Link Cost Optimization for Protection Routing in Meshed Networks

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Abstract: The paper addresses the issue of optimal resource management in meshed networks with shared path or link protection. We formulate the problem of primary and protection path calculation as a Markov decision problem. After decomposition of the problem into a set of link problems, we define the dynamic link costs as state dependent link shadow prices that correspond to predicted lost revenue due to the new connection admission. While exact solution for link shadow prices can be quite complex, we use the Markov decision formulation to derive an approximate relation between the link costs for primary and shared protection connections. This result is then used to formulate an efficient link cost structure that is applied to optimize the primary and protection paths from the bandwidth usage viewpoint. Numerical results show the gain achieved from link cost optimization.

Keywords: Failure protection, Routing, Link cost, Revenue maximization, Markov decision theory.

1 Introduction

In today’s competitive market, network resiliency to failures has become an important feature that is used to attract new customers. At the same time this feature has to be realized in a cost effective fashion due to current industry financial constraints. One of the promising technologies for network resiliency is using meshed topology with shared path or link protection. In this case the link bandwidth reserved for a protection path can be shared with other protection paths if a failure activates only one protection path on a link. This condition is always true in case of link protection while in the case of path protection the sharing can be applied if respective primary paths, corresponding to the shared protection paths, are disjoint. As indicated in [1-5] such an approach can provide significantly reduced consumption of network resources when compared with 1+1 protection.

In this paper we address the issue of primary and protection paths calculations in meshed networks with link or path restoration. First, we formulate the problem as revenue maximization. Then we use the Markov decision framework to solve it. Such an approach was already applied for meshed networks without the protection mechanisms as described in [6]. The main idea is to decompose the network problem into a set of statistically independent link problems. Then it is possible to define link shadow prices as the predicted loss of revenue from connections rejected in the future due to acceptance of the new connection. Using this measure it is easy to optimize the connection paths by minimizing the total path cost. In the case of primary connections it can be shown that the link shadow prices are only a function of the required bandwidth. With the addition of protection paths the issue becomes much more complex since the new protection connection can share capacity with the already established protection...
connections. Intuitively, one might then assume that the link cost is zero since at the moment of acceptance of the new protection connection no additional link bandwidth needs to be reserved. Nevertheless, in this paper it is shown that there is a link cost incurred due to the fact that the link cost should also take into account the future link state development and we discuss this issue in detail.

While exact calculations of the relationship between the link shadow prices for primary and protection connections with and without sharing is quite difficult, we derive approximate relations for certain specific traffic scenarios using the Markov decision model. These results provide a basis for an approximate state dependent link cost function that keeps characteristics of the theoretical solution but can be easily implemented in a real network.

The paper is organized as follows. In Section 2, we present the Markov decision framework applied to the considered protection mechanism. In Section 3, the relation between link shadow prices for primary and protection connections as well as the relation between link shadow prices for shared and non-shared protection connections is analysed. This analysis is based on a combination of simplified and exact link models. Section 4 presents an approximate link cost function that preserves the main features of the Markov decision process framework. Numerical results based on approximate link cost function are provided in Section 5.

2 Markov Decision Process Based Framework

Markov decision theory yields an optimal solution to the routing problem assuming that the connection arrivals and departures form a Markov process and that the objective is to maximize the network reward, \( R \), defined as a sum of accepted connection rewards, \( r_j \), where \( j \) is the connection class index. Connection reward can be thought, for example, as revenue earned by a service provider by accepting (and completing) the call. While the optimal solution is intractable for most realistic examples, a manageable framework is achieved by decomposing the network reward process into a set of separable link reward processes. The result of this decomposition, described in [6], can be presented in a simple formula for call admission control, CAC, and routing. Namely, the new connection should be carried on the path with maximum and positive path net-gain defined as

\[
g_k = r_j - \sum_{s \in S^k} p^j_s(x),
\]

where \( p^j_s(x) \) denotes link \( s \) shadow price for class \( j \) connections, \( x \) is the link state, and \( S^k \) is set of links constituting the \( k \)-th path under consideration. The value of link shadow price can be interpreted as expected loss of link revenue from future connections that are rejected due to consumption of link bandwidth by the new connection. The link shadow price is indeed the link cost that is used to optimize the connections routing. In the following we propose an extension of the MDP based framework that takes into account shared path protection. There are two main issues that are affected by the introduction of shared protection paths: decomposition of the network reward process into a set of separable link reward processes and calculation of link shadow prices.

Decomposition of the network reward process consists of two phases. In the first phase one needs to decompose the Markov process. This can be done by assuming that the connection arrival process seen by a link is a link state-dependent Poisson process and that the link state distributions are statistically independent. These assumptions imply that a connection, established on a primary path consisting of \( k \) links, and protection path consisting of \( l \) links, is decomposed into \( k \) primary and \( l \) protection link connections that are stochastically independent but characterized by the same mean holding time as the original connection. Then the Markov process can be described separately for each link in terms of the link state \( x_0 = [x_i] \) and the transition rates defined by the link arrival rates \( \lambda^j_s(x) \) and departure rates \( \mu_j \) where \( x_i \) denotes the number of class \( j \) link connections carried on the considered link.
The second phase of decomposing the Markov decision process provides separability of the reward process. One way of achieving this feature is to divide the connection reward parameter among the corresponding link connections. Let \( r_{j,p} \) and \( r_{j,r} \) denote link reward for primary and protection link connections, respectively. It is obvious that the division rule should fulfill the following constraint:

\[
\sum_{s_k \in S^p} r_{j,p} + \sum_{s_k \in S^r} r_{j,r} \geq 0 \tag{2}
\]

Optimal allocation of the reward among the links is a complex problem for which it is difficult to find an exact solution. Nevertheless, in [6] it was shown, for the case without protection, that there are two efficient approaches. The first one has an economical interpretation and assumes that the connection reward should be divided proportional to the average link shadow prices. This approach could be applied directly to the considered case with shared protection assuming that a model for calculation of average link shadow prices is available. In the second approach the connection reward is divided equally among all links of the primary path and the numerical study showed [6] that for practical range of network parameters the performance of this approach is equivalent to the first approach. This approach could be extended to the protection case if one would divide the connection reward into the primary, \( r_{j,p} \), and protection, \( r_{j,r} \), rewards first. Then each of these rewards would be divided equally among the links constituting the primary and protection paths, respectively. The division of the connection reward between \( r_{j,p} \) and \( r_{j,r} \) can be done in several ways but once again the ratio of average shadow prices for primary and protection paths could be used as the principal factor since it has natural economical interpretation.

Calculation of the link shadow prices is a challenging problem since they are a function of the link arrival rates, \( \lambda_{j,p}^i(x,\pi) \) and \( \lambda_{j,r}^i(x,\pi) \), and link reward parameters, \( r_{j,p}^i \), \( r_{j,r}^i \), and these parameters are in turn a function of routing policy, \( \pi \), that is defined by the link shadow prices. Nevertheless, we can obtain a solution by the policy iteration algorithm [6] that is proven to converge to the optimal solution. In each cycle of this algorithm, new values of the link shadow prices are calculated based on the link arrival rates and link reward parameters calculated using the values of the link shadow prices from the previous cycle. For given link arrival rates and link reward parameters the exact values of link shadow prices can be calculated by solving the following set of equations

\[
\bar{R}^i(\pi) = q(x) + \sum_{j \in J^p} \lambda_{j,p}^i(x,\pi) g_{j,p}^i(x,\pi) + \sum_{j \in J^r} \lambda_{j,r}^i(x,\pi) g_{j,r}^i(x,\pi) \quad \text{in } X^i
\]

\[
- \sum_{j \in J^p} \lambda_{j,p}^i(x,\pi) g_{j,p}^i(-x,\delta_{j,p}^i,\pi) - \sum_{j \in J^r} \lambda_{j,r}^i(x,\pi) g_{j,r}^i(-x,\delta_{j,r}^i,\pi), \quad x \in X^i
\]

where \( \bar{R}^i(\pi) \) denotes average reward from the link,

\[
q(x) = \sum_{j \in J^p} r_{j,p}^i(\pi) x_{j,p} + \sum_{j \in J^r} r_{j,r}^i(\pi) x_{j,r}
\]

is the rate of link reward in state \( x \) and \( g_{j,p}^i(x,\pi) \), \( g_{j,r}^i(x,\pi) \) are link net gains defined as

\[
g_{j,p}^i(x,\pi) = r_{j,p}^i(\pi) - p_{j,p}^i(x,\pi)
\]

\[
g_{j,r}^i(x,\pi) = r_{j,r}^i(\pi) - p_{j,r}^i(x,\pi)
\]

Inspection of eq. (3) shows that the protection link shadow prices, \( p_{j,r}^i(x,\pi) \), have positive values, even for states where the new protection connection is sharing bandwidth with existing protection connections (assuming that primary link rewards are positive, protection link rewards are non negative and link rates have realistic values). This conclusion can be also derived informally from the fact that even though the new connection shares the bandwidth at the moment of the acceptance, with some probability, during the connection lifetime a new primary connection can be rejected at the state where there is no more sharing due to the departure of the other protection connections. Therefore, by
rejecting the new protection connection the network would receive the reward from this primary connection. This reward, multiplied by the event probability, constitutes a part of protection link shadow price. In summary, the above discussion implies that the link cost for a link on a protection route which shares bandwidth with other protection routes is not zero as one might intuitively expect.

3 Link Shadow Price Analysis

In this Section, we present a study of link shadow prices that is based on a system illustrated in Figure 1 where a link, with capacity of \( N \) bandwidth units, is offered homogeneous primary connections forming a non-state-dependent Poissonian stream with arrival rate \( \lambda_p \). The link is also serving \( K \) protection streams, each with the arrival rate \( \lambda_k \). All connections have bandwidth requirement of one unit. Each of protection streams corresponds to an SRLG (shared risk link group) that is independent from others and therefore the bandwidth can be shared among all protection streams.

![Figure 1. Link and streams structure](image)

In the following we analyze the relation between the primary and protection link shadow prices (Section 3.1), as well as the relation between the shared and non-shared protection link shadow prices (Section 3.2). This study is approximate since it uses some simplifying assumptions and conjectures. To validate this study, in Section 3.3 we present some exact numerical results to validate the approximate analysis.

3.1 Primary vs. Protection Link Shadow Prices

The following comparison of the primary and protection link shadow prices is based on a solution derived for a link with homogeneous primary connections forming a non-state-dependent Poissonian stream with arrival rate \( \lambda_p \). In this case it can be shown [6] that the link average shadow price is given by

\[
p^s = \lambda^s r^s [E(\lambda^s, N^s) - 1] - E(\lambda^s, N^s)
\]

(4)

where \( E(\lambda^s, N^s) \) denotes the Erlang’s formula and \( N^s \) is the link capacity. It follows from eq. (4) that the average link shadow price can be interpreted as the reward lost due to admission of a new connection with infinite holding time (neglecting the reward from the new connection). In the following we will use this feature to calculate the relation between the average link shadow prices for primary and protection connections in the link system from Figure 1. For now we assume that the primary stream has infinitely small arrival rate \( \lambda_p \) and that all protection streams have the same arrival rate \( \lambda_k \). Observe that in this system the link state distribution is governed by \( K \) independent Poissonian distribution with arrival rate \( \lambda_r \), and with blocking probability for each of the protection streams given by \( B_r = E(\lambda_r, N) \) and for primary stream given by \( B_p = 1 - \prod_{k=1}^{K} [1 - E(\lambda_r, N)] \). These blocking
probabilities together with eq. (4) can be used to calculate the average link shadow price for the primary connection as

\[ p_p = K \lambda_p r_p \left[ E(\lambda_p, N-1) - E(\lambda_p, N) \right] \]

and for protection connections as

\[ p_r = \lambda_p r_p \left[ E(\lambda_p, N-1) - E(\lambda_p, N) \right] + \lambda_p r_p \left[ (1 - E(\lambda_p, N)) - (1 - E(\lambda_p, N-1)) \right] \]

Now we can analyze the ratio, \( R \), of primary to protection average link shadow prices. First let us define the ratio separately for parts caused by loss of protection traffic and primary traffic:

\[ R' = \frac{p'_p}{p'_r} = \frac{K \lambda_p r_p \left[ (1 - E(\lambda_p, N)) - (1 - E(\lambda_p, N-1)) \right]}{\lambda_p r_p \left[ (1 - E(\lambda_p, N)) - (1 - E(\lambda_p, N-1)) \right]} = K \]

\[ R^p = \frac{p^p_r}{p^p_p} = \frac{[1 - E(\lambda_p, N)]^K - [1 - E(\lambda_p, N-1)]^K}{[1 - E(\lambda_p, N)]^K - [1 - E(\lambda_p, N-1)]^K} = K \]

Therefore we have \( R \approx K \). This result is of importance for allocation of the connection reward parameter among the primary and protection paths. A remaining question is whether this ratio holds for the cases where primary connection arrival rate has some significant value. This will be verified in Section 3.3 using numerical results from the exact model.

### 3.2 Shared vs. Non-Shared Protection Link Shadow Prices

While the ratio of average shadow prices is important information for allocation of the connection reward parameter among the primary and protection links, equally important information is the relation between values of protection shadow price with sharing and without sharing. To be more precise, we are interested in comparison of protection link shadow price for connection from SRLG \( i \) for which \( x_i = \max_k x_k \) with link shadow price from SRLG \( n \) for which \( x_n < \max_k x_k \) assuming that the link state is the same in both cases. Let us consider again the system with \( K \) independent protection streams. The part of shadow price associated with loss of protection traffic within one protection stream can be calculated exactly from

\[ p'_r(x) = \frac{E(\lambda_p, N)}{E(\lambda_p, x)} \]

due to system homogeneity and non-state-dependent Poissonian arrivals [7]. From that we have

\[ \frac{p'_r(x_i)}{p'_r(x_n)} = \frac{E(\lambda_p, x_n)}{E(\lambda_p, x_i)} \]

As expected, in the considered link state, this ratio is always larger than 1 since \( x_n < x_i \) and the value depends strongly on the difference between \( x_n \) and \( x_i \). While this is of some importance, note that the previous consideration indicated that the link reward from the primary link connection is significantly larger than the one from the protection link connection. This, combined with the fact that the arrival rate of primary link connection is larger than the arrival rate of protection connections from particular SRLG, in realistic network, indicates that our comparison should be focused on the part of protection shadow price due to loss of primary traffic.

In our system the probability of losing some primary traffic is a direct function of available capacity that is defined by \( AC = N - \max_k x_k \). Obviously, the smaller available capacity the more likely is the loss of primary traffic during the new protection connection lifetime. Now let us compare the two cases under consideration. When the protection connection requires reservation of additional bandwidth it reduces directly the available capacity and therefore increases probability of primary traffic loss. When new protection connection can share the reserved bandwidth, the available capacity is not reduced at the
moment of the connection acceptance. Still the new protection connection increases probability of available capacity reduction in the future but this increase may be significantly smaller compared to the first case for two reasons. First, there is a difference between the states $x_n$ and $x_i$. Second, there are $K$ parallel streams. These factors imply that the new connection may not influence the available bandwidth at all during its lifetime. The above arguments indicate that the protection link shadow price is significantly smaller when sharing is available. This conclusion in itself increases further the difference between the shared and non-shared link shadow prices. Namely, in a full network example, the arrival rates of protection link connections for given SRLG will be larger when sharing is available. This follows from the fact that the protection link shadow price will be significantly smaller compared to the non-shared case and therefore paths comprising this link will be more likely to be used for protection. Hence, when a new protection connection does not share bandwidth, it increases the number of states with larger protection arrival rates for all SRLGs and therefore the probability of primary traffic loss is further increased. This is not the case for connections with sharing.

In summary, the above considerations indicate that the protection link shadow price without sharing is close to the primary link shadow price while on average the link shadow price with sharing is significantly smaller. The numerical study in Section 3.3 gives some examples of these relations.

### 3.3 Exact link model

To validate the results presented in the previous sub-sections, we implemented the exact solution for the link shadow prices in the considered link model. We used the value iteration algorithm which is a convenient method for solving large Markov decision problems due to the numerical simplicity [6]. The basic recurrent formula for our link model is stated as follow:

$$V_n(x) = q(x)\tau + \tau \sum_{j=0}^{K} \mu_j[V_{n+1}(x + \delta_j) - V_{n+1}(x)] + \tau \sum_{j=0}^{K} x_j \mu_j[V_{n+1}(x - \delta_j) - V_{n+1}(x)] + V_{n+1}(x) \quad; \quad x \in X$$

- $V_n(x)$ is the expected reward for the link within $n$ transition periods assuming state $x$ at the beginning of the considered time and terminal reward of $V_0(x)$ at the end of the time,
- $x = [x_0, x_1, x_2, \ldots, x_K]$ is the link state where $x_0$ is the number of primary connections and $x_j$; $j = 1, \ldots, K$, is the number of class $j$ protection connections,
- $q(x) = \sum_{j=0}^{K} r_j x_j \mu_j$, is the rate of link reward in state $x$,
- $\tau$ is a parameter defined by the uniformization technique of the Markov processes [6]
- $\delta_j$ is the $K+1$ vector with 1 at the $j^{th}$ position and 0 elsewhere

From our perspective the important feature is that once the value functions are found, the link net gains can be defined as

$$g_j(x) = \lim_{n \to \infty} [V_n(x + \delta_j) - V_n(x)]$$

Then the primary and protection shadow prices are obtained from the following equation:

$$p_j(x) = r_j - g_j(x) \quad for \quad j = 0, \ldots, K$$

Using the above solution for link shadow prices we performed several numerical experiments to illustrate and validate conclusions achieved in the previous sub-sections. It should be underlined that in the presented examples the link capacities, $N$, and protection class numbers, $K$, were constrained by internal limitation of the used Matlab software and not by the method itself which can handle much bigger number of states (we plan to implement the exact model without the mentioned limitations).

First we analyzed the ratio of the average primary shadow price to average protection shadow prices:
\begin{equation}
R^p_j = \frac{E\left[\frac{p_0(x)}{x \in Y}\right]}{E\left[\text{mean}_{j=1,K}\frac{p_j(x)}{x \in Y}\right]} \quad ; \quad Y = X - \{x / AC=0\}
\end{equation}

This ratio is presented in Figure 2 as a function of the primary to protection arrival rate ratio \(\lambda_p / \lambda_r\) for several system configurations. The results are consistent with the analysis presented in Section 3.1 in that the ratio is close to \(K\) for small arrival rates of primary connections. While for larger shares of the primary connections arrivals the ratio is reduced, still the primary shadow prices are significantly larger than the protection shadow prices.

Figure 2. Average primary to protection shadow prices ratio vs. primary to protection arrival rates ratio.

The second part of this numerical study is aimed at comparison of the protection shadow prices when sharing is not available with the protection shadow prices when the sharing is available. Since the link shadow prices depend strongly on many factors including the available bandwidth and the number of connections, we calculated the ratios of the average non-shared and shared shadow prices as a function of available capacity, \(AC\), and the maximum number of protection connections of given class, \(n\). We considered two definitions of these ratios. The first one is given by

\begin{equation}
R1(AC,n) = E\left[p_j(x/x_j = \max_{k=1,K} (x_k) = n) / \text{mean}_{i=1,K} p_i(x/x_i < n) / x \in Y \right]
\end{equation}

where for given \(AC\) and \(n\) we calculate the expectation of ratio of non-shared protection shadow price to average shared protection shadow prices. The second definition is given by

\begin{equation}
R2(AC,n) = \frac{E\left[p_j(x/x_j = \max_{k=1,K} (x_k) = n) / x \in Y \right]}{E\left[p_j(x/x_j = n \neq \max_{k=1,K} (x_k) / x \in Y \right]}
\end{equation}

which is the ratio of the expectation of non-shared shadow price to the expectation of shared shadow prices for the same number of protection connections. The results presented in Figure 3 show that, as expected, the non-shared protection link shadow prices are significantly larger than the shared ones.
The results presented in Figure 3 show that, as expected, the non-shared protection link shadow prices are always larger than the shared ones. In particular the considered ratio is higher when the available capacity is smaller. Also the ratio is especially high when the number of protection connections is small.

4 Approximate Link Cost Function

In this section we describe a simple method to implement the link cost function that, although approximate, preserves the main features of the theoretical framework described above.

4.1 Link Cost for Primary and Non-shared Protection Connections

As discussed above, we assume that the link cost for the primary and non-shared protection link connections is the same. Since calculation of the link shadow price (link cost) as described in the previous subsection is not straightforward, we propose to use a function that it is proportional to the inverse of link available capacity, $AC$, and the administrative weight, $AW$:

$$w_p = \frac{AW}{AC^{0.4}} MWC$$

where $MWC$ is a maximum weight coefficient used to smooth transition of the link cost value as the link load changes from low to high. The power of the inverse of $AC$ is chosen so that the function is similar to the link shadow price function. The motivation, detailed model and numerical study for this approximation are described in [6] for systems without protection. Moreover, to allow operators to include policy factors in path selection, under light and medium link load the link cost is set equal to the operator provisioned administrative weight, $w_p = AW$.

4.2 Shared Protection Case

As indicated in the previous section, when the link protection bandwidth can be shared, the link cost (link shadow price) should be significantly smaller than in the non-shared case but not equal to zero. Therefore we propose the following link cost function

$$w_r = \frac{w_p}{1 + \delta SC}$$

Administrative weight is a static value associated with each link which can be used by the operator to implement routing policies such as avoiding or preferring links regardless of their dynamic link costs.
, where $b$ is an empirical coefficient, $SC$ is available shared capacity (the available shared capacity is defined as the maximum bandwidth of new protection paths, that can be reserved on the link without increasing the total bandwidth reserved for protection). Here, coefficient $b$ is used to choose the ratio between the shared and non-shared link shadow prices.

5 Numerical Results

Using the link cost function presented in Section 4 we performed a thorough numerical study of several distributed path and link restoration mechanisms with different link cost advertisement schemes as presented in [8, 9]. The focus in these papers was on comparing different protection mechanisms and different advertisement schemes that minimize the amount of data to be advertised. In this paper we concentrate on the network performance sensitivity to the relation between link cost for shared and non shared protection connections. The network examples used in the study are described in Table 1. They are based on real network data.

Table 1

<table>
<thead>
<tr>
<th>Network examples</th>
<th>Europe</th>
<th>US2</th>
<th>US1</th>
</tr>
</thead>
<tbody>
<tr>
<td># Links</td>
<td>55</td>
<td>43</td>
<td>53</td>
</tr>
<tr>
<td># Nodes</td>
<td>29</td>
<td>27</td>
<td>42</td>
</tr>
<tr>
<td># Links per node (average)</td>
<td>3.8</td>
<td>3.2</td>
<td>2.5</td>
</tr>
<tr>
<td># Traffic offered (Erlangs)</td>
<td>3245</td>
<td>1626</td>
<td>804</td>
</tr>
</tbody>
</table>

Figure 4 shows a representative sample of network performance vs. the $b$ parameter values of shared protection link cost function, eq.(15). The performance is expressed as connection blocking probabilities under overload conditions. In general the numerical study showed that the optimal results were obtained for values in the $2.5 < b < 15$ ranges. The sensitivity for values of $b$ larger then optimal was relatively small while the performance for values of $b$ smaller than 2 was deteriorating rapidly in most cases. The numerical results confirm that the link cost for shared connections should not be equal to zero.

In Table 2 we present network performance expressed as the average protection bandwidth overhead (the average protection bandwidth overhead is expressed as percentage of average bandwidth used for...
primary connections) for the cases with optimized protection link cost described in Section 4 and the protection link cost equal to the primary link cost. Additionally the performance for the 1+1 protection is also given. The results show that significant gains in resource usage are obtained when the link cost captures the sharing of capacity between protection paths.

Table 2
Average protection bandwidth overhead for three network examples

<table>
<thead>
<tr>
<th></th>
<th>Europe</th>
<th>US2</th>
<th>US1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1+1 protection</td>
<td>188 %</td>
<td>221 %</td>
<td>233 %</td>
</tr>
<tr>
<td>Shared path protection, no link cost optimization</td>
<td>101 %</td>
<td>88 %</td>
<td>122 %</td>
</tr>
<tr>
<td>Shared path protection with optimized link costs</td>
<td>72 %</td>
<td>64 %</td>
<td>94 %</td>
</tr>
</tbody>
</table>

6 Summary

In this paper we addressed the issue of primary and protection path calculation in meshed networks with link or path protection. In particular we concentrate on the link cost function that should serve to optimize the bandwidth utilization. To achieve this objective we used the Markov decision framework to derive the relation between the link cost functions for shared and non-shared bandwidth. Both approximate and exact link models were used for analysis. We showed that even when the bandwidth sharing is available for protection connections the link cost should not be assumed to be zero although it may be a common conclusion. Based on the theoretical model we proposed an approximate state dependent function that incorporates features derived from the theoretical analysis. The numerical study of network examples illustrates sensitivity of the network performance to the ratio of link cost for connections with shared and non shared bandwidth. Also the effect of link cost optimization on total network performance is given illustrating that by optimizing the protection path calculations the protection overhead can be reduced by 20 to 30 %.

References