Survivable GMPLS networks with QoS guarantees

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Abstract: A scheme is proposed to provide multiple QoS guarantees for survivable generalised multiprotocol label switching (GMPLS) networks. The shared risk link group (SRLG) information is considered to provide failure-independent protection. Based on the problem formulation, the service level agreement (SLA) parameters, such as the expected recovery failure probability, the expected recovery time and the expected signal loss are analysed to reveal the bound of the backup path length. Under the constraint of such a backup path length limit, a heuristic algorithm is further proposed for online path configuration. The simulation results demonstrate that the heuristic algorithm provides recovery quality guaranteed backup paths with high bandwidth multiplexing gain.

1 Introduction

Generalised multiprotocol label switching (GMPLS), extended from multiprotocol label switching (MPLS), establishes label switched paths (LSPs) to facilitate connection-oriented services. Packets with the same label follow the same LSP, and a different label implies a different LSP that could provide a different QoS. As a common control and measurement plane for IP over WDM networks, GMPLS provides dynamic wavelength routing and enhanced network survivability [1–3]. Network survivability has become a critical issue for the GMPLS networks, in which the signalling (RSVP, CR-LDP) and routing (OSPF, IS-IS) protocols are extended from the respective MPLS versions by including the traffic engineering (TE) information, such as network topology, resource availability and control constraints. Among the TE information, the shared risk link group (SRLG) is critical for resource sharing of the backup LSPs [4]. An SRLG is a union of all links that utilise a given fibre span. Links directly interconnect logical cross-connects but may traverse multiple physical fibre spans, and may thus be in multiple SRLGs. When the shared fibre span fails, all the links in this SRLG are disconnected [5]. Any link in such a union is said to be in this SRLG. An LSP is in SRLG l if at least one of its intermediate links is in SRLG l. Two LSPs are SRLG-disjoint if neither of them is in the same SRLG. Since SRLG-disjoint LSPs do not share any common risk, their backup LSPs can share common resources to achieve higher efficiency.

To the best of our knowledge, only a few algorithms have been proposed to tackle the problem of traffic survivability with SRLG information. Reference [6] proposes an integer linear programming (ILP)-based method to minimise the cost of SRLG-disjoint LSP pair assignment. The computational complexity is extremely high and is intolerable for large-scale networks. This method has been improved by Xu *et al.* [7] with a two-stage ILP with bandwidth sharing among the backup LSPs. Oki *et al.* [4] considered the number of SRLGs that a link belongs to as a factor of the link cost, and extended the k-shortest path routing by avoiding the links with many SRLGs. However, these studies only consider bandwidth as the only QoS metric. Hence, other paramount metrics for traffic recovery, such as the traffic recovery probability, the recovery time and the signal loss, may not be satisfied, i.e. QoS of the recovered traffic is not completely guaranteed.

Our proposal in this paper accommodates traffic recovery in the GMPLS networks by taking into consideration the QoS metrics mentioned above. Our work differentiates itself from previous works by proposing an online traffic recovery scheme, which incorporates the SRLG information provided by the GMPLS control plane and multiple QoS metrics from the service level agreement (SLA) together for the purpose of ensuring network survivability. We assume that in a certain time interval, at most one failure occurs, and thus at most the traffic through one SRLG is affected.

2 Problem formulation

In order to survive all of the intermediate link failures in the primary LSP, it is necessary to assign a link-disjoint backup LSP to a specific primary LSP. To prevent the primary and backup LSPs from failing at the same time, the backup LSP must be *SRLG-disjoint* from its corresponding primary LSP. Given a network $\boldsymbol{G}(N, E)$, where N is the set of nodes and E is the set of links, define

N node set, numbered from 1 to n

(i,j) link between node i and node j, $(i,j) \in E$

l SRLG l, $l \in L$, where L is the SRLG set

$[x,y]$ carried network traffic from x to y, $[x,y] \in R$, where R is the carried traffic set

LSP$_{xy}$ primary LSP set up to carry traffic $[x,y]$

LSP$_{b,xy}$ backup LSP set up to protect traffic $[x,y]$

$C(i,j)$ cost of utilising link (i,j) to carry/protect traffic.

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Therefore, the cost of an LSP is the sum of its intermediate link costs, which is represented as

$C(\mathrm{LSP}_{xy})$ cost of LSP_{xy}

$$C(LSP_{xy}) = \sum_{(i,j)\in LSP_{xy}} C(i,j)$$

$C(\mathrm{LSP}_{b,xy})$ cost of $\mathrm{LSP}_{b,xy}$

$$C(LSP_{b,xy}) = \sum_{(i,j)\in LSP_{b,xy}} C(i,j)$$

We assume link *(i,j)* supports W_{ij} wavelength channels, and an entire wavelength channel is allocated to a single traffic. The problem we are facing now is: given the above network information, for the new incoming traffic [*s*,*t*], find its primary LSP (i.e. LSP_{st}) and its backup LSP (i.e. $\mathrm{LSP}_{b,st}$) such that the cost to carry and protect traffic [*s*,*t*] is minimised, while QoS guarantees for traffic recovery are provisioned.

In order to formulate the problem, we further define the following indicator functions:

$$O_{ij}^{xy} = \begin{cases} 1, & \mathrm{LSP}_{xy} \text{ uses link } (i,j) \\ 0, & \text{otherwise} \end{cases}$$

$$B_{ij}^{xy} = \begin{cases} 1, & \mathrm{LSP}_{b,xy} \text{ uses link } (i,j) \\ 0, & \text{otherwise} \end{cases}$$

$$T_l^{xy} = \begin{cases} 1, & \mathrm{LSP}_{xy} \text{ is in SRLG } l \\ 0, & \text{otherwise} \end{cases}$$

$$Z_l^{ij} = \begin{cases} 1, & \text{link } (i,j) \text{ is in SRLG } l \\ 0, & \text{otherwise} \end{cases}$$

Given the above, the problem is expressed as
Objective:

$$Min(C(LSP_{st}) + C(LSP_{b,xy})) \tag{1}$$

Subject to the following constraints:

flow continuity constraints:

$$\begin{aligned} \sum_{j\in N} O_{ij}^{st} - \sum_{j\in N} O_{ji}^{st} &= \begin{cases} 1 & i = s \\ -1 & i = t \\ 0 & i \neq s,t \end{cases} \\ \sum_{j\in N} B_{ij}^{st} - \sum_{j\in N} B_{ji}^{st} &= \begin{cases} 1 & i = s \\ -1 & i = t \\ 0 & i \neq s,t \end{cases} \end{aligned} \tag{2}$$

disjoint constraints:

$$\sum_{(i,j)\in E} B_{ij}^{st} O_{ij}^{st} = 0 \tag{3}$$

$$B_{ij}^{st} T_l^{st} Z_l^{ij} = 0 \quad \forall (i,j) \in E \quad \forall l \in L \tag{4}$$

$$\left(\sum_{l\in L} T_l^{st} T_l^{xy}\right) B_{ij}^{st} B_{ij}^{xy} = 0 \quad \forall [x,y] \in R \quad \forall (i,j) \in E \tag{5}$$

link capacity constraint:

$$\sum_{[x,y]\in R} O_{ij}^{xy} + O_{ij}^{st} + \max_{[x,y]\in R}\left\{B_{ij}^{xy}, B_{ij}^{st}\right\} \le W_{ij} \quad \forall (i,j) \in E \tag{6}$$

path length constraint:

$$\sum_{(i,j)\in E} B_{ij}^{st} \le H \tag{7}$$

As indicated in (1), minimising the cost of assigning the primary and the backup LSP for transporting the new traffic [*s*,*t*] is the objective. The minimisation is subject to several sets of constraints. The flow continuity constraints in (2) guarantee that on LSP_{st} and $\mathrm{LSP}_{b,st}$, the source node s only has outgoing flow (i.e. $i = s$), the destination node t only has incoming flow (i.e. $i = t$), and the flow at the intermediate nodes is balanced (i.e. $i \neq s,t$). The disjoint constraints impose the backup LSP being link-disjoint from its corresponding primary LSP (i.e. (3)), and being SRLG-disjoint from its primary LSP (i.e. (4)). Two primary LSPs are SRLG-disjoint if $\sum_{l\in L} T_l^{st} T_l^{xy} = 0$ where $[x,y] \in R$. Equation (5) indicates that the backup LSPs can share common backup resources *if and only if* the two corresponding primary LSPs are *SRLG-disjoint*. Furthermore, the sum of the primary and the maximum backup traffic in a link is no more than the link capacity W_{ij}, as indicated in (6). In order to guarantee the QoS of traffic recovery, the backup LSP length is upper-bounded by H in (7) to satisfy the customer requirement on the recovery time, the successful recovery probability and the signal loss. The selection of a proper H will be further discussed in Section 3.

3 Backup path length

3.1 Recovery failure probability

The backup LSPs will be attempted from the source to the destination after a failure occurs. The channels along the backup LSPs need to be reserved in order to switch the disrupted traffic onto the backup LSPs. The 'expected recovery failure probability' is a parameter in SLA to specify the upper bound of the failure probability of reserving a backup LSP. Suppose such a limit θ is specified, and assume that the failure probability of reserving a link is α (referred to as one of the network provisioning parameters) and the maximum length of a backup LSP is H, we have

$$P\{\text{fail to recovery}\} = [1 - (1 - \alpha)^H] \le \theta \tag{8}$$

The maximum backup LSP length is bounded by

$$H \le \frac{\ln(1-\theta)}{\ln(1-\alpha)} \tag{9}$$

This means that given the network provisioning parameter of α, the backup LSP length must be upper bounded by (9) to meet the customer requirement of θ. As shown in Fig. 1, for the same θ, the smaller α is the higher the probability that a link is reserved successfully; more hops can be attempted until reaching the SLA limit θ, and thus the backup LSP length limit is bounded by a higher value. For the same α, the smaller θ is the stricter the SLA requirement is on the successful recovery probability, and hence less hops can be attempted in a backup LSP.

3.2 Recovery time

Our analysis of recovery time focuses on the backup LSP reservation time T. Since the backup LSPs share common channels whenever possible, an attempt will be made to reserve the intermediate channels along the backup LSP as soon as a failure is detected on the primary LSP. Suppose the expected recovery time in SLA is τ, and assume the time required to reserve a channel is exponentially distributed

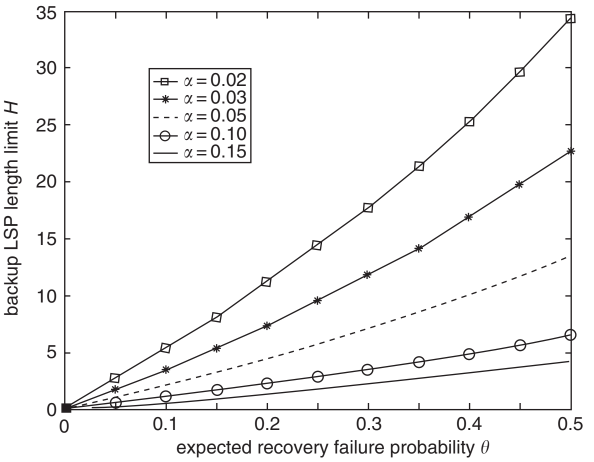

Fig. 1 *Backup LSP length limit against expected recovery failure probability*

with mean β, then the average recovery time is formulated as

$$\begin{aligned} E[T] &= \alpha\beta + 2(1-\alpha)\alpha\beta + 3(1-\alpha)^2\alpha\beta \\ &\quad + \cdots + (H-1)(1-\alpha)^{H-2}\alpha\beta + H(1-\alpha)^{H-1}\beta \\ &= \beta(1-(1-\alpha)^H)/\alpha \le \tau \end{aligned} \tag{10}$$

and the maximum backup LSP length is bounded by

$$H \le \frac{\ln(1-\alpha\tau/\beta)}{\ln(1-\alpha)} \tag{11}$$

Given the network provisioning of α and β, the backup LSP length must be limited by (11) to ensure that the expected recovery time is guaranteed. Figure 2 illustrates the impact of β and τ on H. The bound of the backup LSP length H is lower if the single link reservation time β is longer. Such a bound decreases as the customer requires faster recovery, i.e. smaller τ.

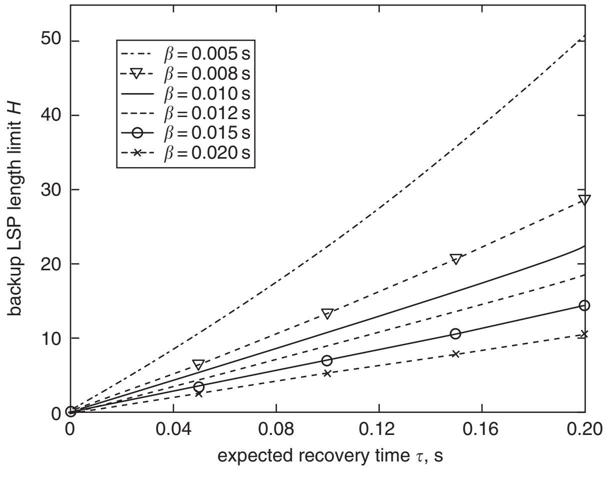

Fig. 2 *Backup LSP length limit against expected recovery time, $\alpha = 0.01$*

3.3 Signal loss

The distortion coming from fibre transmission and cross-connect (OXC) noise results in signal loss. The expected signal loss σ in SLA specifies the customer requirement on the upper bound of the signal loss in a path. Suppose the signal loss probability through a link transmission is γ, and assume the signal loss probability through an OXC is η, then

$$P\{\text{signal loss}\} = 1 - (1-\gamma)^H(1-\eta)^{H+1} \le \sigma \tag{12}$$

The maximum backup LSP length is bounded by

$$H \le \frac{\ln(1-\sigma) - \ln(1-\eta)}{\ln(1-\gamma) + \ln(1-\eta)} \tag{13}$$

Figure 3 illustrates the impact of σ and η on H. The more signal loss on each OXC, the less hops can be attempted, and thus a smaller upper limit on the backup LSP length.

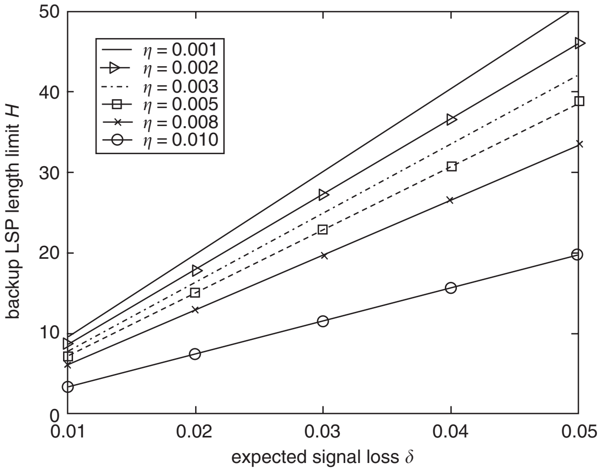

Fig. 3 *Backup LSP length limit against expected signal loss, $\gamma = 0.0005$*

Combining (9), (11) and (13), the upper bound of the backup LSP length H is

$$\begin{aligned} H \le \min\Bigg\{ &\frac{\ln(1-\alpha\tau/\beta)}{\ln(1-\alpha)}, \\ &\frac{\ln(1-\theta)}{\ln(1-\alpha)}, \frac{\ln(1-\sigma)-\ln(1-\eta)}{\ln(1-\gamma)+\ln(1-\eta)} \Bigg\} \end{aligned} \tag{14}$$

Given the SLA parameters θ, τ and σ, the upper bound of the backup LSP length H is decided by (14). H is closely related to the network provisioning parameters (i.e. α, β, γ and η) and the customer QoS requirements (i.e. θ, τ and σ). Implementing such an H in (7) reduces the search space for the backup LSPs into the range of H hops apart from the source nodes. Such an H also ensures that the backup LSPs solved from the formulations have guaranteed recovery quality.

4 Heuristic algorithm

The problem formulated in Section 2 is essentially a SRLG diverse routing problem, and has been shown to be NP-complete [6]. The number of variables and constraints increase rapidly with the size of the network, and it is practically infeasible to achieve online traffic recovery; thus, heuristics must be employed. We employ the following heuristic algorithm as a rapid real-time solution with polynomial time complexity.

The backup channel sharing (BCS) algorithm assumes that we are given: the network topology $G(N,E)$, the already carried traffic R in G (including the primary LSPs and the corresponding backup LSPs), the SRLG information L and the new traffic $[s,t]$. The purpose of BCS is to find LSP_{st} and $\text{LSP}_{b,st}$ while minimising the network cost and satisfying the

SLA parameters. The key idea of BCS is accommodating the SLA parameters into the backup LSP length limit and employing online computation with polynomial time complexity.

In the following, the term 'link' refers to the fibre link between two adjacent nodes in *G*; the term 'channel' refers to the wavelength connection between two adjacent nodes in the layered graph [8, 9]. Each link supports several wavelengths, and thus has several channels. Two values are maintained by a channel. The 'channel cost' shows the value of employing a channel for traffic transmission; while the 'shared bucket' value records the number of backup LSPs going through a channel. Each channel maintains a 'channel cost' value for the minimum cost path routing. Each channel also maintains a 'shared bucket', which indicates the number of backup LSPs sharing the channel. Each source–destination traffic pair is assigned an 'SRLG list', which lists all the SRLGs that the primary LSP goes through.

The BCS algorithm addresses this problem in the following steps.

(i) Initialisation: The network topology is extended into the layered graph. The layered graph G_L can be obtained from the given network topology G by replicating the given graph G for $W = max\{W_{ij}\}$ times in G_L. Each layer represents the wth wavelength, i.e. λ_w, $\lambda_w \in \{\lambda_1, \lambda_2, \ldots, \lambda_W\}$. The connection between two nodes in each layer is called a channel, which denotes an actual wavelength connection in G between the two nodes. Set the 'channel cost' values of all channels to one. Set the 'shared bucket' values of all channels to zero. Set all the 'SRLG list' of traffic $[x,y]$, $[x,y] \in R$, to zero. Calculate the backup LSP length limit H according to (14).

(ii) For a carried traffic $[x,y]$, $[x,y] \in R$, set the 'channel cost' value of the channels along LSP_{xy} as ∞. Record the SRLG information of LSP_{xy} in the 'SRLG list' of traffic $[x,y]$. Increase the 'shared bucket' values of all the channels that have been assigned to $\text{LSP}_{b,xy}$ by one. Do this for all the already carried traffic.

(iii) For the new traffic $[s,t]$, among the channels with zero 'shared bucket' value, assign LSP_{st} by the least-channel-cost routing, such as Dijkstra's algorithm [10], and set the 'channel cost' of the channels that have been assigned to LSP_{st} as ∞. Record the SRLGs into the corresponding 'SRLG list'.

(iv) Compare the 'SRLG list' of traffic $[s,t]$ with all other nonzero 'SRLG list'. If the 'SRLG list' of traffic $[s,t]$ has at least one common SRLG with other traffic $[x,y]$, $[x,y] \in R$, set the 'channel cost' of the channels belonging to $\text{LSP}_{b,xy}$ to ∞.

(v) In the leftover channels with finite 'channel cost', find the least-channel-cost path within length H as $\text{LSP}_{b,st}$; if there is a tie, select the path with the largest sum of the 'shared bucket' of its intermediate channels as $\text{LSP}_{b,st}$.

(vi) Increase the 'shared bucket' value of each intermediate channel in $\text{LSP}_{b,st}$ by one. Update R by adding $[s,t]$, and recover the 'channel cost' in step (iv).

(vii) Redo step (iii)–(vi) for the new incoming traffic.

(viii) For a leaving source–destination traffic pair, reset the 'channels cost' along its primary LSP to one, and decrease the 'shared bucket' by one along its backup LSP.

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$G_L$ = Initialise(G, N, E, W, SRLG)
$A$ = AssignCostOfCarriedTraffic($G_L$, R, ChannelCost, SharedBuket, SRLGList)
if incoming traffic $[s,t]$
        $\text{LSP}_{st}$ = FindPrimaryLSP($[s,t]$, $A$)
        if ($\text{LSP}_{st}$ = Null) return NO PRIMARY LSP FOUND FOR $[s,t]$;
        $A1$ = UpdateCost($\text{LSP}_{st}$, $A$)
        $\text{LSP}_{b,st}$ = FindBackupLSP($[s,t]$, $A1$, $H$)
        if ($\text{LSP}_{b,st}$ = Null) return NO BACKUP LSP FOUND FOR $[s,t]$;
        $A$ = UpdateCost($\text{LSP}_{st}$, $\text{LSP}_{b,st}$, $A$)
        $R = R + [s,t]$
        return $\text{LSP}_{st}$ and $\text{LSP}_{b,st}$;
end if
if leaving traffic $[x,y]$
        $A$ = UpdateCost($\text{LSP}_{xy}$, $\text{LSP}_{b,xy}$, $A$)
    return $A$;
end if
```

Fig. 4 *BCS algorithm*

The pseudocode of BCS is shown in Fig. 4, where LSP_{st} and $\text{LSP}_{b,st}$ are the primary and the backup LSP for the new incoming traffic $[s,t]$, respectively; LSP_{xy} and $\text{LSP}_{b,xy}$ are the primary and the backup LSP for the leaving traffic $[x,y]$, respectively. The channels of the primary LSPs are occupied, and cannot be shared by the backup LSPs; therefore, such channels are pruned from the backup LSP routing by assigning their 'channel cost' to ∞. The SRLG-disjoint constraint from its primary LSP in (4) and (5) is accomplished by assigning the 'channel cost' of those intermediate channels that are in the same SRLG with the primary LSP to ∞. Step (i) extends the network topology into the layered graph, ensuring that the backup LSP assignment is done in the wavelength granularity instead of the fibre link granularity. The time complexity of step (iii) is $O(w|E|\log_{10} n)$, where $|E|$ is the total number of logical links in G, w is the maximum number of wavelengths in each link and n is the total number of nodes in G. Step (iv) ensures that the backup LSP of traffic $[s,t]$ is multiplexed with other backup LSPs if and only if the corresponding primary LSPs are *SRLG-disjoint*, and its time complexity is $O(|R||L|)$, where $|R|$ is the total number of source–destination traffic pairs in G and $|L|$ is the total number of SRLGs. The link-disjoint constraint of (3) is guaranteed by setting the 'channel cost' of those channels in the same SRLG to ∞. The time complexity of step (v) is also $O(w|E|\log_{10} n)$. 'Shared bucket' is an indicator for the backup LSP multiplexing. In order to improve the bandwidth sharing among the backup LSPs, step (v) chooses the backup LSP with the largest 'shared bucket' value when there is a tie. The objective of minimising path cost in (1) is accomplished by employing the least-cost routing to find the primary and the backup LSP. The overall time complexity of BCS is $O(w|E|\log_{10} n + |R||L|)$.

5 Results and discussions

Simulations are conducted on the networks listed in Table 1, which are taken from [6]. Each link contains eight wavelengths, and thus there are eight channels supported in one link. For comparison purposes, we applied the weighted-SRLG scheme [4], the two-stage ILP [7] and our proposed BCS on these networks. When simulated on a Pentium IV 2.3G PC, the average time of finding a pair of SRLG-disjoint LSPs for a new source–destination traffic

Table 1: Simulation networks

Network	Nodes	Links	SRLGs
I	47	47	65
II	49	185	72
III	144	298	198
IV	226	353	303

Table 2: Infeasible ratio

SLA paramters			Network parameters				BCS (%)	Weighted-SRLG (%)	Two-stage ILP (%)
α (%)	θ (%)	τ (ms)	β (ms)	σ (%)	η (‰)	γ (‰)			
1	10	50	10	1	0.5	0.5	0	2	6
1	20	50	10	1	1	0.5	0	4	10
3	20	20	5	3	5	1	0	6	14
3	10	20	5	1	1	1	0	10	16

pair by BCS, the weighted-SRLG and the two-stage ILP are 22, 64 and 205 ms, respectively. The two-stage ILP is expected to have the longest running time since it is basically an ILP-based scheme, and thus intrinsically time-consuming. The weighted-SRLG runs slower than BCS because the calculation of the *k*-shortest path from the source to the destination in the weighted-SRLG requires a long time.

The bandwidth multiplexing gain, i.e. g_b, is defined as the ratio between the average number of carried traffic under a scheme against the number under the SRLG diverse routing scheme proposed in [6], in which there is no resource sharing among the backup LSPs. Figure 5 shows the simulation results in terms of the bandwidth sharing efficiency. A larger value of g_b means more backup LSPs are multiplexed into the backup channels, and thus better bandwidth sharing is achieved. As the number of source–destination traffic pairs increases, the bandwidth sharing among the backup LSPs increases too. The result that weighted-SRLG has the lowest g_b is reasonable since the SRLG disjointness is its primary objective. Both BCS and the two-stage ILP achieve high bandwidth sharing by considering the bandwidth sharing among the backup LSPs, while BCS provides much better QoS guarantees than the latter (which is shown by the next simulation).

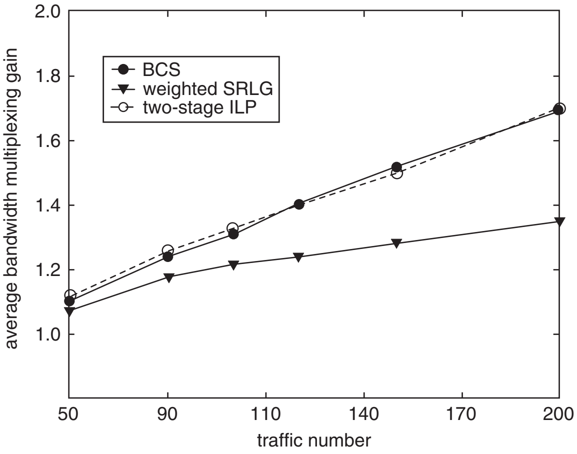

Fig. 5 *Bandwidth multiplexing gain when $\alpha = 1\%$, $\theta = 10\%$, $\tau = 50\,ms$, $\beta = 5\,ms$, $\sigma = 1\%$, $\eta = 0.5‰$ and $\gamma = 0.5‰$*

Although the two-stage ILP provides the similar bandwidth multiplexing gain as BCS, not all of its backup LSPs guarantee the required traffic recovery quality, such as the recovery time, the successful recovery probability and the signal loss. The infeasible ratio is defined as, for the specified SLA parameters, the number of source–destination traffic pairs whose backup LSP fails to meet the recovery QoS requirements against the total number of traffic that has been carried by a scheme. Table 2 summarises the simulation results. Since BCS considers the SLA parameters, all of the backup LSPs found by BCS are QoS-guaranteed, and the corresponding infeasible ratio is zero. Since bandwidth is the only QoS metric considered in the two-stage ILP, it may choose the backup LSPs that has a longer length and share more channels with other backup LSPs, and thus bears the highest infeasible ratio.

6 Conclusions

The problem of providing QoS-guaranteed traffic recovery in GMPLS networks has been introduced and formulated. Three SLA parameters, i.e. the expected recovery failure probability, the expected recovery time and the expected signal loss are analysed in terms of the network performance and the backup LSP length. The upper bound of the backup LSP length has been derived to guarantee multiple traffic recovery QoS metrics. The proposed BCS algorithm provides online path assignment solution for dynamic network traffic with multiple QoS guarantees and backup resource sharing. Simulations indicate that such a scheme achieves relatively high bandwidth sharing among the backup LSPs, and the backup LSPs are guaranteed with the recovery quality specified by SLA.

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