mathbf{U}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}$. Therefore for given a (s,d) pair the set of links $\mathbf{\Upsilon}_{\mathbf{s,d}}$ between balls and urns is

$$\mathbf{\Upsilon}_{\mathbf{s,d}} = \left\{ \rho_{\hat{l}^{\bar{l}}_{j,s,d}}^{k,i,s,d,\bar{l}} : b_{s,d}^{k,i,\bar{l}} \in \mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}, u_{\hat{l}^{\bar{l}}_{j,s,d}} \in \mathbf{U}^{\bar{\mathbf{l}}}_{\mathbf{s,d}} \right\}, \tag{22}$$

where $|\mathbf{\Upsilon}_{\mathbf{s,d}}| = |\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}| \cdot |\mathbf{U}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}|$.

The probability $Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}}^{k,i,s,d,\bar{l}})$ represents the likelihood of the link $\rho_{\hat{l}^{\bar{l}}_{j,s,d}}^{k,i,s,d,\bar{l}}$ to be used by ball $b_{s,d}^{k,i,\bar{l}}$. Because each ball of a given (s,d) pair must utilize one of the urns to which it is linked, it results that

$$\sum_{j=1}^{|\mathbf{U}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}|} Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}}^{k,i,s,d,\bar{l}}) = 1, \forall k, i. \tag{23}$$

Moreover, if full wavelength conversion is available at each network node, balls belonging to the same (s,d) pair are indistinguishable and therefore they have the same probability to utilize a particular urn. Thus

$$Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}}^{k,i,s,d,\bar{l}}) = Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}}^{s,d,\bar{l}}), \forall k, i. \tag{24}$$

Therefore probability $Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}}^{s,d,\bar{l}})$ represents also the probability $Pr^{\bar{l}}_{p^j_{s,d}}$ that the path $p^j_{s,d}$ is activated as restoration lightpath by any disrupted connection $d_{s,d}^{k,i}$ between pair (s,d).

In addition, because of equation 18, balls belonging to different (s,d) pairs may share the same urn. The set $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}_{\mathbf{m}}}$ of balls $b_{s,d}^{k,i,\bar{l}}$ sharing the same urn $u_{\hat{l}^{\bar{l}}_m}$ consists of the balls representing connections whose possible restoration paths include bottleneck link $\hat{l}_m$

$$\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}_{\mathbf{m}}} = \{ b_{s,d}^{k,i,\bar{l}} \in \mathbf{B}^{\bar{\mathbf{l}}} : p^j_{s,d} \in \mathbf{\Psi}^{\bar{\mathbf{l}}}, \hat{l}_m \in \mathbf{L}_{\mathbf{p}^{\mathbf{j}}_{\mathbf{s,d}}} \}, \tag{25}$$

where $|B^{\bar{l}}_{\hat{l}_m}| = \lambda^{\bar{l}}_{\hat{l}_m}$ and $\mathbf{B^{\bar{l}}_{\hat{l}_m}} \subset \mathbf{B^{\bar{l}}}$.

Nevertheless, balls sharing the same urn $u_{\hat{l}^{\bar{l}}_m}$ but belonging to different (s,d) pairs have, generally, different probabilities to utilize that urn. Indeed balls representing connection between different (s,d) pairs may be linked to a different set of urns, and not, as the connections between the same (s,d) pair, to a common set of urns

$$Pr(\rho^{s,d,\bar{l}}_{\hat{l}^{\bar{l}}_m}) \neq Pr(\rho^{o,e,\bar{l}}_{\hat{l}^{\bar{l}}_m}). \tag{26}$$

Completed the global model construction the central node computes the expression for the expected number of lost balls, $E[B^*]$. Thanks to the property of the expected value of random variables the expected number of lost balls, $E[B^*]$ (i.e., the expected number of balls that cannot be contained in any urn), can be written as the sum of the expected number of lost ball on each urn

$$E[B^*] = E[B^*_{u_{\hat{l}^{\bar{l}}_1}}] + \cdots + E[B^*_{u_{\hat{l}^{\bar{l}}_k}}] + \cdots + E[B^*_{u_{\hat{l}^{\bar{l}}_{|\mathbf{U^{\bar{l}}}|}}}]. \tag{27}$$

Each term of equation 27 is then computed considering the balls that can be assigned to the urn

$$E[B^*_{u_{\hat{l}^{\bar{l}}_k}}] = \underbrace{\sum_{v=0}^{|\mathbf{B^{\bar{l},\hat{l}_k}_{s,d}}|} \cdots \sum_{w=0}^{|\mathbf{B^{\bar{l},\hat{l}_k}_{o,e}}|}}_{|\mathbf{P_{u_{\hat{l}^{\bar{l}}_k}}}|} b^*_{u_{\hat{l}^{\bar{l}}_k}} \binom{|\mathbf{B^{\bar{l},\hat{l}_k}_{s,d}}|}{v} Pr(\rho^{s,d,\bar{l}}_{\hat{l}^{\bar{l}}_k})^v (1 - Pr(\rho^{s,d,\bar{l}}_{\hat{l}^{\bar{l}}_k}))^{|\mathbf{B^{\bar{l},\hat{l}_k}_{s,d}}|-v} \cdots$$

$$\binom{|\mathbf{B^{\bar{l},\hat{l}_k}_{o,e}}|}{w} Pr(\rho^{o,e,\bar{l}}_{\hat{l}^{\bar{l}}_k})^w (1 - Pr(\rho^{o,e,\bar{l}}_{\hat{l}^{\bar{l}}_k}))^{|\mathbf{B^{\bar{l},\hat{l}_k}_{o,e}}|-w}, \tag{28}$$

where $\mathbf{P_{u_{\hat{l}^{\bar{l}}_k}}}$ is the set of (s,d) pairs whose disrupted connections share urn $u_{\hat{l}^{\bar{l}}_k}$, $\mathbf{B^{\bar{l},\hat{l}_k}_{s,d}}$ is the set of balls belonging to the pair (s,d) that can be assigned to urn $u_{\hat{l}^{\bar{l}}_k}$, and $b^*_{u_{\hat{l}^{\bar{l}}_k}}$ is the number of lost balls for urn $u_{\hat{l}^{\bar{l}}_k}$.

$\mathbf{P_{u_{\hat{l}^{\bar{l}}_k}}}$, $\mathbf{B^{\bar{l},\hat{l}_k}_{s,d}}$, and $u_{\hat{l}^{\bar{l}}_k}$ are defined as follows

$$\mathbf{P}_{\mathbf{u}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{k}}}} = \{(s,d) : (\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}} \cap \mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}_{\mathbf{k}}} \neq \emptyset)\}, \tag{29}$$

$$\mathbf{B}^{\bar{\mathbf{l}},\hat{\mathbf{l}}_{\mathbf{k}}}_{\mathbf{s,d}} = \{b^{k,i,\bar{l}}_{s,d} \in (\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}} \cap \mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}_{\mathbf{k}}})\} \tag{30}$$

$$b^{*}_{u_{\hat{l}^{\bar{l}}_{k}}} = \begin{cases} \underbrace{v + \ldots + w}_{|\mathbf{P}_{\mathbf{u}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{k}}}}|} - c_{u_{\hat{l}^{\bar{l}}_{k}}}, & \text{if } \underbrace{v + \ldots + w}_{|\mathbf{P}_{\mathbf{u}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{k}}}}|} - c_{u_{\hat{l}^{\bar{l}}_{k}}} > 0 \\ 0, & \text{otherwise} \end{cases} \tag{31}$$

where $|\mathbf{P}_{\mathbf{u}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{k}}}}| = \sum_{p^{j}_{s,d} \in \Psi^{\bar{l}}} \delta^{\hat{l}_k}_{p^{j}_{s,d}}$[4], $|\mathbf{B}^{\bar{\mathbf{l}},\hat{\mathbf{l}}_{\mathbf{k}}}_{\mathbf{s,d}}| = |\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}|$.

The optimal values of the probabilities $Pr(\rho^{s,d,\bar{l}}_{\hat{l}_k})$ for any s, d, $\hat{l}_k$ are the ones minimizing $E[B^{*}]$. To compute these optimal values the central node, for example, can calculate $\nabla E[B^{*}]$ with respect to $Pr(\rho^{s,d,\bar{l}}_{\hat{l}^{\bar{l}}_{k}})$ and then solve the non-linear system of equations obtained. However minimizing $E[B^{*}]$ for complex network scenarios may require a large amount of computational resources. A simple example of the the centralized BU model construction is depicted in Figure 2 and more extensively elaborated in [25].

While the global BU model offers a complete formulation of the problem of assignment of disrupted connections to available restoration paths it presents some weaknesses:

- it implies global knowledge, either at a centralized controller or at each network node, of the network status. This would involve a large amount of information being broadcast in the network and it would require coordination among the network nodes;
- it represents an approximated model because of the mapping of the available restoration path $p^{j}_{s,d}$ to the urn $u_{\hat{l}^{\bar{l}}_{j,s,d}}$ representing the path bottleneck link $\hat{l}^{\bar{l}}_{j,s,d}$.
- imply the solution of a non-linear system of equations to find the optimal values for $Pr(\rho^{s,d,\bar{l}}_{\hat{l}^{\bar{l}}_{k}})$

[4] This expression is valid when the restoration paths $p^{j}_{s,d} \in \Psi^{\bar{l}}$ are mutually link disjoint.

- the total number $|\mathbf{U}^{\bar{\mathbf{l}}}|$ of urns involved in the model cannot be predicted *a-priori*.

Therefore, even though the optimal values for the probabilities $Pr(\rho^{s,d,\bar{l}}_{\hat{l}^{\bar{l}}_k})$ are obtained, the solution of the global BU model can only approximate the optimal solution of the problem of assigning the disrupted connections to the available restoration paths, also called Path Restoration Routing (PRR) problem [19]. On the other hand the optimal solution of the PRR problem can be obtained by optimally solving, at a central node, the ILP PRR formulation.

Nevertheless a simplified *local BU model* can be utilized to implement the distributed SPR-BW scheme. In the distributed scenario each agent associated with a disrupted connection $d^{k,i}_{s,d}$, builds its own BU model without communicationg with other agents. This lack of coordination while representing the main factor that permits to expedite the restoration process mainly contributes to the approximations of the *local BU model* .

The information necessary to the agent for building the local BU model is the same required in the SPR-PW scheme. Received the notification of the failure of link $\bar{l}$ each restoration agent finds whether or not its connection $d^{k,i}_{s,d}$ is routed along a working lightpath $p^i_{s,d}$ traversing the failed link $\bar{l}$. If so, each agent associated with a failed connection, starts building, independently from any other agent, its local BU model. The only information the agent can exploit is the information gathered at the node at which it resides (e.g., the source node s of the pair (s, d)) during the off-line phase of the restoration scheme. This information consists of c_l, μ_l, $\lambda^{\bar{l}}_l$ for any network link l, the set $\mathbf{P_{s,d}}$ of paths between the pair (s, d) and the working lightpath $p^i_{s,d} \in \mathbf{W_{s,d}}$ along which the failed connection $d^{k,i}_{s,d}$ is routed.

With this limited information the agent is not able, during phase $\mathcal{B}$, of finding neither the set $\mathbf{B^{\bar{l}}_{s,d}}$ nor the set $\mathbf{B^{\bar{l}}}$ of the global model. Therefore it immediately starts phase $\mathcal{U}$ and it computes the set $\mathbf{\Psi^{\bar{l}}_{s,d}}$ of available restoration paths. Calculated the set $\mathbf{\hat{L}^{\bar{l}}_{s,d}}$ of bottleneck links for the restoration paths in $\mathbf{\Psi^{\bar{l}}_{s,d}}$, it finds the set $\mathbf{U^{\bar{l}}_{s,d}}$ of urns to which the ball $b^{k,i,\bar{l}}_{s,d}$ representing the failed connection $d^{k,i}_{s,d}$ can be assigned. Given the set $\mathbf{U^{\bar{l}}_{s,d}}$ the agent calculates the set $\mathbf{B^{\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}}$ of balls that can be assigned to urn $u_{\hat{l}^{\bar{l}}_{j,s,d}}$

$$\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}} = \{b^{1}_{\hat{l}^{\bar{l}}_{j,s,d}}, \cdots, b^{m}_{\hat{l}^{\bar{l}}_{j,s,d}}\}, \tag{32}$$

where $|\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}}| = \lambda_{\hat{l}^{\bar{l}}_{j,s,d}}$. The main difference between the set $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}_{\mathbf{m}}}$ in the global BU model (see equation 25) and the set $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}}$ is that the the balls in the set $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}}$ are indistinguishable. Indeed with the aggregated and limited information available, i.e., $\lambda_{l^{\bar{l}}_{j,s,d}}$, the agent is not able to classify the balls into different subsets based on their source-destination pair. To approximate the set $\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}$ of the global BU model the agent computes the minimum number of balls among the sets $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}}$ as

$$\lambda^{\bar{l}}_{s,d} = \min_{j:p^{j}_{s,d} \in \mathbf{\Psi}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}} \{\lambda^{\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}\}. \tag{33}$$

Therefore the set of balls representing the estimated failed connection between the pair (s, d) coincides with the set $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}}$ of minimal cardinality

$$\bar{\mathbf{B}}^{\bar{\mathbf{l}}}_{\mathbf{s,d}} = \mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}} : \min_{j:p^{j}_{s,d} \in \mathbf{\Psi}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}} \{|\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}}|\} = \min_{j:p^{j}_{s,d} \in \mathbf{\Psi}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}} \{\lambda^{\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}\} \tag{34}$$

During phase $\mathcal{L}$ the agent links all the balls in the set $\bar{\mathbf{B}}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}$ to all the urns in the set $\mathbf{U}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}$ by means of link $\rho^{\bar{m},\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}$. The subset of balls belonging to the difference $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}} \setminus \bar{\mathbf{B}}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}$ are linked only to the urn $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}}$ by means of link $\rho^{n,\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}$.

However, because the balls belonging to a set $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}}$ are indistinguishable the agent is not able to assign different probabilities to links $\rho^{\bar{m},\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}$ and $\rho^{n,\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}$. Therefore it results that

$$Pr(\rho^{\bar{m},\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}) = Pr(\rho^{n,\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}) = Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}}) \forall \bar{m}, n : b^{\bar{m},\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}} \in \bar{\mathbf{B}}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}, b^{n,\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}} \in (\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j,s,d}}} \setminus \bar{\mathbf{B}}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}) \tag{35}$$

with the constraint that

$$\sum_{j:p^j_{s,d}\in\mathbf{\Psi^{\bar{l}}_{s,d}}} Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}}) = 1 \tag{36}$$

As in the global BU model the probability $Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}})$ represent the probability $Pr^{\bar{l}}_{p^j_{s,d}}$ that restoration path $p^j_{s,d}$ is activated as restoration lightpath of the failed connection $d^{k,i}_{s,d}$.

The agent computes the expected number of lost balls as the sum of the expected number of lost balls for each urn in the set $\mathbf{U^{\bar{l}}_{s,d}}$

$$E[B^*_{s,d}] = \sum_{j=1}^{|\mathbf{U^{\bar{l}}_{s,d}}|} E[B^*_{u^{\bar{l}}_{\hat{l}_{j,s,d}}}] \tag{37}$$

where each term of equation 37 is expressed as

$$E[B^*_{u^{\bar{l}}_{\hat{l}_{j,s,d}}}] = \sum_{k=0}^{\lambda^{\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}} w_{u_{\hat{l}^{\bar{l}}_{j,s,d}}} b^*_{u_{\hat{l}^{\bar{l}}_{j,s,d}}} \binom{\lambda^{\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}}{k} Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}})^k (1 - Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}}))^{(\lambda^{\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}} - k)}, \tag{38}$$

where

$$b^*_{u_{\hat{l}^{\bar{l}}_{j,s,d}}} = \begin{cases} k - c_{u_{\hat{l}^{\bar{l}}_k}}, & \text{if } k - c_{u_{\hat{l}^{\bar{l}}_k}} > 0 \\ 0 \quad, & \text{otherwise} \end{cases} \tag{39}$$

and

$$w_{u^{\bar{l}}_{\hat{l}_{j,s,d}}} = \frac{\lambda^{\bar{l}}_{s,d}}{\lambda^{\bar{l}}_{\hat{l}_{j,s,d}\bar{l}}}. \tag{40}$$

Equation 38 shows that, in the local BU model, a different number of balls (i.e., the balls in the set $\mathbf{B^{\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}}$) can be assigned to urn $u_{\hat{l}^{\bar{l}}_{j,s,d}}$. However because the balls in the set $\mathbf{B^{\bar{l}}_{\hat{l}^{\bar{l}}_{j,s,d}}}$ are indistinguishable they have the same probability to be assigned to that urn even if they do not correspond to failed connections between the pair (s,d). This represents the main approximation of the local BU model. The weight $w_{u_{\hat{l}^{\bar{l}}_{j,s,d}}}$ represents the ratio between the estimated number of balls belonging to the pair (s,d) and the total number of balls in the set $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{j},\mathbf{s},\mathbf{d}}}$. The weight is a way of approximating the fact that the ball representing the agent's connection may share urns with balls representing connections between different source-destination pairs.

The only cases in which the local BU model coincide with the global BU model are when the considered network is completely connected and when the global BU model has symmetry properties both from the urn capacity and the potential number of balls assignable to the urn viewpoints. In the first case, with shortest path routing of the working connections, only connections belonging to the same (s,d) are simultaneously disrupted by the failure of link $\bar{l}$. Therefore the global BU model coincides with the local BU model. In the second case, only for trivial scenarios it is possible to find necessary and sufficient conditions to prove its symmetry [25].

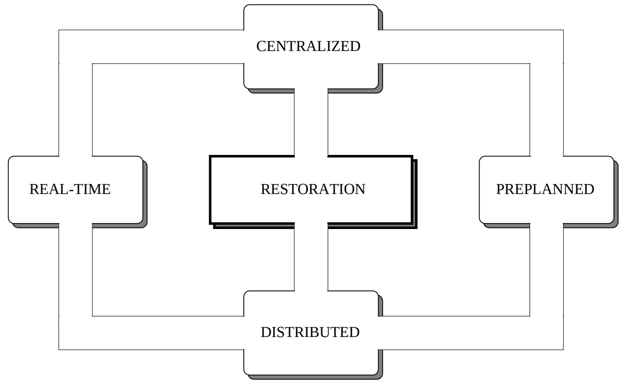

Fig. 1. Restoration techniques.

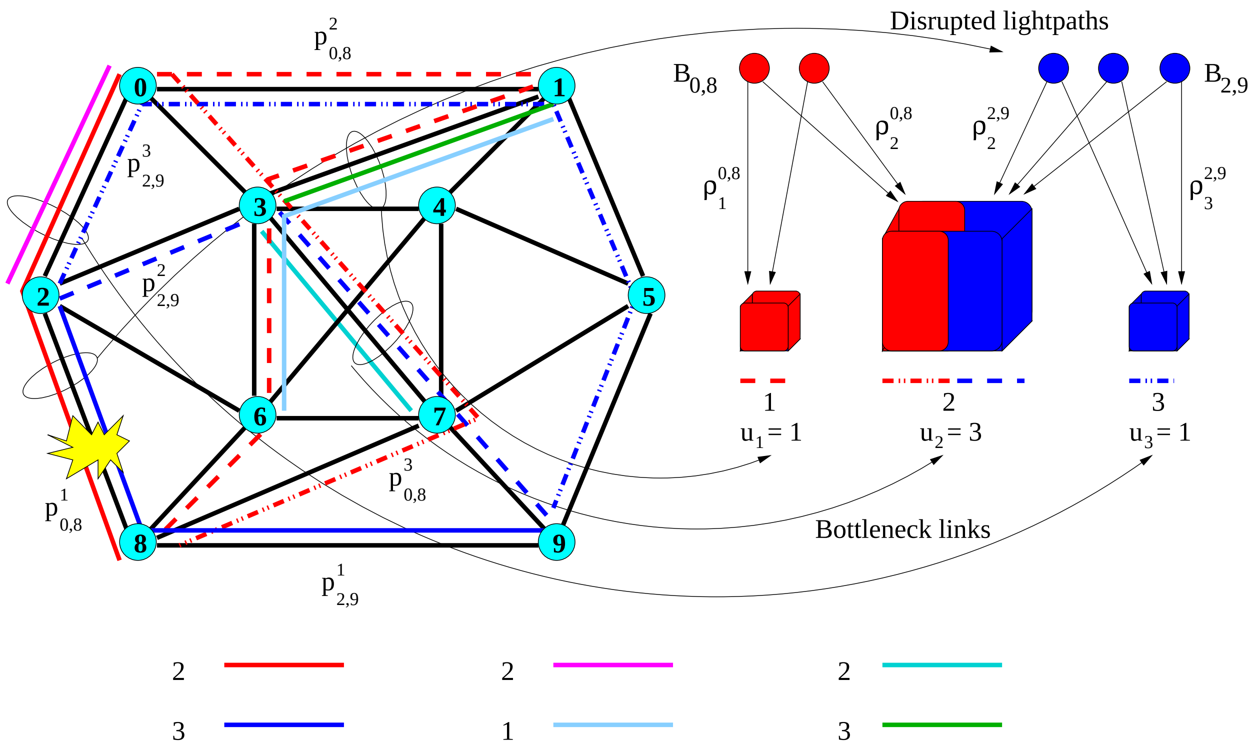

Fig. 2. Ball and urs model construction.

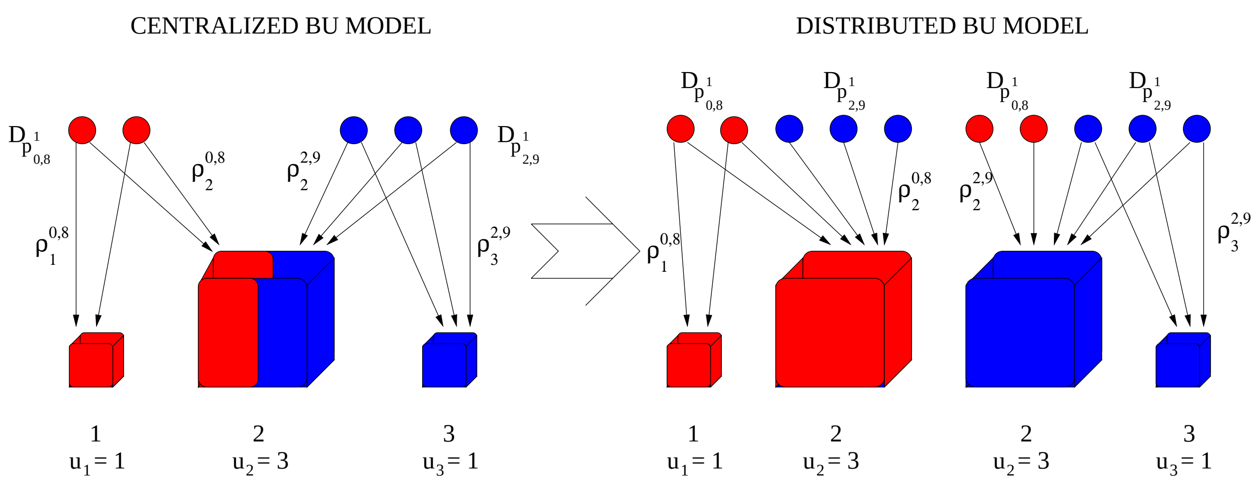

Fig. 3. Ball and urn distributed model construction.

D.2 Computation of the Restoration Path Choice Probability

In SPR-U and SPR-PW the agent associated with the disrupted connection between the pair (s,d) computes the probabilities $Pr^{\bar{l}}_{p^j_{s,d}}$ simply by applying formula 1 and formula 6, respectively. Instead, in the distributed SPR-BW, the values of $Pr^{\bar{l}}_{p^j_{s,d}}$ must be obtained from the expression of the expected number of lost balls of the local BU model [5] as values of the probabilities $Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}})$ (see equation 38) .

A way of analytically computing the optimal values for the probabilities $Pr(\rho_{\hat{l}^{\bar{l}}_{j,s,d}})$, i.e., the values that minimize $E[B^*_{s,d}]$, is to calculate $\nabla E[B^*_{s,d}]$ subject to the constraint that a ball must be assigned to one of the available urns (see equation 36). For example, assume that the number of possible urns to which a ball belonging to the pair (s,d) can be assigned is m and that the probability to assign the ball to urn j, $1 \leq j \leq m$, is p_j. Equation 37 can be rewritten as

$$E[B^*_{s,d}] = \sum_{j=1}^{m} E[B^*_j(p_j)], \tag{41}$$

where each term of the summation in 41 is function of the probability p_j.

The constraint 36 on the probabilities p_j can be rewritten as

$$\sum_{j=1}^{m} p_j = 1. \tag{42}$$

Because of constraint 42 one of the probabilities in 41, e.g., p_m, can be rewritten as

$$p_m = 1 - \sum_{j=1}^{m-1} p_j. \tag{43}$$

[5] Because of the complexity of the global BU model the analytical computation of the restoration path choice probabilities from the global BU model is impractical and therefore it is not considered in the paper.

Therefore the expression for $\nabla E[B^*_{s,d}]$ becomes

$$\nabla E[B^*_{s,d}] = \left(\frac{\partial E[B^*_{s,d}]}{\partial p_1}, \frac{\partial E[B^*_{s,d}]}{\partial p_2}, \dots, \frac{\partial E[B^*_{s,d}]}{\partial p_{m-1}} \right) \tag{44}$$

The optimal values for the probabilities p_j is then computed by solving the system of $m-1$ equations with $m-1$ unknowns expressed by

$$\nabla E[B^*_{s,d}] = \bar{0}. \tag{45}$$

However, as shown in [25], finding the optimal values for p_j by solving the system of equation 45 implies, in the most of the cases, the solution of a non-linear system of equations.

Several traditional methods are available for solving constrained minimization problems [26]. In this study the aim is to utilize an efficient yet simple algorithm that can be executed by each agent to compute the values of the probabilities p_j.

The proposed algorithm is depicted in Fig. 4. The algorithm is based on the idea of iteratively increasing the probability of urns whose incremental contribution to the expected number of lost ball is minimal.

The probability incremental step Δp is calculated so that the maximum Euclidean distance between two possible final solutions is less than the solution resolution Δs:

$$\Delta s = \bar{p} + \Delta\bar{p} = \Delta p \sqrt{m} \tag{46}$$

In the algorithm, the calculation of $\nabla E[B^*]$ is approximated by assuming the probabilities p_j independent (e.g., constraint 42 is not taken into account). Thus the agent approximates $\nabla E[B^*_{s,d}]$ as

$$\nabla E[B^*_{s,d}] \approx \left(\frac{dE[B^*_1]}{dp_1}, \frac{dE[B^*_2]}{dp_2}, \dots, \frac{dE[B^*_m]}{dp_m} \right) \tag{47}$$

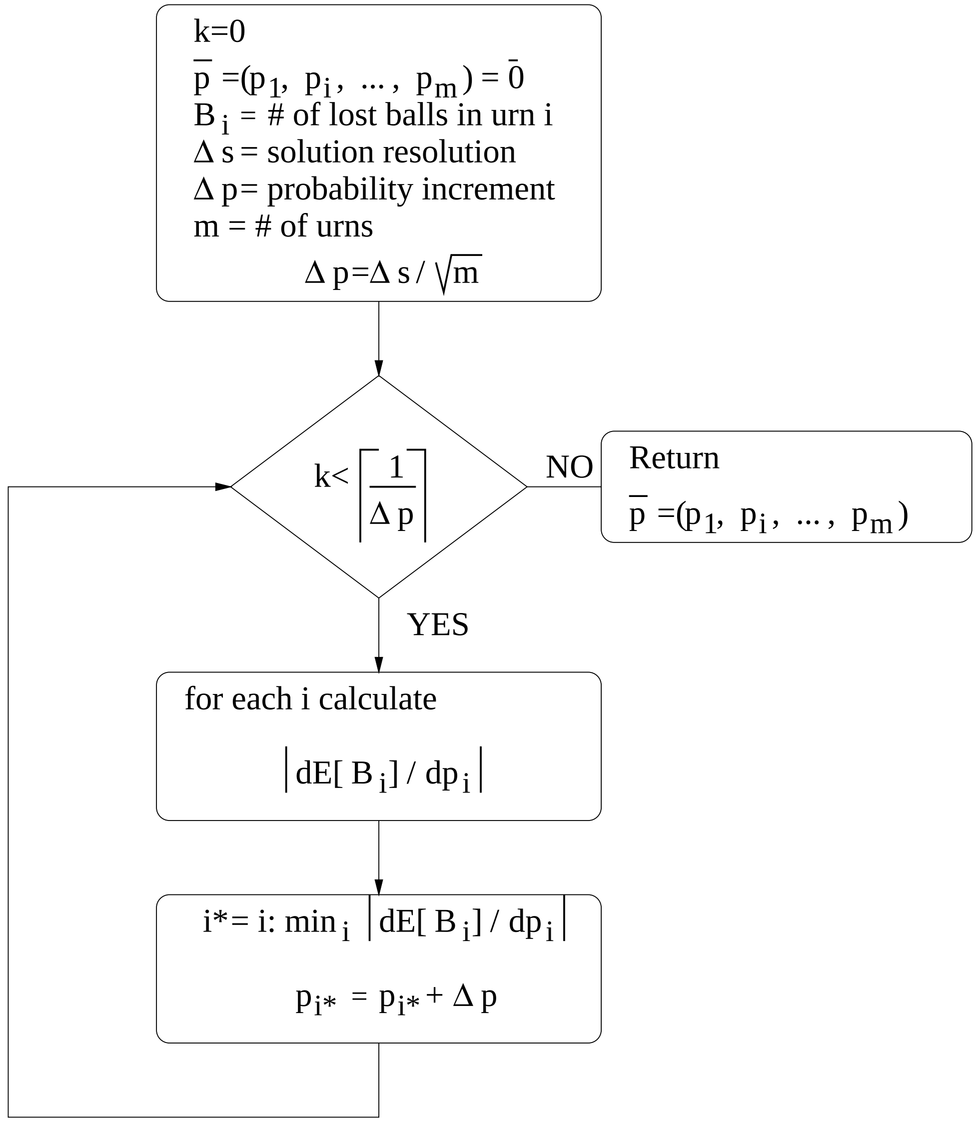

Fig. 4. Solution algorithm.

The algorithm terminates after a finite number of iterations $k = \lceil \frac{1}{\Delta p} \rceil$ converging to the values of the probabilities p_j for which the incremental contribution $dE[B_i^*]/dp_i$ to the expected number of lost balls $E[B_{s,d}^*]$ of each urn is the same [25]. The values obtained for the probabilities p_j represent the probability near-optimal values with a resolution of Δp. In addition, because of the algorithm implementation, the solution is guaranteed to satisfy the constraint on the probabilities p_j expressed by equation 42 with a resolution of Δs. The deterministic algorithm execution time makes it possible to trade solution optimality with computational time. Therefore the agent may decide to differently tune the probability incremental step Δp to exploit the trade-off between solution speed and solution resolution.

IV. Performance of the SPR Schemes

This section provides the evaluation of the SPR scheme performance. The section is organized in four parts. The first part defines other restoration schemes that are compared against the proposed scheme, the second part defines the figure of merit that is used to evaluate the performance of the schemes, the third part describes the simulation set-up, and the fourth part presents and discusses the obtained results.

A. Other Restoration Schemes

The schemes to which the SPR schemes are compared represent two previously proposed solution for restoration in optical networks. Where possible, the formalism introduced in Section III is used to provide a formal description of the scheme.

Alternate Routing (AR). This scheme, also commonly known as *diverse routing*, consists in guaranteeing to each working lightpath between any pair (s, d) one alternate path, link or node-disjoint from the working path, along which reroute connections disrupted by a network failure. This restoration scheme presented in [27], [28], [29] is the adaptation to restoration of the well known alternate routing scheme [30]. Upon failure occurrence, the affected lightpath is rerouted along the second shortest path. This scheme requires knowledge of the global network topology but does not need to know the current link utilization. The AR is equivalent to the SPR-PW case in which $w^{\bar{l}}_{p^{j*}_{s,d}} = 1$ and $w^{\bar{l}}_{p^{j}_{s,d}} = 0$ for $j \neq j^{*}$, where $p^{j^*}_{s,d}$ is such that $|L_{p^{j*}_{s,d}}| = \min_{j \neq i} |L_{p^{j}_{s,d}}|$, $p^{j}_{s,d} \in \mathbf{R^{i}_{s,d}}$, and i identifies the working path.

Centralized ILP (CILP). This scheme is similar to the the NETSPAR scheme presented in [17]. CILP is based on the centralized solution of the Path Restoration Routing (PRR) [19] problem originated by the network failure. For each considered network failure scenario the central node solves the PRR through a linear solver obtaining an optimal solution. Given a set of available restoration paths between each (s, d) pair affected by the failure, the linear solver maximizes the number of working connections restored utilizing the spare capacity available along the restoration path links. This scheme represents also a lower bound for any of the SPR schemes.

B. Performance Evaluation Criteria

SPR, AR, and CILP schemes are evaluated assuming that the disrupted connections carry traffic with stringent delay constraints that allow for one restoration attempt only. If, due to resource contention, the disrupted lightpath is not successfully restored with the first attempt made by the source, it will be assumed that the restoration of the connection has been blocked and unsuccessful. (In general, this assumption may be too restrictive. However, the study of multiple restoration attempts for the same disrupted connection is beyond the scope of the paper.)

In the presence of a resource contention, i.e., two or more agents are attempting to secure the same network resource to restore their respective disrupted lightpaths, only one attempt will be successful, while the other(s) will be blocked. Agents active at master nodes close to the failed link $\bar{l}$ receive failure notification before agents active at master nodes that are far from it. Consequently, it is assumed that agent active at master nodes close to the failed link are the first to attempt restoration of their disrupted lightpaths and thus the ones which will complete the restoration attempt successfully.

Let $\mathbf{\Pi}^{\bar{\mathbf{l}}} = \{\pi_1, \pi_2, \cdots, \pi_j\}$ be the sorted set of restoration lightpaths, $p^j_{s,d} \in \mathbf{\Psi}^{\bar{\mathbf{l}}}$, along which, upon failure of link $\bar{l}$, the disrupted lightpaths carried by $p^i_{s,d} \in \mathbf{\Phi}^{\bar{\mathbf{l}}}$ are rerouted. Set $\mathbf{\Pi}^{\bar{\mathbf{l}}}$ is sorted in terms of increasing distance, along the working lightpath $p^i_{s,d} \in \mathbf{\Phi}^{\bar{\mathbf{l}}}$, of the master node s, from the failed link $\bar{l}$. When two master nodes have the same distance from the failure location, the source node identification s brakes the tie. Following the order in set $\mathbf{\Pi}^{\bar{\mathbf{l}}}$, lightpaths are restored on a first come first serve basis.

The expected restoration blocking probability $\overline{Pr_b}$ for any single link failure is finally computed as follows. Let $Pr^{\bar{l}}_b$ be the conditional restoration blocking probability to the failed link, $\bar{l}$

$$Pr^{\bar{l}}_b = \frac{\sum_{j=1}^{|\mathbf{\Pi}^{\bar{\mathbf{l}}}|} \max\{0, \max_{l \in L_{\pi_j}} \{D_{\pi_j} - [a_l - r_l(j-1)]\}\}}{\mu_{\bar{l}}} \tag{48}$$

where $a_l = c_l - \mu_l$ is the available capacity on link l not taken by working lightpaths and $r_l(j)$ is the number of wavelengths on link l already assigned to restoration lightpaths. The quantity $r_l(j), \forall l$, is computed using the following equations

$$r_l(0) = 0 \tag{49}$$

$$r_l(j) = \min\left\{\sum_{k=1}^{j} D_{\pi_k} \cdot \delta^l_{\pi_k}, a_l\right\} \tag{50}$$

Finally, the expected restoration blocking probability $\overline{Pr_b}$ is derived averaging over all possible single link failure

$$\overline{Pr_b} = \sum_{\bar{l}=0}^{L-1} Pr^{\bar{l}}_f \cdot Pr^{\bar{l}}_b \tag{51}$$

where $Pr^{\bar{l}}_f$ is the probability that, in presence of a single link fault, the fault is at link $\bar{l}$.

By computing the *coefficient of variation (CV)* of the probabilities $Pr_{p^j_{s,d}}$ assigned by agents resident at different master nodes to restoration paths represented by a single shared urn, it is possible to evaluate, *a-posteriori*, the approximation introduced by the utilization of the local BU model instead of the global BU model. Indeed a necessary condition of the global BU model symmetry and therefore of the correspondence between the local BU model and the global BU model is that probabilities assigned to restoration paths represented by the same urn by agents resident at different master nodes are the same.

In general the coefficient of variation of a set of n probabilities p_i is defined as

$$CV = \frac{\sigma}{\mu} \tag{52}$$

where μ is the average value of the probabilities p_i and σ^2 is the variance. Given a set of n samples (i.e., n values for the probabilities p_i), μ and σ are estimated as

$$\mu = \frac{\sum_{i=1}^{n} p_i}{n} \tag{53}$$

$$\sigma^2 = \frac{1}{n-1} \sum_{i}^{n} (p_i - \mu)^2 \tag{54}$$

Therefore, utilizing the terminology defined for the global BU model, given an urn $u_{\hat{l}^{\bar{l}}_m}$ shared by a set of balls $\mathbf{B}^{\bar{\mathbf{l}}}_{\hat{\mathbf{l}}_m}$ it is possible to calculate

$$\mu_{u_{\hat{l}^{\bar{l}}_m}} = \frac{\sum_{(s,d) \in \mathbf{P}_{\mathbf{u}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{m}}}}} |\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}| Pr(\rho^{s,d,\bar{l}}_{\hat{l}^{\bar{l}}_m})}{\left(|\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}| \cdot |\mathbf{P}_{\mathbf{u}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{m}}}}|\right)} \tag{55}$$

$$\sigma^2_{u_{\hat{l}^{\bar{l}}_m}} = \frac{\sum_{(s,d) \in \mathbf{P}_{\mathbf{u}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{m}}}}} |\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}| \left(Pr(\rho^{s,d,\bar{l}}_{\hat{l}^{\bar{l}}_m}) - \mu_{u_{\hat{l}^{\bar{l}}_i}}\right)^2}{\left(|\mathbf{B}^{\bar{\mathbf{l}}}_{\mathbf{s,d}}| \cdot |\mathbf{P}_{\mathbf{u}_{\hat{\mathbf{l}}^{\bar{\mathbf{l}}}_{\mathbf{m}}}}|\right) - 1} \tag{56}$$

$$CV^{\bar{l}}_{u_{\hat{l}_m}} = \frac{\sigma_{u_{\hat{l}^{\bar{l}}_m}}}{\mu_{u_{\hat{l}^{\bar{l}}_m}}} \tag{57}$$

Then the average coefficient of variation $\overline{CV^{\bar{l}}}$ is obtained by averaging among all the urns in the global BU model, i.e., among all the bottleneck links

$$\overline{CV^{\bar{l}}} = \frac{\sum_{m: u_{\hat{l}_m} \in \mathbf{U}^{\bar{\mathbf{l}}}} CV^{\bar{l}}_{u_{\hat{l}_m}}}{|\mathbf{U}^{\bar{\mathbf{l}}}| - 1} \tag{58}$$

By averaging over all the possible single link failures we obtain the expected value of the average coefficient of variation

$$E[\overline{CV}] = \sum_{\bar{l}=0}^{L-1} Pr_f^{\bar{l}} \overline{CV^{\bar{l}}} \quad (59)$$

C. Simulation Scenario

The network depicted in Fig. 5 (first presented in [19]) is the basic network used to attest the performance of the proposed SPR schemes. In some cases customized modifications of the topology depicted in Fig. 5 are also utilized. The network is represented by a graph consisting of $N = 10$ nodes and $L = 22$ bidirectional links. In this case, $l \in L$ indicates the bidirectional link between node pair (i, j). Full wavelength conversion capability is assumed to be available at every node. The link capacity in each direction, c_l, is expressed in terms of number of wavelengths and in each experiment it is the same for all network links.

A dynamic lightpath scenario is assumed in which lightpaths are established and torn down on demand. The lifetime of a lightpath is measured in minutes or above. Lightpath demands are symmetric ($D_{(s,d)} = D_{(d,s)}$) and lightpaths between the same (s, d) pair are bundled to follow the same path along the same bidirectional links ($\mathbf{L}_{\mathbf{p}^{\mathbf{i}}_{\mathbf{s,d}}} = \mathbf{L}_{\mathbf{p}^{\mathbf{i}}_{\mathbf{d,s}}}$). Thus, upon failure of the bidirectional link $\bar{l}$, all the working lightpaths passing along $\bar{l}$ in both directions are disrupted. Upon restoration, the pair of lightpath ought to be rerouted using the same path. Set $\mathbf{\Pi^{\bar{l}}}$ is sorted using the closest master node for each (s, d) pair for the working lightpaths in both directions. Wavelength continuity is not required due the OXC wavelength conversion capabilities, therefore a lightpath can be carried using multiple wavelengths. A set of link-disjoint shortest paths are available as restoration paths for each source-destination pair.

D. Results

The performance of the restoration schemes of interest is evaluated using the expected restoration blocking probability $\overline{Pr_b}$ assuming that the link failure probability is uniformly distributed among all bidirectional network links $Pr_f^l = 1/L$. The restoration schemes are tested by varying the network achievable throughput,

θ_{ac}, defined as

$$\theta_{ac} = \frac{\sum_{s,d} \sum_{i} D_{p^{i}_{s,d}} |L_{p^{SP}_{s,d}}|}{\sum_{l=0}^{L-1} c_l} \tag{60}$$

where $\mathbf{L_{p^{SP}_{s,d}}}$ is the set of links along which the shortest path $p^{SP}_{s,d}$ among the working paths $p^{i}_{s,d} \in \mathbf{W_{s,d}}$ is routed.

Each experiment consists of simulating 2000 traffic patterns randomly generated to achieve the desired network achievable throughput. Statistics for each restoration scheme are collected for every possible link fault and every traffic pattern. For the schemes that resort to a stochastic choice of the restoration path, i.e., the SPR schemes, one thousand restoration instances are computed and averaged for each link fault and traffic pattern. The value of $Pr^{\bar{l}}_{b}$ is therefore averaged over one thousand randomly selected restoration attempts and for each traffic pattern.

The first set of experiments aims to compare the efficiency of the SPR schemes with respect to the AR and CILP algorithm. In this case each working path is routed along the shortest available path. As the reader can notice in Fig. 12 the performance obtained by the SPR-PW and SPR-BW are largely better than the AR and SPR-U schemes. In addition SPR-PW and SPR-BW are able to almost match the performance of the ideal scheme CILP. In the end, the performance of SPR-PW and SPR-BW are comparable. This is due to the approximations utilized in the implementation of the local BU model. Therefore for networks in which the local BU model does not correspond to the global BU model, SPR-PW is preferable because to compute values of the path choice probabilities it requires mathematical manipulations simpler than the ones required by SPR-BW.

Another set of experiments prove the ability of each scheme to decrease the average restoration blocking probability by increasing the number of link-disjoint paths available for restoration. All the working connections are routed along the shortest available path. In this case the completely connected version of the network depicted in Fig. 5 is utilized. This configuration permits to maintain for any set of paths the same working path (i.e., the shortest path in the set is always the same) and therefore guarantees a fair comparison among the different experiments. The respective number of paths available are 3, 6, and 9. As we can see from Fig. 6, 8, and 10 by increasing the number of available paths the average blocking probability for the same θ_{ac} decreases. In addition this set of simulation helps to better attest the difference between the proposed algorithms. In this particular network configuration, as previously underlined, the only connections disrupted by a failure are the ones belonging to only one (s, d) pair. Therefore the distributed local BU model coincides with the exact centralized global BU model. As the reader can notice the SPR-BW outperform all the other methods beside the (optimal) CILP method. It is important to notice that the average restoration blocking probability obtained by the CILP method could be obtained if coordination among the agents representing the failed connections between the pair (s, d) is allowed. For example, if the connection master node is responsible for the assignment of the disrupted connections to the available restoration paths it may apply a greedy algorithm to minimize the number of blocked restoration attempts, i.e., the average restoration blocking probability. The node, starting from any available restoration path $p^j_{s,d} \in \mathbf{R^i_{s,d}}$, assigns to the path $p^j_{s,d}$ the maximum number of connections it can carry. This number corresponds to the capacity $a_{\hat{l}^{\bar{l}}_{j,s,d}}$ available along its bottleneck link $\hat{l}^{\bar{l}}_{j,s,d}$. The algorithm terminates when either all the $D_{s,d}$ connections disrupted are assigned to a restoration path or when all the available restoration paths have been considered. In the latter case the connections not rerouted are considered blocked.

Fig. 12 and Fig. 14 show the behavior of the considered restoration schemes in case of two different working lightpath routing policies. In Fig. 12 the working connections between each (s, d) pair are routed along the shortest path $p^{SP}_{s,d}$ in the set $\mathbf{P_{s,d}}$ of pre-calculated paths for the pair (s, d). In this case the network is able to sustain the maximum achievable throughput $\theta_{ac} = 1$. On the other hand in the experiment related to Fig. 14 the working lightpaths are uniformly distributed (balanced) among all the available paths (i.e., $\mathbf{W_{s,d}} \equiv \mathbf{P_{s,d}}$). In case of failure the disrupted lightpaths can be rerouted along any of the surviving paths already carrying working connections. By comparing the plots in Fig. 12 and in Fig. 14 it is possible to notice that balancing the working lightpaths among the available restoration paths not always guarantees a lower average blocking probability. Indeed for $\theta_{ac} \geq 0.55$ all the considered schemes obtain a lower average restoration blocking probability with shortest working path routing than with balanced working path routing. In addition balancing the connections among the available paths does not permit to fully utilize the network capacity. This behavior is reconductable to the connection oriented characteristics of the lightpaths. Therefore for high values of θ_{ac}, i.e., for high network loads, balancing working lightpaths among the available shortest paths may be inefficient because potential resources available (in case of routing of working paths along the shortest path) for restoration are occupied by working paths. This, however does not influence the network at low loads. On the contrary, indeed, by balancing lightpaths among different working paths the number of failed connections for the same (s, d) pair diminishes. This helps to distribute the failure among several source-destination pairs that look for restoration resources in different parts of the network. This, on average, lowers the localized network congestion as it is the case if all the failed connections belong to the same (s, d) pair.

By comparing Fig. 12, Fig. 16, and Fig. 18 we can attest the scalability in terms of number of connections and network capacity of the proposed algorithms. By increasing the number of available wavelengths along each network link from 32 up to 1024 the performance of the proposed schemes do not decrease for correspondent values of θ_{ac}. Instead they slightly improve due to the increased connection granularity.

In the end, to attest the approximation introduced by the local BU model utilized in the SPR-BW scheme is built a set of simulation on modified topology for the network presented in [31] has been conducted. In this case from the completely connected version of the network one link at a time has been eliminated until reaching the original network configuration. In Fig. 21 and Fig.20 the expected coefficient of variation, $E[\overline{CV}]$ of the probability values respectively for each network link and for only the restoration lightpath bottleneck links is represented. It is possible to observe that decreasing the average nodal degree of the network the maximum value of the coefficient of variation increases confirming the local BU model larger approximation.

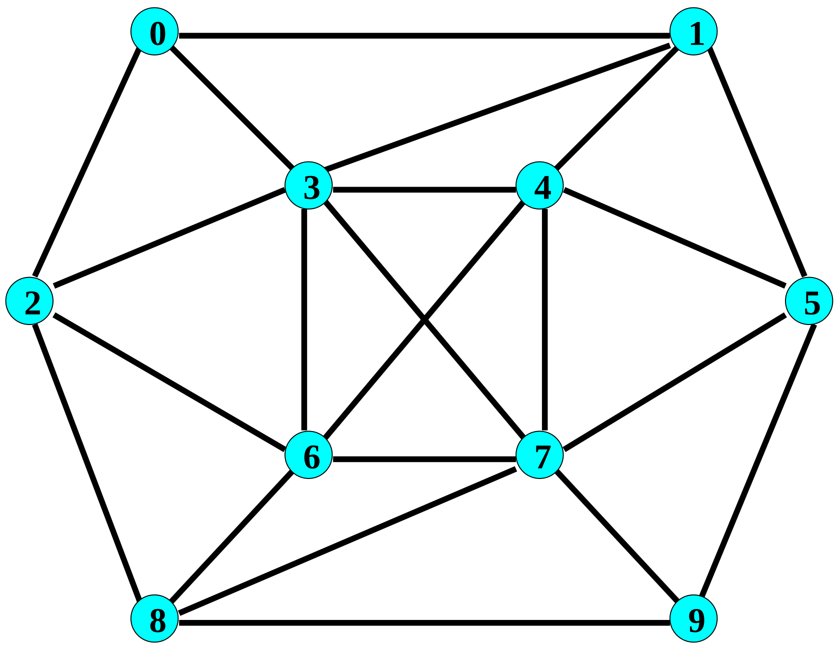

Fig. 5. Typical regional network.

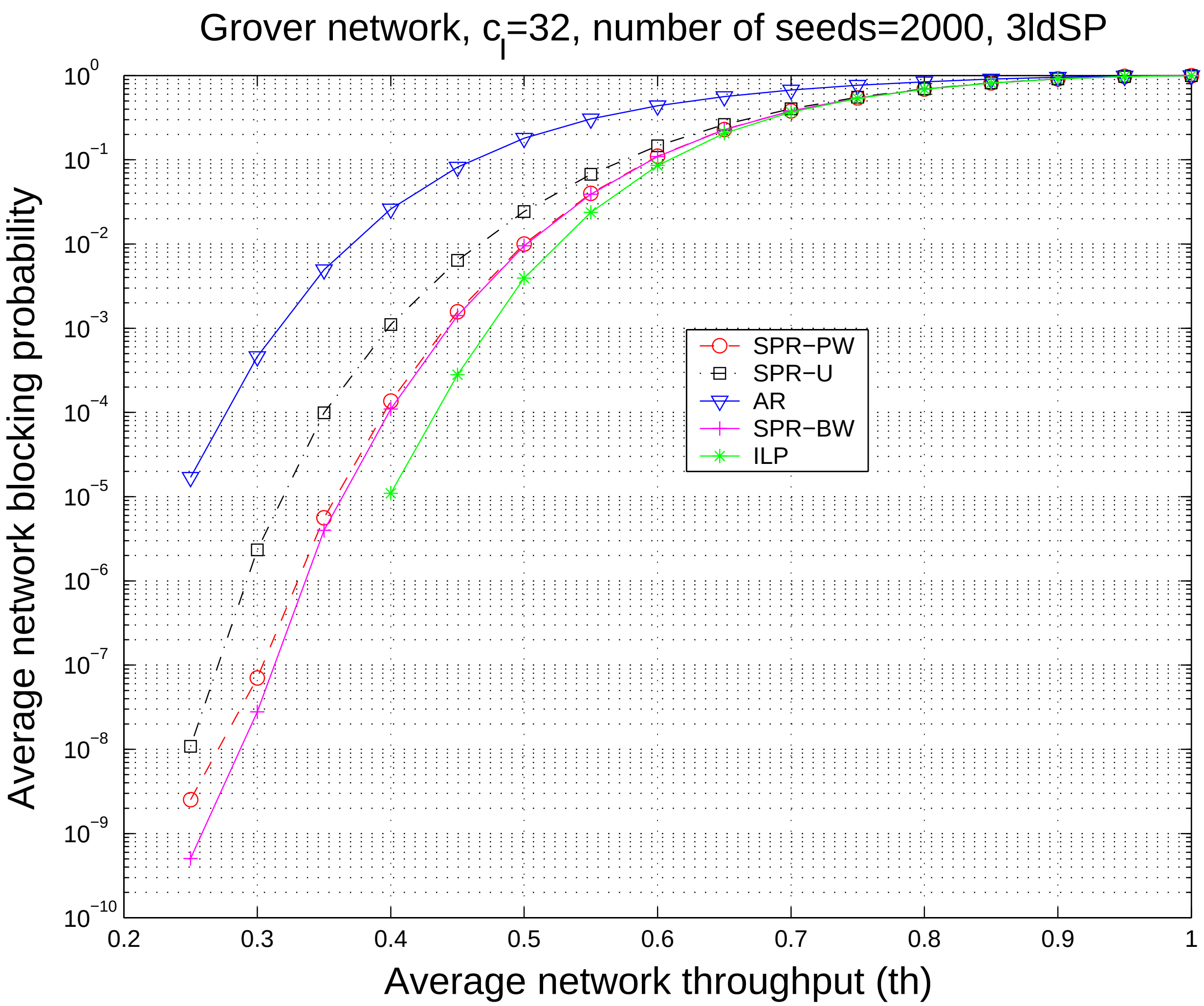

Fig. 6. $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 32$.

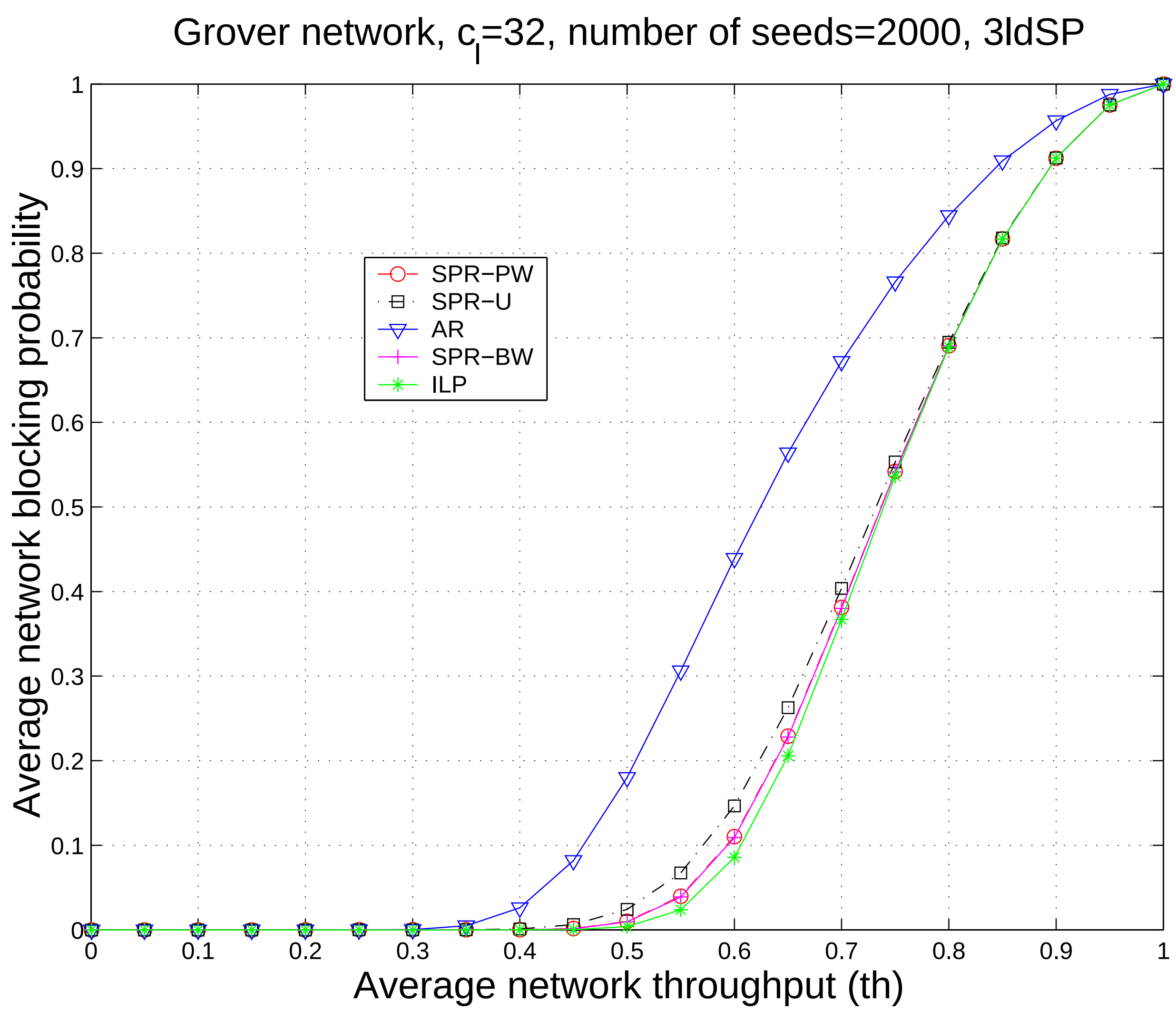

Fig. 7. Linear scale $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 32$.

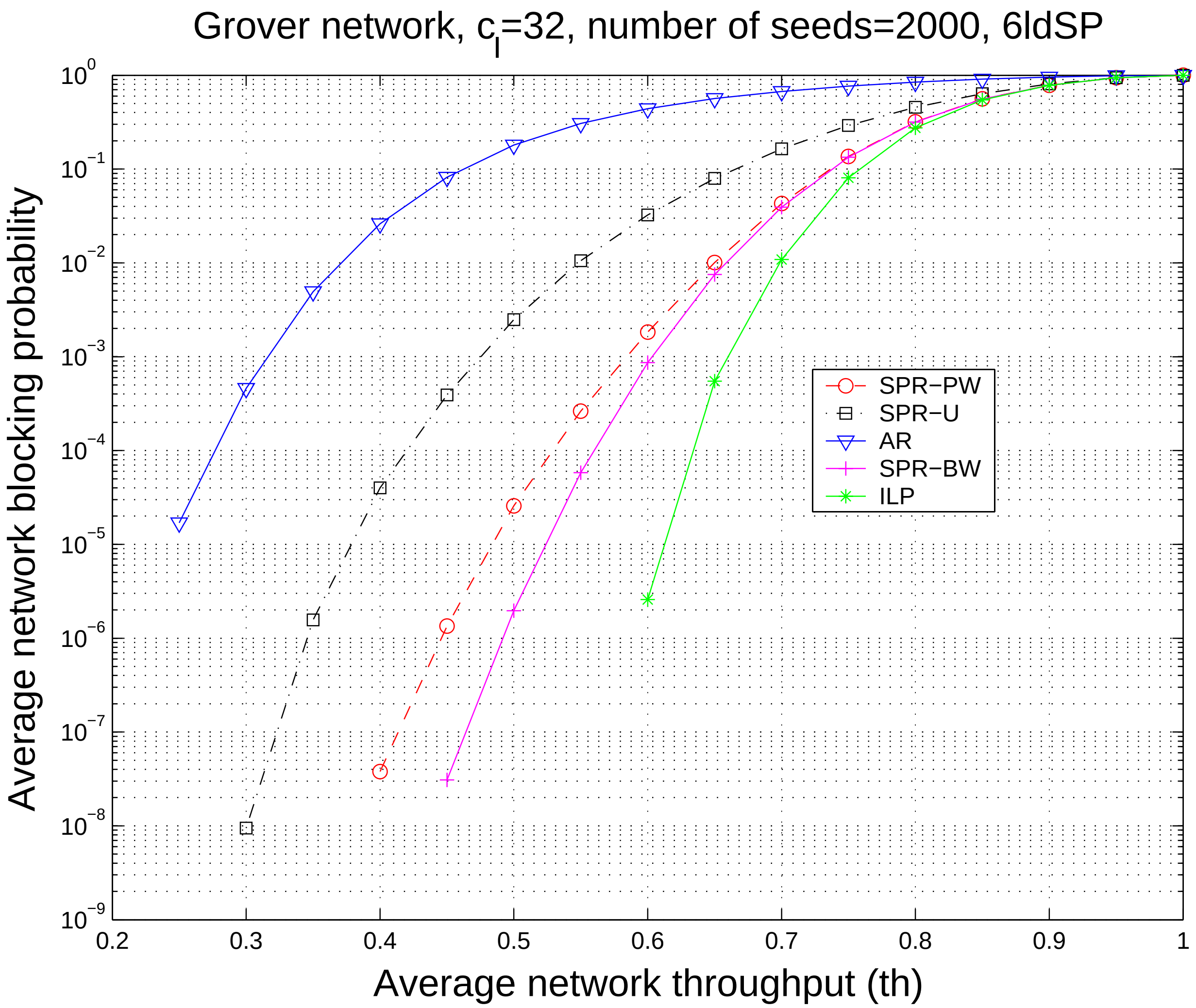

Fig. 8. $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 32$.

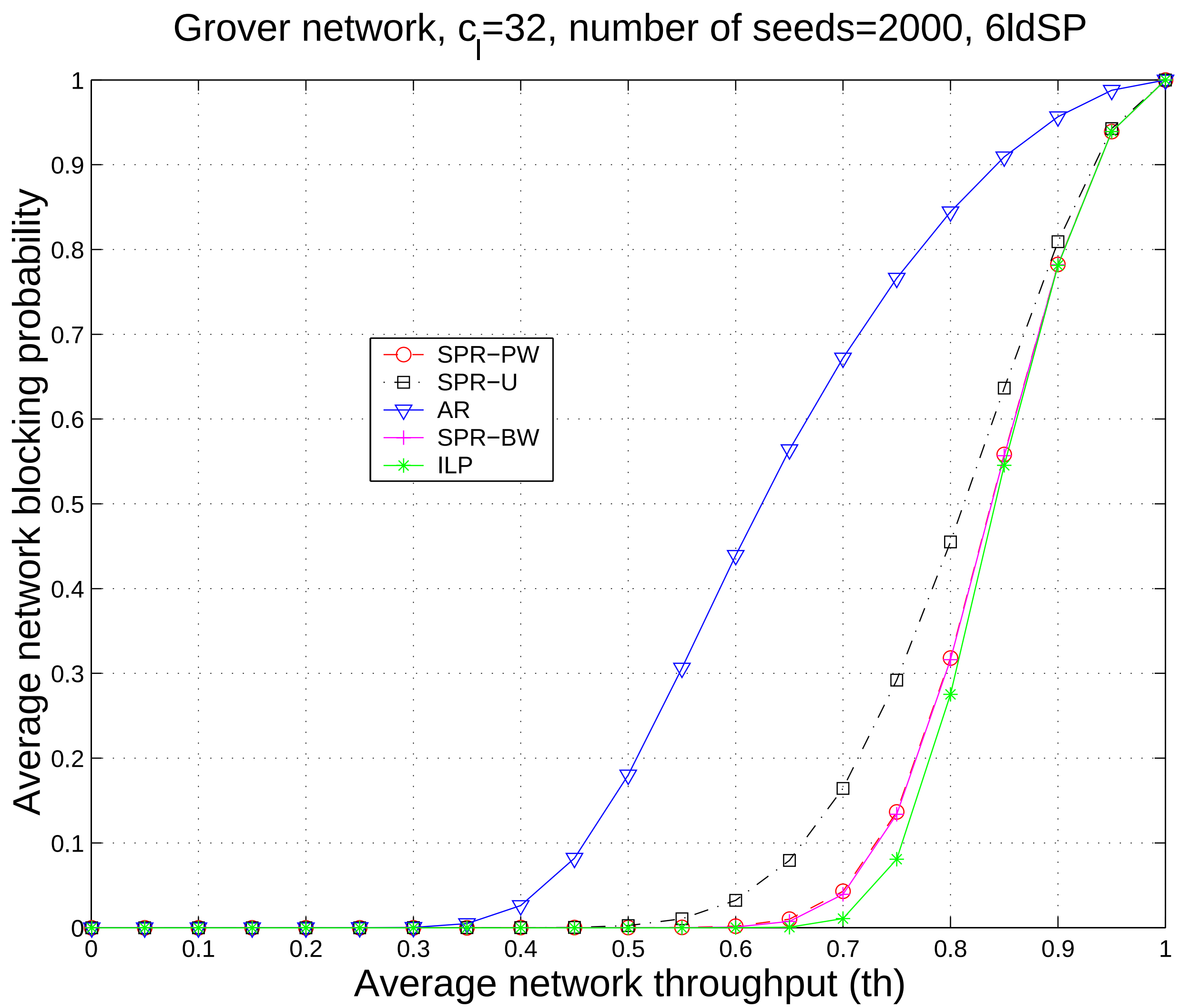

Fig. 9. Linear scale $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 32$.

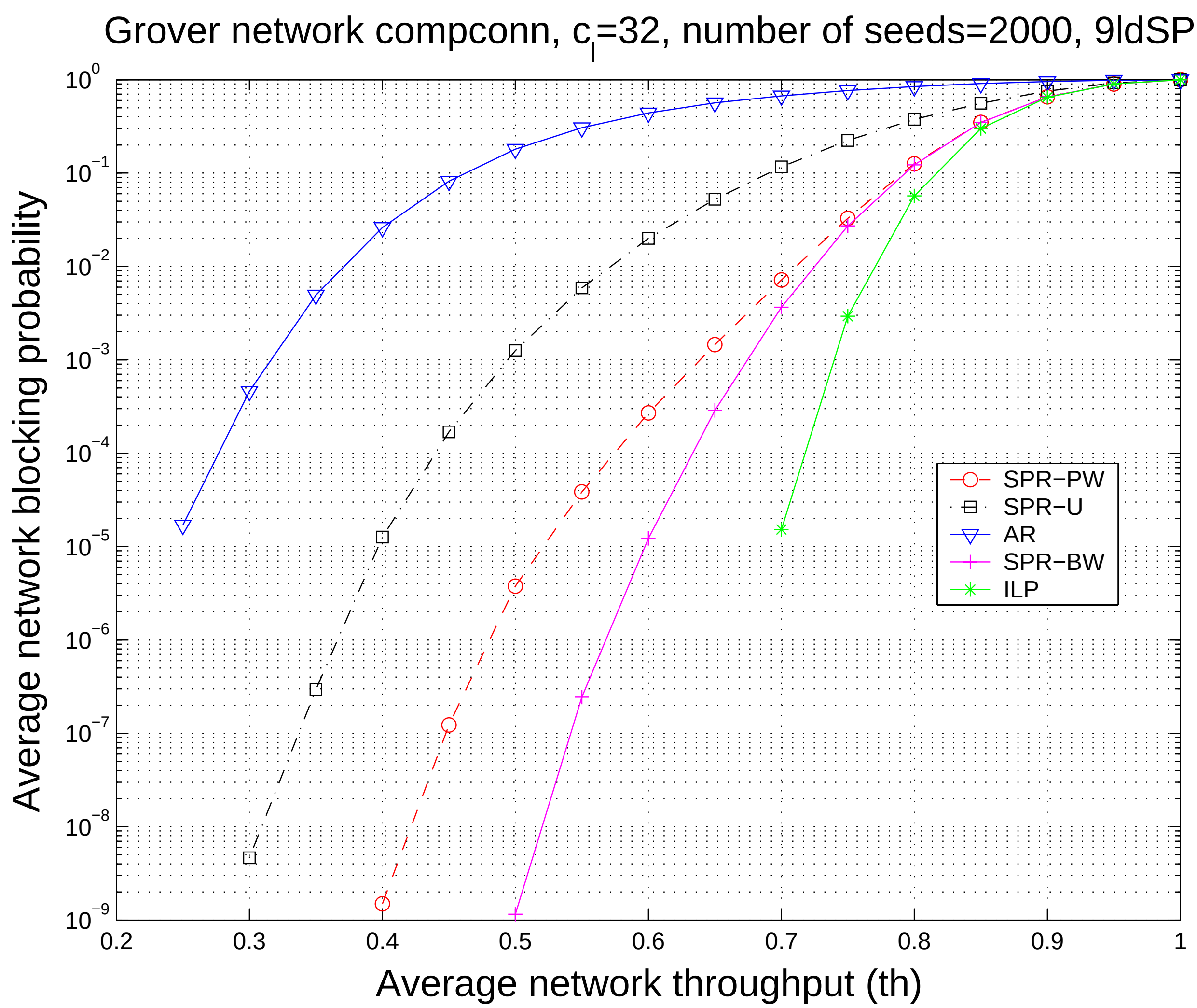

Fig. 10. $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 32$.

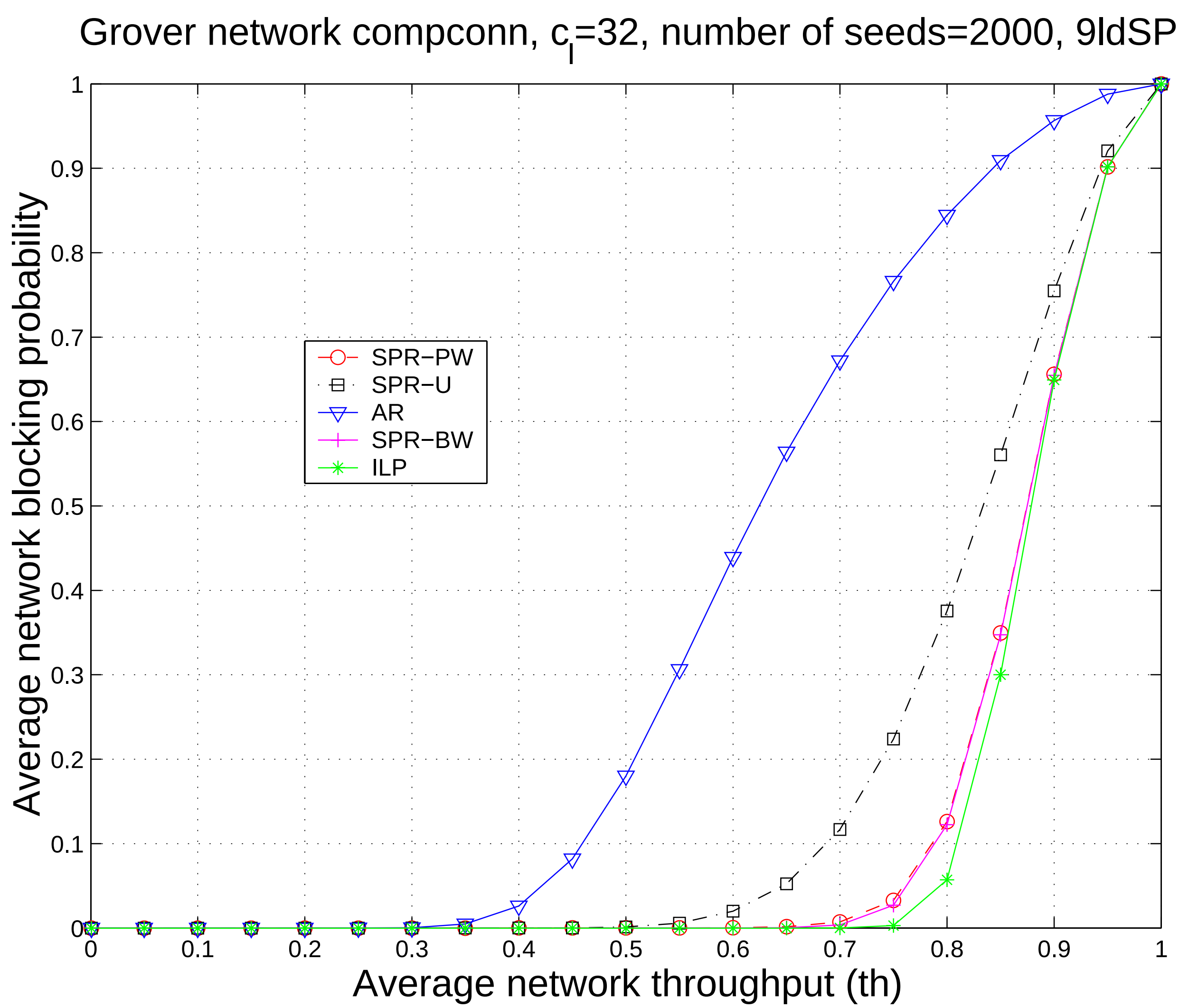

Fig. 11. Linear scale $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 32$.

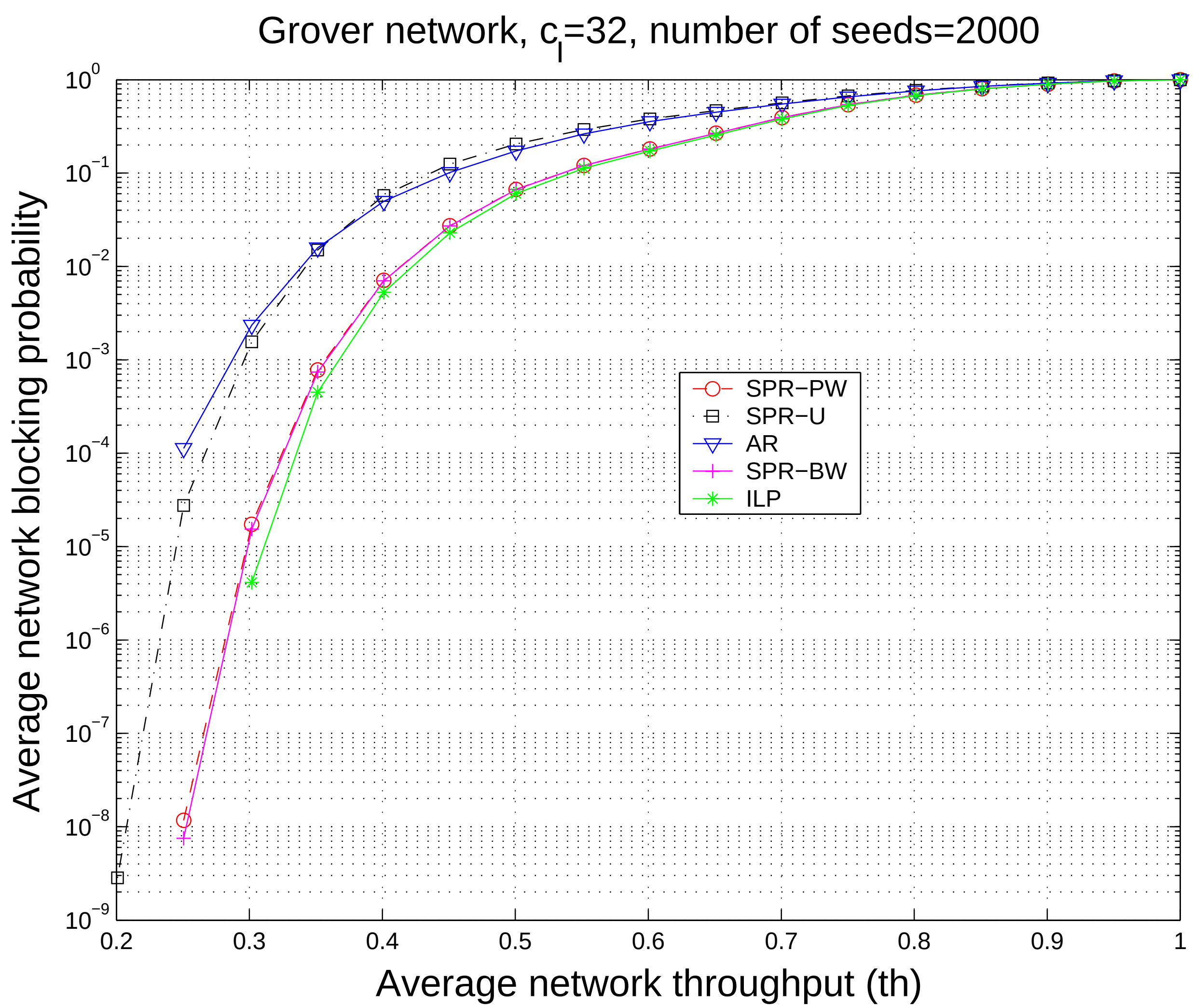

Fig. 12. Logarithmic scale $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 32$ with shortest path working connection routing.

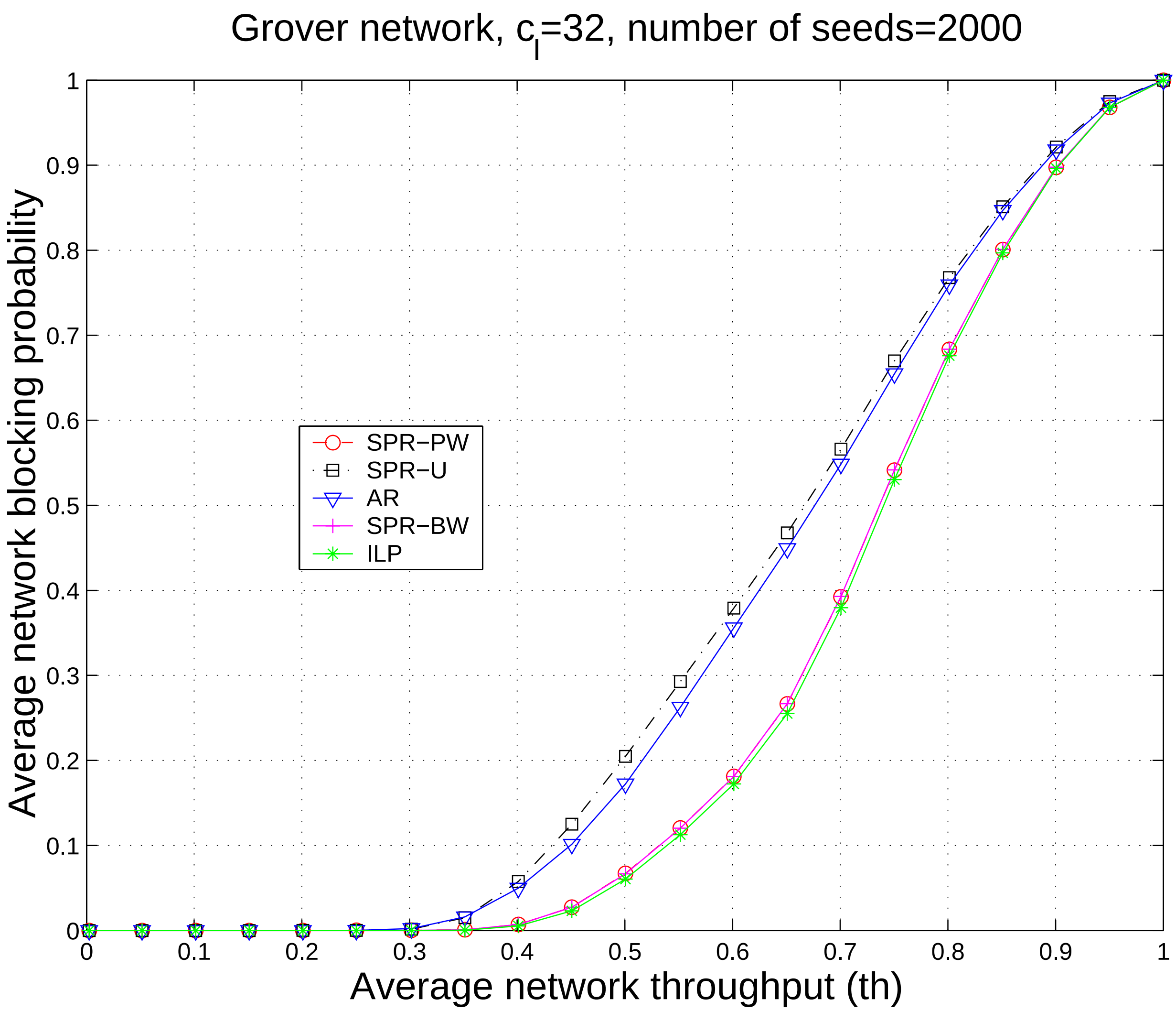

Fig. 13. Linear scale $\overline{Pr_b}$ vs. θ for $c_l = 32$ for shortest path working connection routing.

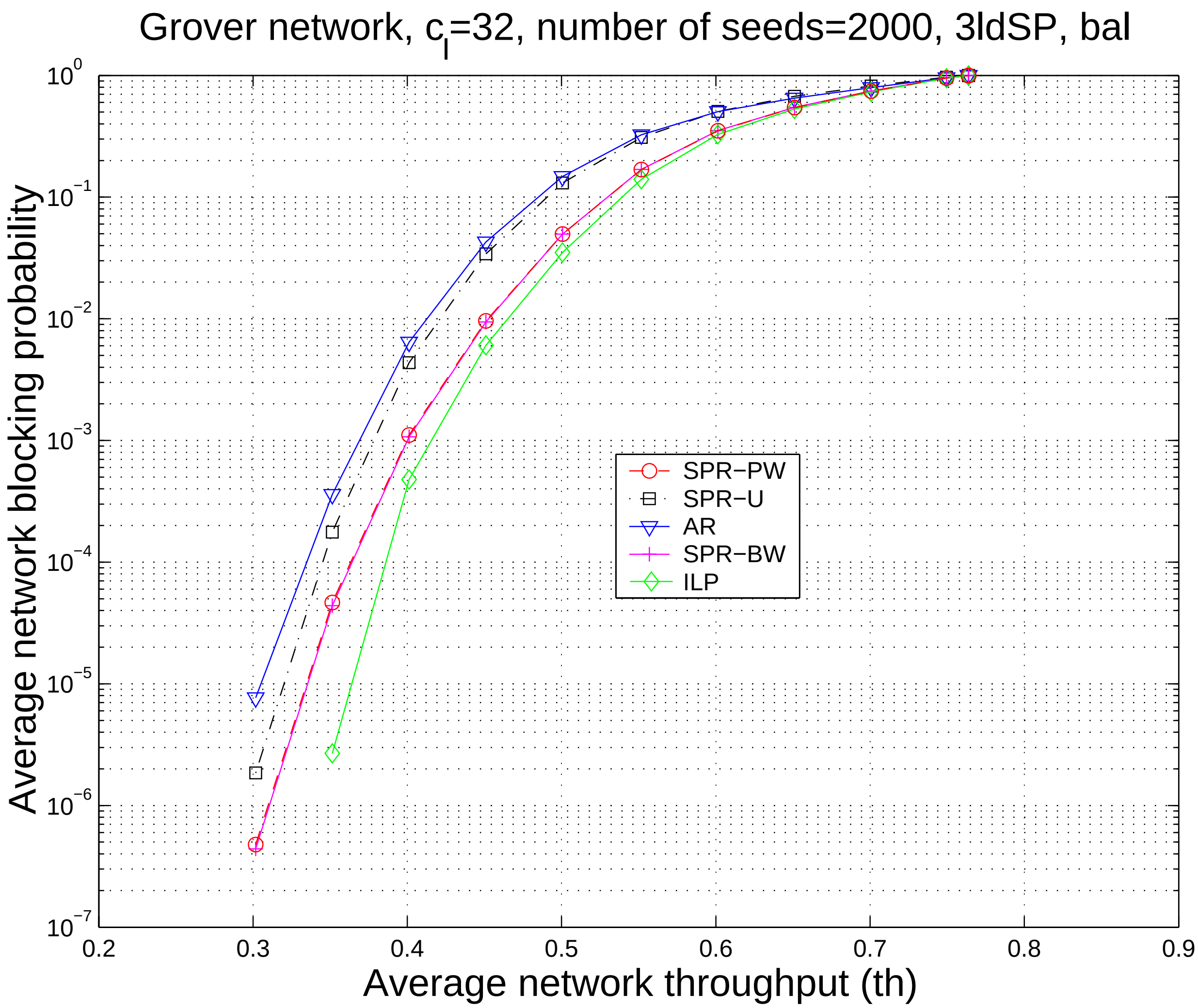

Fig. 14. Logarithmic scale $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 32$ with balanced working connection routing.

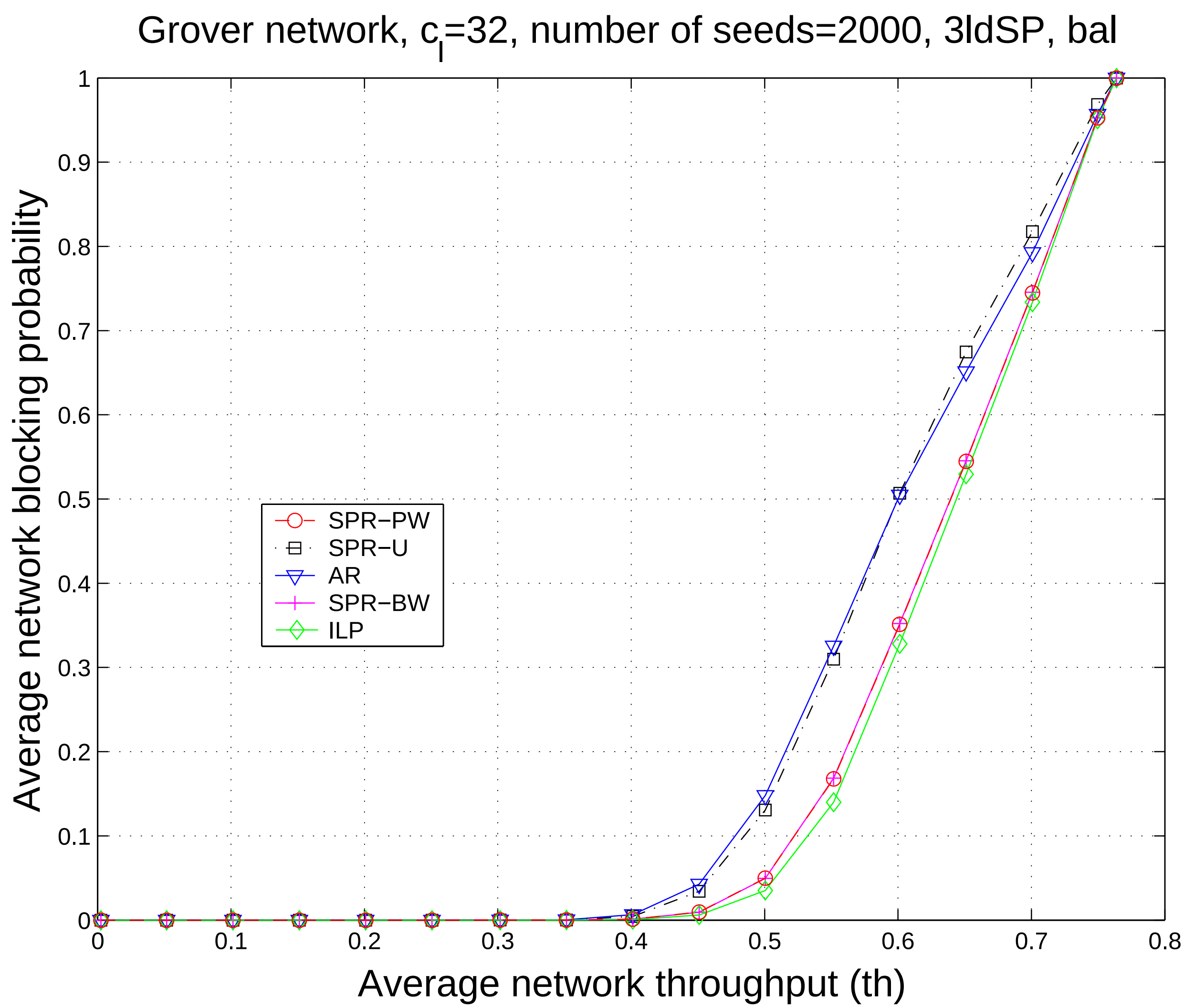

Fig. 15. Linear scale $\overline{Pr_b}$ vs. θ for $c_l = 32$, with balanced working connection routing.

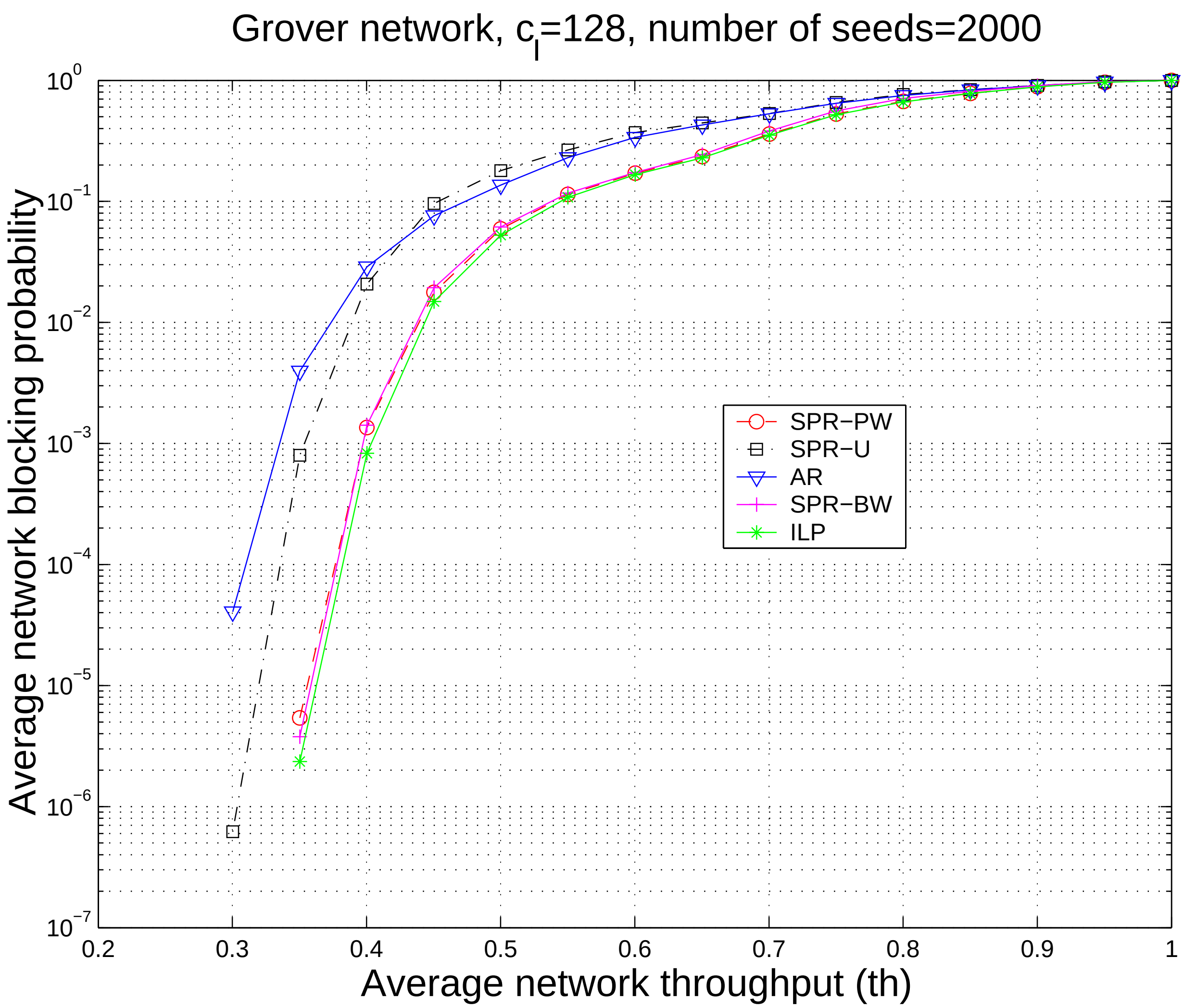

Fig. 16. Logarithmic scale $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 128$ with shortest path working connection routing.

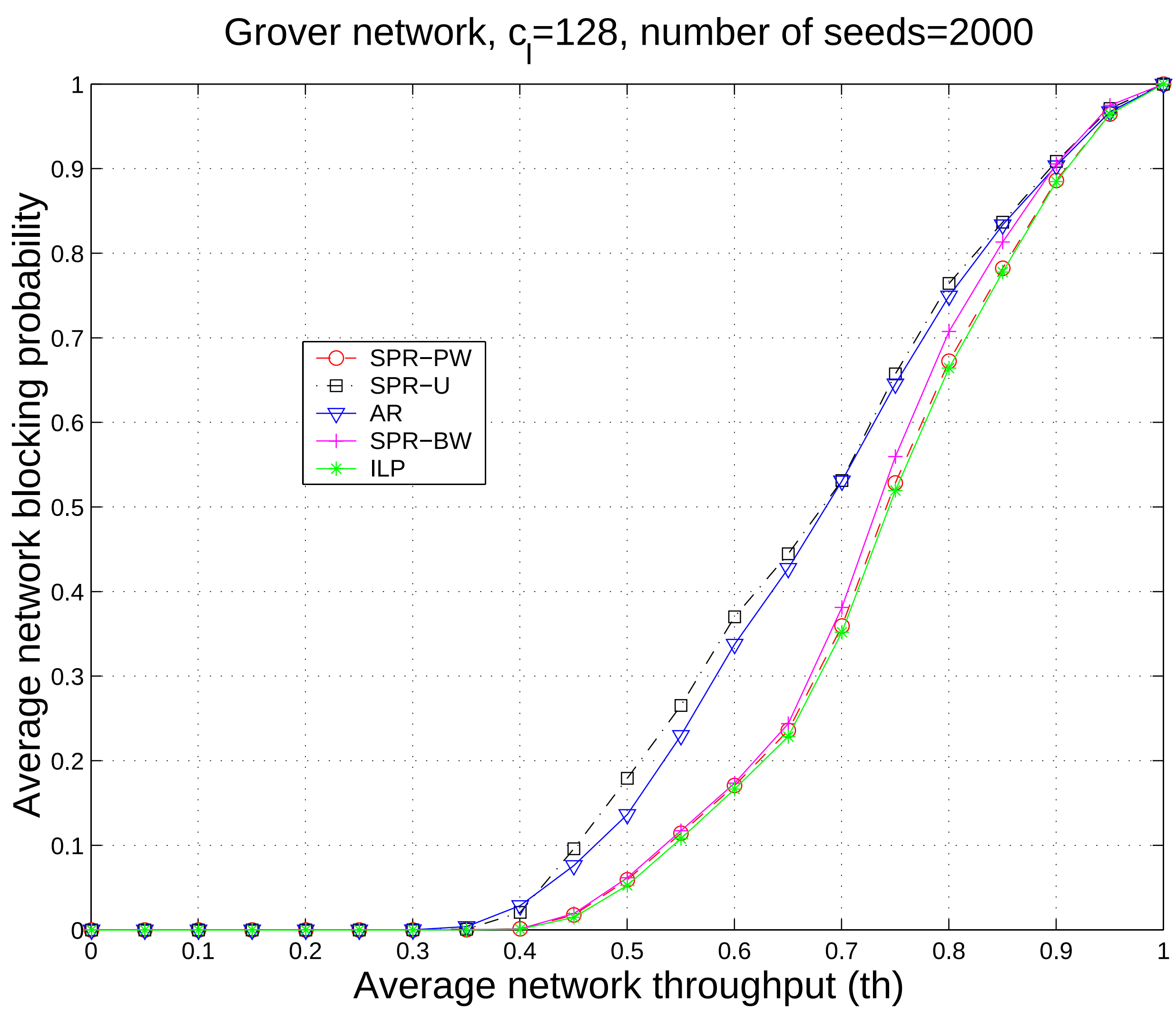

Fig. 17. Linear scale $\overline{Pr_b}$ vs. θ for $c_l = 128$ with shortest path working connection routing.

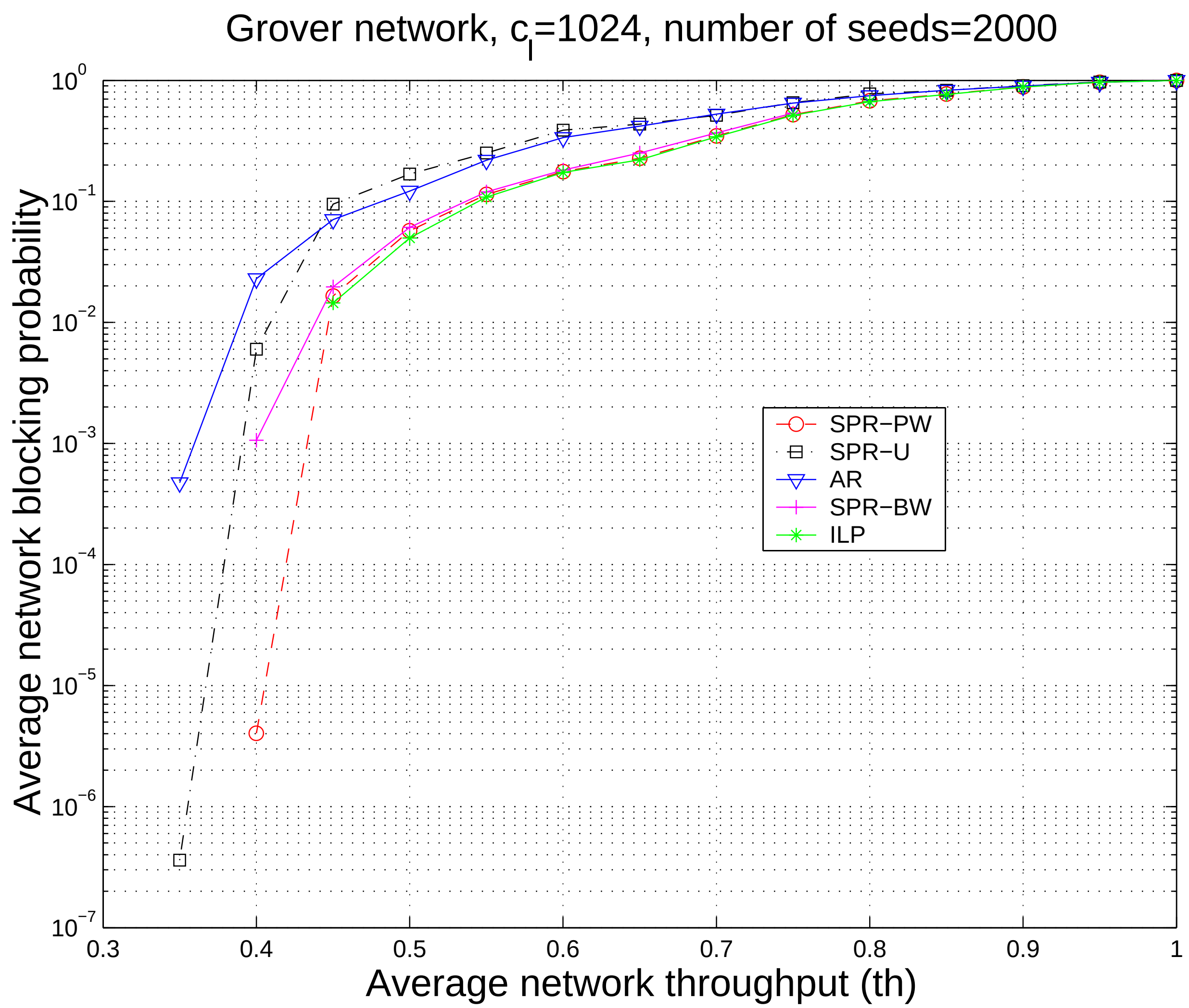

Fig. 18. Logarithmic scale $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 1024$ with shortest path wrking connetion routing.

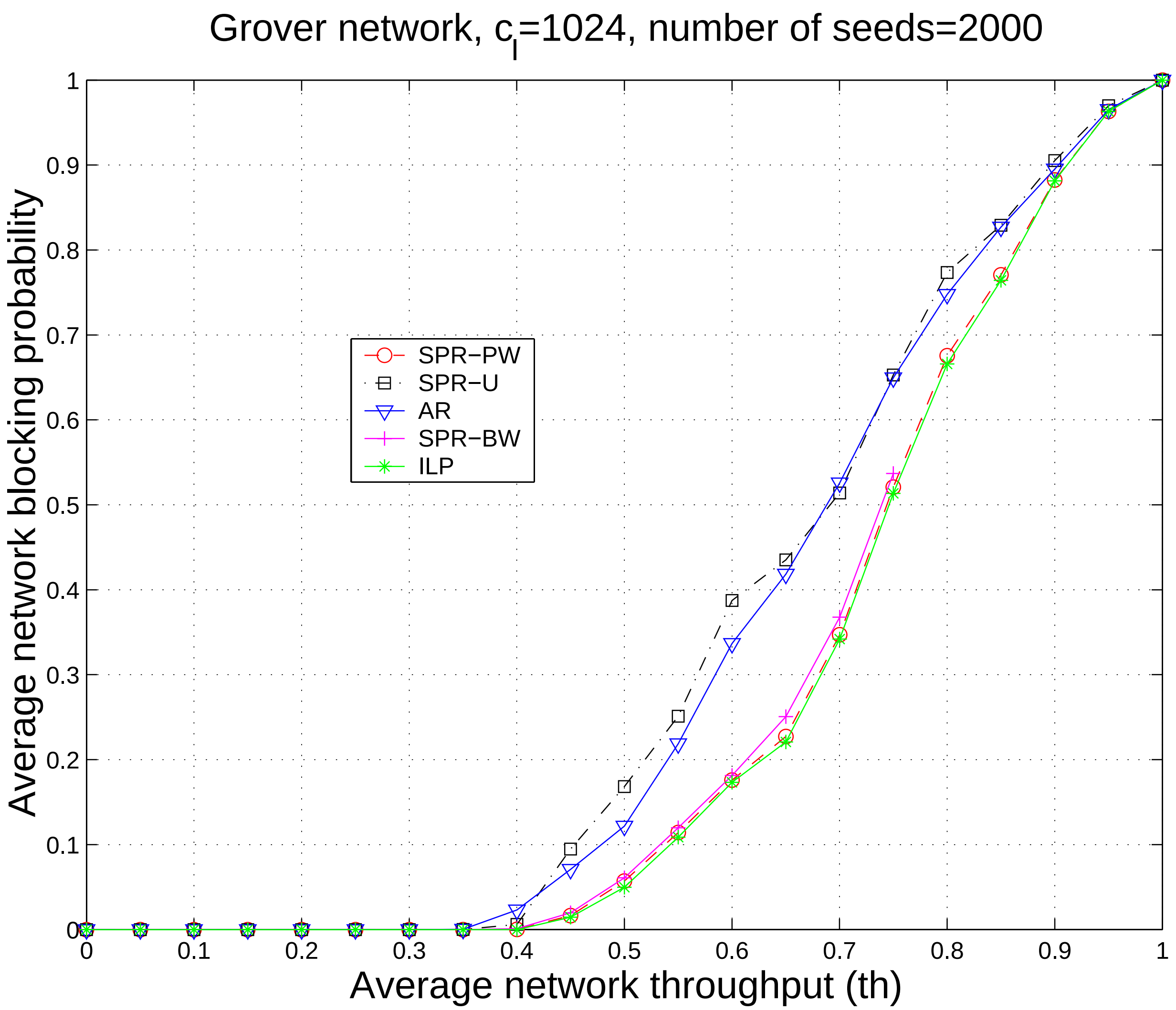

Fig. 19. Linear scale $\overline{Pr_b}$ vs. θ_{ac} for $c_l = 1024$ with shortest path working connection routing.

V. Conclusions

The paper proposed a class of stochastic approaches to implement a fast-restoration schemes with low-blocking probability in wavelength routing networks. The proposed class of schemes, called Stochastic Preplanned Restoration (SPR) class, is based on the preplanning of the restoration paths and the probabilistic choice of the restoration path to be activated driven by its likelihood not to be blocked due to resource contention. The rerouting of each disrupted connection is performed by an agent that acts independently from any other agent associated with an active connection. This approach permits to circumvent some of the problems found in existing restoration techniques, such as high blocking probability and/or lengthy restoration times. The SPR class schemes require contained signalling when the working lightpath is established and reduces the signalling required upon network failure to achieve restoration lightpath activation. Furthermore, the SPR class schemes do not require coordination among restoration attempts while restoration takes place. Thus SPR schemes are scalable in number of nodes, wavelengths, and lightpaths. The SPR class schemes differ on needed network status information and computational complexity. Thus the network adminstrator could exploit the trade-off betweenme their simplicity and their efficiency. Comparison with a number of preplanned restoration schemes illustrated the efficiency of the proposed approach by revealing significant restoration blocking probability improvements with respect previously proposed solutions, such as AR. Furthermore some SPR class schemes, such as SPR-PW and SPR-BW, have shown to be able to closely approximate the optimal value in terms of average network blocking probability given by the CILP scheme. Another interesting result obtained during this study showed that, in fixed capacity networks, balancing the routing of active connections among the available preplanned paths not only do not permit to fully utilize the network capacity but degrade the restoration blocking probaility at medium-high loads In conclusion the performance obtained by the SPR class schemes make them suitable for their implemetation in typical regional IP over WDM networks.

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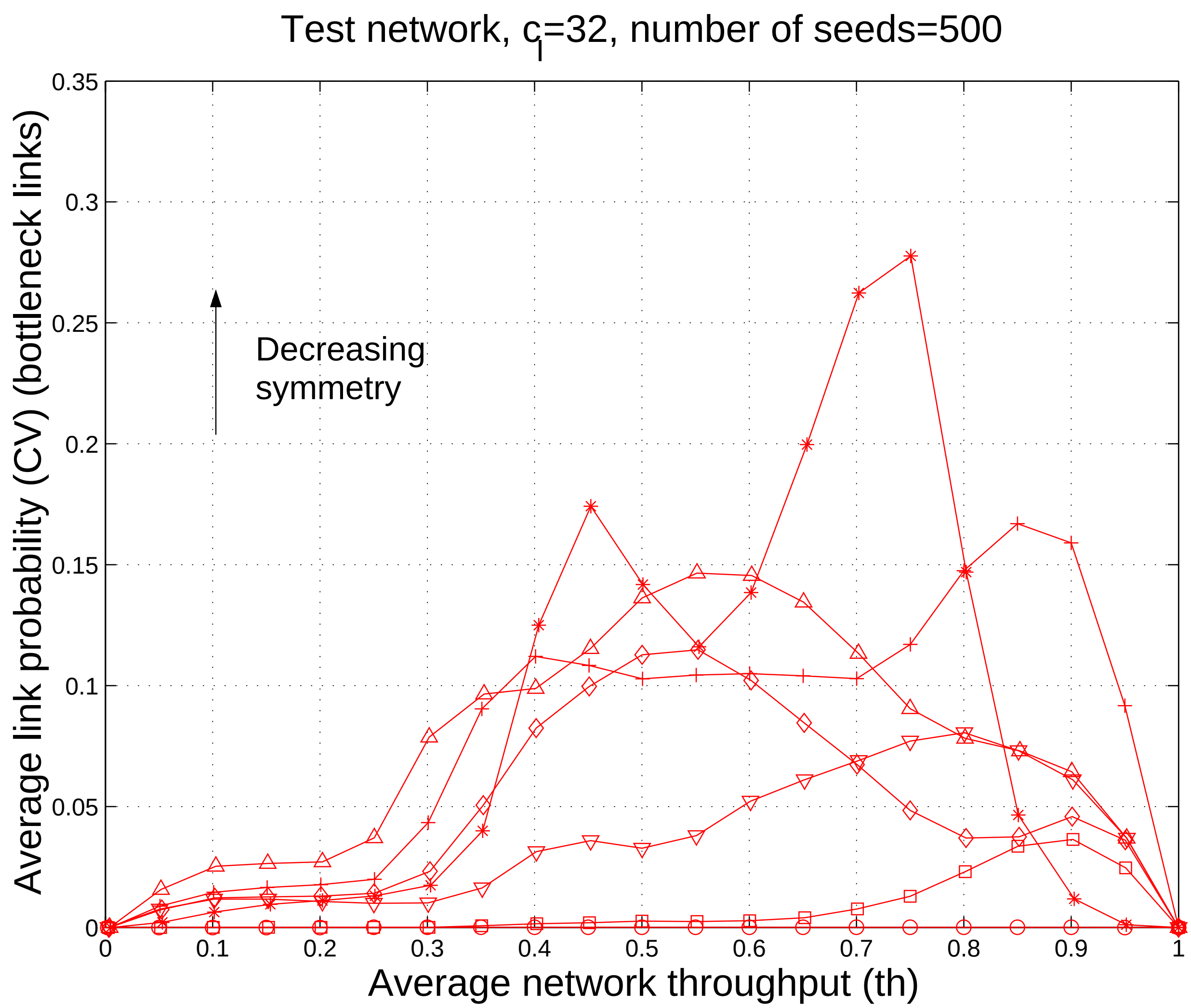

Fig. 20. $\overline{CV}$ vs. θ_{ac} only for the bottleneck links.

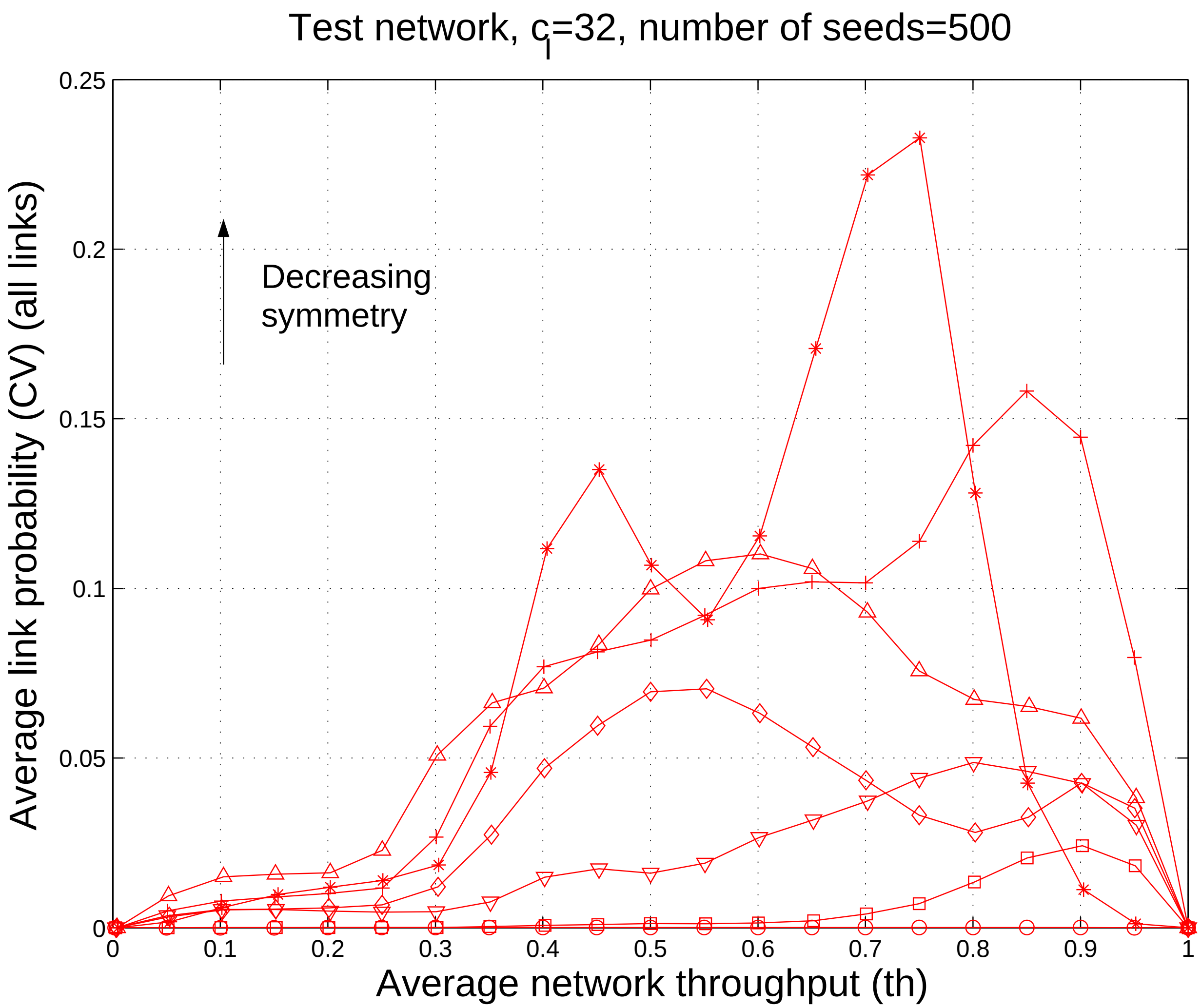

Fig. 21. $overline CV$ vs. θ_{ac} only for all links.