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Adaptive time- and location-aware routing in telecom mesh networks

Ferhat Dikbiyik[1], *Biswanath Mukherjee*[2], *Massimo Tornatore*[3]

[1]*Department of Electrical and Computer Engineering, University of California, Davis, CA 95616, USA*
[2]*Department of Computer Science, University of California, Davis, CA 95616, USA*
[3]*Department of Electronics and Information, Politecnico di Milano, Milan 20133, Italy*
E-mail: fdikbiyik@ucdavis.edu

Abstract: In telecom mesh networks, connections can be provisioned considering their availability requirements. A connection's availability can be estimated based on the links' statistical availability (e.g., depending on historical failure occurrences and repair times).The authors remark that the actual failure statistics depend on (i) when and (ii) where a connection is routed (as failure rates throughout the year and in different locations may be different). Moreover, the failure rate is not homogeneous along a link and a detailed time- and location-aware availability calculation is required. Most link failures are caused by dig-ups, thus there is a direct relationship between construction works, which require excavations, and link failures. So, the probability of a link failure at a certain location depends on (i) the time/day when dig-up works are performed and (ii) population of the location (assuming that the more crowded the location is, the more constructions occur). By exploiting the time- and location-dependent failure information, the authors investigate a novel adaptive time- and location-aware routing scheme, which provisions connections on highly available paths depending on a connection's duration and availability requirements. The authors' approach shows significant upgrade-cost savings, while satisfying the service requirements, compared with traditional approaches.

1 Introduction

In an operational network, service availability is defined as the ratio of a connection's 'up' time over a specific penalty period. Network operators (NO) usually promise a certain availability to the customers depending on their demands and this requirement is stated in a service level agreement (SLA). Based on this SLA specification, the NO has to guarantee that a connection's actual availability is equal to or greater than its target availability, stated in its SLA, at the end of the penalty period or a penalty must be paid by the NO. NO uses a statistical availability value for each network component to estimate a connection's availability. However, since (i) availability value of a network component depends on failure rate and repair time and (ii) failure rate and repair time vary by time and location because of, for example, visibility, weather conditions, intensity of human activities, such as constructions or plowing [1] etc., the availability attribute describing a network element cannot be defined by a single value. To accurately estimate the availabilities of network components, a detailed analysis on the causes of the failures should be done. In this study, we discuss that the failure probability of a link depends on how many urban locations it traverses and the season of the year; and we provide a detailed time- and location-specific failure analysis, and an adaptive reprovisioning strategy is introduced. Here, we focus on fibre cuts, since node failures and other failures are less frequent [some representative failure frequency values for different network elements, represented by 'failure-in-time' (FIT) number of failures of a network element in 10^9 h, are 10^4 FITs per 10 km of fibre link, 10^5–10^6 FITs per SONET equipments etc. [2]. In the rest of the study, failure refers to link failure unless noted otherwise].

Crawford [1] analyses causes of fibre cuts and shows that dig-ups are the major cause of fibre cuts (Fig. 1) and historical data about companies involved in fibre-optic cable dig-ups is provided in [3] (Fig. 2). Most companies causing fibre-optic cable dig-ups (electric and gas, telephone company, water and sewer etc.) do excavations in urban areas, whereas other companies may do excavations in rural areas. Thus, it is more likely for a link to experience a failure (e.g. cut) in urban areas than in rural areas. It is noted that the number of failures on a 100 km-link which traverses several urban areas is expected to be larger than on a 1000 km-link, which traverses less urban areas.

The number of works that require dig-ups depends on weather conditions [4–7]. If the weather is too rainy, snowy, hot or cold, for a safe working environment, these works are usually not scheduled for these days. There might be some maintenance works scheduled on these days, which usually do not involve dig-ups, for example,

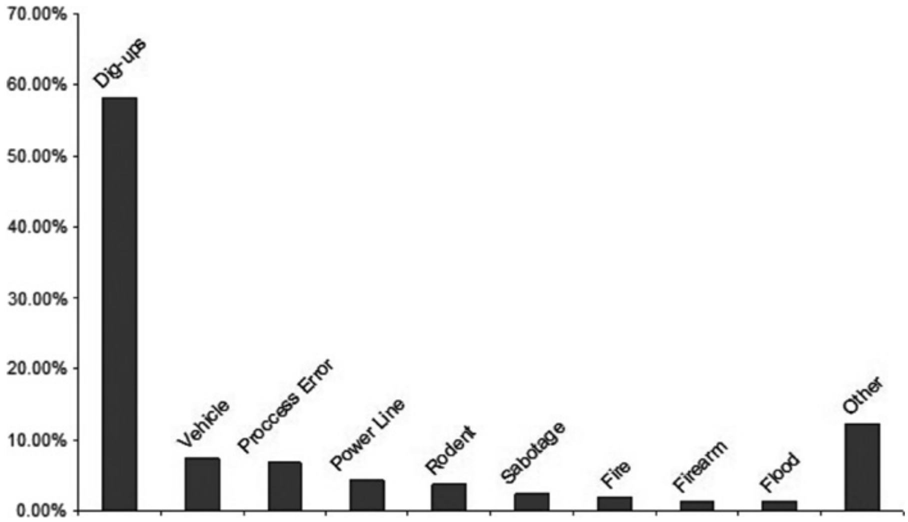

Fig. 1 *Immediate causes of fibre-optic cables [1]*

anti-icing/de-icing on roads/highways [7]. Also, weather conditions vary for different locations. Some locations might be more available for dig-ups during the winter than others. For instance, in San Diego, CA, the average number of rainy days in January is six, whereas it is more than 25 in Erie, Pennsylvania, for the same month [8]. Thus, the probability of a construction which might cause a cable cut in San Diego is more than Erie in January. The population of the location is also related to the number of construction/maintenance works in a city. The more populated the city is, the more link failures caused by construction/maintenance works are expected. Not only the probability of failure, but also time to repair (TTR) a failure depends on weather conditions. If the weather conditions are not sufficiently good to perform repair, then the repair can be postponed. In this study, we explore time and location effects on probability of failure and TTR, and we propose a time- and location-aware routing (TILA) scheme, which may adapt routing by exploiting time and location information [The time of the day, for example, daytime or night, also affects the number of works that require dig-ups. However, it does not affect the decision on routing, if we just scale the amount of work during the day to night.]. We focus on optical wavelength-division multiplexing mesh backbone telecom networks with wavelength conversion and fibre link cuts. Note that our approach is also applicable to general mesh networks.

The rest of this study is organised as follows. Section 2 describes the effects of time and location on failure probability and TTR. The adaptive TILA is proposed in Section 3. In Section 4, we provide illustrative numerical examples to compare our approach with traditional approaches. Finally, Section 5 concludes the study.

2 Probability of failure and time to repair

2.1 Probability of failure

We define X_e, the set of urban 'locations' in which link e traverses, including locations of end nodes. First, we

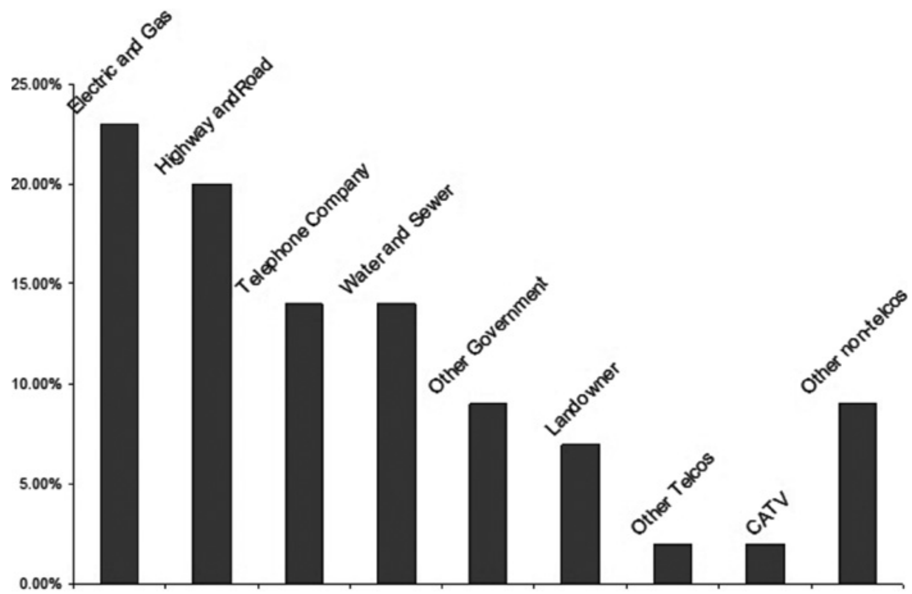

Fig. 2 *History of companies involved in fibre-optic cable dig-ups [3]*

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estimate probability of failure at these locations of a link. Note that the major reason for a link failure is dig-ups, and let P_f denote the probability of a link failure because of a dig-up. Since the probability of a dig-up depends on time (t) and location (x), the probability of failure on a specific location at a given time can be defined as $P_\mathrm{f}(x,\ t) = P_\mathrm{f} \times P_\mathrm{d}(x,\ t)$, where $P_\mathrm{d}(x,\ t)$ is the probability of a dig-up at location x at a given time t. $P_\mathrm{d}(x,\ t)$ can be estimated by using statistical weather conditions and the population percentage (η_x) of location x (i.e. the ratio of location's population to the total population). Let P_a and P_u denote the probability of a dig-up work on the days which are available and unavailable for dig-up, respectively ($P_\mathrm{a} \gg P_\mathrm{u}$), and $P^\mathrm{a}_{x,t}$ and $P^\mathrm{u}_{x,t}$ denote the probability that the observed period of time t falls in a work-available day and in a work-unavailable day at location x, respectively. A day's work availability depends on weather conditions, where some weather condition thresholds for work availability are provided in [4–6]. Then, we can be define $P_\mathrm{d}(x,\ t)$ as $P_\mathrm{d}(x, t) = \left(P_\mathrm{a}P^\mathrm{a}_{x,t} + P_\mathrm{u}P^\mathrm{u}_{x,t}\right)\eta_x$. Then, the probability of failure at a specific location at a given time is given by

$$P_\mathrm{f}(x, t) = P_\mathrm{f} \times \left(P_\mathrm{a}P^\mathrm{a}_{x,t} + P_\mathrm{u}P^\mathrm{u}_{x,t}\right)\eta_x \tag{1}$$

Let $P_\mathrm{f}(e,\ t)$ denote probability of failure on link e at time t. This probability depends on the urban locations where link e traverses. The probability that link e is available $(1 - P_\mathrm{f}(e,\ t))$ is equal to the product of probabilities of no failure at any of the locations traversed by link e, since link e is available if and only if there is no failure at any location where link e traverses. Then, $(P_\mathrm{f}(e,\ t))$ can be estimated by

$$P_\mathrm{f}(e, t) = 1 - \left(\prod_{x\in X_e}\left(1 - P_\mathrm{f}(x, t)\right)\right) \tag{2}$$

Similarly the probability of failure on the path of a connection c can be defined as follow

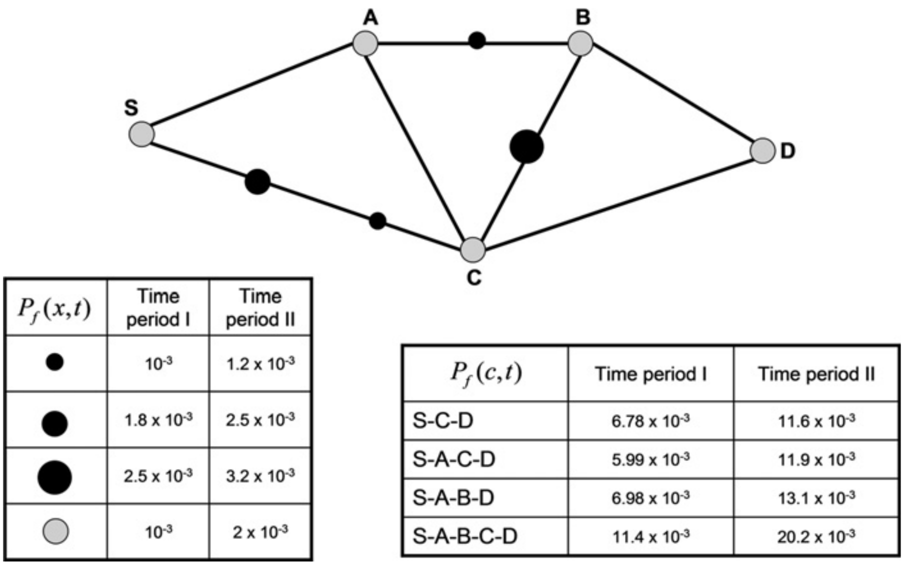
$$\begin{aligned} P_\mathrm{f}(c, t) &= 1 - \left(\prod_{e\in E_c}\left(1 - P_\mathrm{f}(e, t)\right)\right) \\ &= 1 - \left(\prod_{e\in E_c}\prod_{x\in X_e}\left(1 - P_\mathrm{f}(x, t)\right)\right) \end{aligned} \tag{3}$$

where E_c is the set of links on which connection c is routed.

Fig. 3 demonstrates the effects of time and location on probability of failure on a small topology. The black dots are urban location where links traverse and their radius are proportional to their populations. Let c be a connection request from nodes S to D. The table on lower left shows the probability of failure in different location types during two different time periods. The table on lower right shows the probability of failure for connection c [calculated by (3)] if it is routed on different paths during two different time periods. During time period I, route S–A–C–D and during time period II, route S–C–D have less failure probability than others. If holding time of c is less than any of the time periods, it should be routed on S–A–C–D or S–C–D depending on in which time period c arrives; otherwise, an adaptive routing scheme (routing on S–A–C–D in first time period and on S–C–D in second time period) can be applied. We discuss this adaptive routing in Section 3.

2.2 Time to repair

TTR is the sum of time to detect failure, determine the failure location, prepare and/or direct a repair team to the failure location and repair time. Although some studies (e.g. [9]) on fault recovery set a mean TTR (MTTR) of 12 h, in fact, TTR varies depending on the distance between repair team and location of failure and the availability of the day (i.e. weather conditions) to repair. In this study, we define TRR



$P_f(c,t)$	Time period I	Time period II
S-C-D	6.78×10^{-3}	11.6×10^{-3}
S-A-C-D	5.99×10^{-3}	11.9×10^{-3}
S-A-B-D	6.98×10^{-3}	13.1×10^{-3}
S-A-B-C-D	11.4×10^{-3}	20.2×10^{-3}

Fig. 3 *Five-node topology with urban locations on links, failure probabilities of these locations (left table) and alternative routes of a connection from node S to D (right table) in two different time periods*

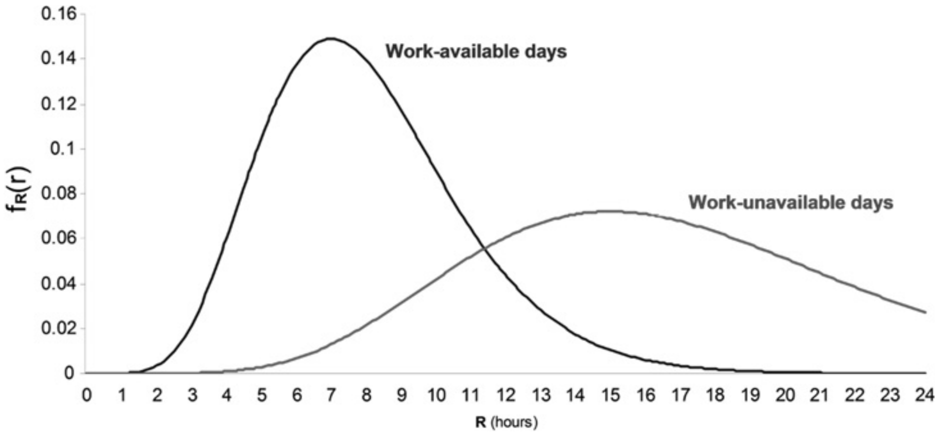


Fig. 4 *Sample pdfs of repair time for work-available and unavailable days*

as follows

$$\mathrm{TTR}(x, t) = F + d(x)/v + E[\boldsymbol{R}] \tag{4}$$

where F is the time to detect failure and determine the failure location x, $d(x)$ is the distance from x to the nearest central office (where the repair team resides), v is the average speed of repair team, and $\boldsymbol{R}$ is a Weibull random variable which defines the repair time [10]. Weibull distribution is usually defined by a couple of parameters: shape α and scale β parameters. In this study, we consider that these parameters depend on time and location of the repair. Let $\alpha_{t,x}$ and $\beta_{t,x}$ denote shape and scale parameters, respectively. Then, the expectation of repair time can be given by

$$E[\boldsymbol{R}] = E[\boldsymbol{R}]_{\alpha_a,\beta_a} P^{a}_{t,x} + E[\boldsymbol{R}]_{\alpha_u,\beta_u} P^{u}_{t,x} \tag{5}$$

where (α_a, β_a) and (α_u, β_u) are parameters for work-available and unavailable days, respectively; and $E[\boldsymbol{R}]_{\alpha,\beta}$ is expectation of Weibull variable $\boldsymbol{R}$ with parameters α and β. Note that on a work-available day, $E[\boldsymbol{R}]$ is expected to be small with a low standard deviation, whereas for a work-unavailable day, $E[\boldsymbol{R}]$ is larger and standard deviation is high since it is difficult to know when the weather conditions will be available for repair. Fig. 4 shows example probability density functions (pdfs) of repair time for work-available and unavailable days, drawn by these assumptions.

3 Adaptive time- and location-aware routing scheme

Availability-aware routing (AAR) algorithms have been proposed [11–13], where the most-reliable path(s) are computed based on the availabilities of links to satisfy availability requirements set in SLAs. The availability of a link is estimated based on historical data for the mean time between failures (MTBF) and MTTR, and calculated by [14]

$$A_e = \frac{\mathrm{MTBF}}{\mathrm{MTBF} + \mathrm{MTTR}} \tag{6}$$

However, as explained in previous section, availability of a link on a specific location may vary with time. Let $A_e(x, T)$ define the availability of a link at location x and time interval $T = [t_0, t_1]$. $\mathrm{MTTR}(x, T)$ is equal to $\frac{1}{T}\int_{t_0}^{t_1} \mathrm{TTR}(x, t)\,\mathrm{d}t$. MTBF can be defined as a function of failure rate ($\lambda(x, T)$) at location x during time interval T, as $\mathrm{MTBF}(x, T) = 1/\lambda(x, T)$. If we consider exponential failure occurrence [15] in time interval T, then $\lambda(x, T) = -(1/T)\ln(1 - P_f(x, T))$, where $P_f(x, T)$ is probability of failure during time period T, which can be estimated by

$$P_f(x, T) = \frac{1}{T}\int_{t_0}^{t_1} P_f(x, t)\,\mathrm{d}t \tag{7}$$

Then (see (8))

Link e is available, if and only if all the locations where link e traverses (X_e) are available. Then, the availability of link e during time period T is defined by

$$A_e(T) = \prod_{x \in X_e} A_e(x, T) \tag{9}$$

These calculations show that the availabilities of links may change for different time periods. We can estimate $A_e(h_c)$ to provision connection c, where h_c denotes the holding time of the connection such that $A_\theta \geq A_c$ (A_θ is the availability of connection's path θ), and calculated by $A_\theta = \prod_{e \in E_\theta} A_e(h_c)$, where E_θ is the set of links θ traverses [we call this approach TILA, which does not adapt routing of connections for different time intervals]. However, for small time intervals, A_θ might be less than A_c and cause SLA violation penalties. For instance, in the sample topology shown in Fig. 3, let h_c be the sum of time periods I and II (T_1 and T_2), where the length of each period is equal to T, and TTRs in periods I and II are $0.016T$ and $0.008T$, respectively. If we just consider $A_e(h_c)$ for availability of links, then $A_{\theta_1}(h_c) > A_{\theta_2}(h_c)$, where θ_1 and θ_2 are paths S–A–C–D and S–C–D, respectively, so path S–A–C–D is preferable. However, $A_{\theta_1}(T_2) < A_{\theta_2}(T_2)$; therefore the

$$A_e(x, T) = \frac{\mathrm{MTBF}(x, T)}{\mathrm{MTBF}(x, T) + \mathrm{MTTR}(x, T)} = \frac{1}{1 - \left(1/\left(T^2\right)\right)\ln\left(1 - (1/T)\int_{t_0}^{t_1} P_f(x, t)\,\mathrm{d}t\right)\int_{t_0}^{t_1} \mathrm{TTR}(x, t)\,\mathrm{d}t} \tag{8}$$

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connection might suffer in time period II while there is a better path (S–C–D). If we provision the connection on path S–A–C–D in the first time period (since $A_{\theta_1}(T_1) > A_{\theta_2}(T_1)$), and reprovision it on path S–C–D in the second time period, we can increase the availability and decrease the SLA violation penalty. Thus, we propose the adaptive time- and location-aware routing scheme (ATLAS), an adaptive provisioning scheme which calculates time- and location-dependent link availabilities for small time intervals and reprovision connections on most-reliable path (s) for each time interval. Let h_c be defined in multiple of T, for example, $h_c = mT$, where m is a positive integer, and $\theta^c(T_i)$ be the reliable path chosen to provision the connection in the ith time interval ($i = 0, 1,\ldots, m$). Our approach first finds k-most reliable paths' set [We use Yen's k-shortest path algorithm [16], which finds k' eligible paths ($0 \le k' < k$) if less than k paths exist.] ($\Theta^c(T_i) = \{\theta_1^c(T_i), \ldots, \theta_k^c(T_i)\}$) for connection c during the ith time interval, where $A_{\theta_j^c(T_i)} \ge A_c$ for all $j = 1,\ldots, k$ [If all the paths' availabilities in $\Theta^c(T_i)$ are less than A_c, then our approach provisions connection on the most-reliable path $\theta*^c(T_i)$, that is, $\forall j, \theta_j^c(T_i) \in \Theta^c(T_i), \theta_j^c(T_i) = \theta*^c(T_i)$: $A_{\theta*^c(T_i)} \ge A_{\theta_j^c(T_i)}$.]. Then, it selects the one which has more free resources to balance the load in the network, where the less-utilised links are preferable to avoid capacity exhaustion. Algorithm 1 (see Fig. 5) shows provisioning a connection $c = <s, d, h_c, A_c>$ given the topology $G(V, E)$ (V is set of nodes and E is the set of links), where s, d, h_c and A_c are source, destination, holding time and availability requirement of connection c, respectively.

3.1 Reprovisioning

Reprovisioning of connections have been widely discussed [17–22], where connections are typically reprovisioned when network state changes by failures/repairs or capacity changes in the network, etc. In this study, we discuss that reprovisioning may be also required with the change of failure profile of links in time because of time- and location-dependent failure statistics. Thus, we investigate a reprovisioning scheme that exploits dynamic failure profiles. After the initial provisioning, connections can be reprovisioned, that is, provisioning connections on other paths and release the resources on the current paths, at each time period. The reprovisioning of existing connections can be done one by one. The order of reprovisioning (i.e. which connections should be reprovisioned first) may affect the path availability provided to a connection, because the connections reprovisioned first might have shorter paths (which provide higher availability) than the other connections. Thus, we use urgency level (UL) concept [22] to define the order of reprovisioning.

UL is defined as a function of allowed number of failures (ANFs), and remaining holding time (RHT). First, we try to estimate the ANF of connection c for the next period, T_i, which describes the risk of SLA violation

$$\mathrm{ANF}_c(T_i) = \left\lfloor \frac{(1 - A_c) \times h_c - \mathrm{DT}_c(t_{0,i})}{\mathrm{MTTR}(\theta^c(T_{i-1}), T_i)} \right\rfloor \tag{11}$$

where $t_{0,\,i}$ is the time period when T_i starts, $\mathrm{DT}_c(t_{0,\,i})$ is down time experienced by connection at time $t_{0,\,i}$ since the beginning of current penalty period, and $\mathrm{MTTR}(\theta^c(i-1), T_i)$ is the expected MTTR in period T_i if the connection keeps its path on which it was provisioned in the previous period, T_{i-1}. When ANF = 0, a connection cannot afford any more failures and it needs a better path than the current one (i.e. its UL is high). RHT and UL are directly proportional since the shorter is the time left to terminate the connection, the lower risk the connection has. If SLA is violated, UL is proportional to how much SLA is violated, which can be defined by the SLA down time of connection c (SDT_c), where $\mathrm{SDT}_c = DT_c - (1 - A_c) \times h_c$. UL of connection c at the end of T_i is given by

$$\mathrm{UL}_c(T_i) = \begin{cases} \mathrm{RHT}_c/\mathrm{ANF}_c(T_i), & \text{if } \mathrm{ANF}_c(T_i) > 0 \quad (12a) \\ \mathrm{RHT}_c, & \text{if } \mathrm{ANF}_c(T_i) = 0 \quad (12b) \\ \mathrm{SDT}_c \times \mathrm{RHT}_c & \text{if otherwise} \quad (12c) \end{cases}$$

where (12a) means that connection c can afford failure(s) and its UL is proportional to its RHT and inversely proportional to how many more failures it can afford, (12b) shows that

Algorithm 1

Estimate availability of each link for period T_0, $A_e(T_0)$, by Eqn. (9), where T_0 is the time interval when c arrives.
Update link costs by the following equation:

$$C(e) = \begin{cases} -log\,(A_e(T_0)) & \text{if } F(e) > 0 \\ \infty & \text{if } F(e) = 0 \end{cases} \tag{10}$$

where $F(e)$ number of free wavelength channels on link e.
Find initial k-shortest-paths' set from node s to d, $\bar{\Theta}^c(T_0)$, where $|\bar{\Theta}^c(T_0)| = k'$ and $0 \le k' \le k$.
if $k' > 0$, **then**
  Compute each path's availability by $A_{\theta_j^c(T_0)} = \prod_{e \in E_{\theta_j^c(T_0)}} A_e(T_0)$ and add paths to reliable-paths' set, $\Theta^c(T_0)$, if $A_{\theta_j^c(T_0)} \ge A_c$.
  if $|\Theta(T_0)| = 0$, **then**
    Find the shortest path in $\bar{\Theta}^c(T_0)$ and provision connection on this path.
  else
    Update link costs as follows: $C(e) = 1 + \epsilon \times (W(e) - F(e))$, where $W(e)$ is number of wavelength channels on link e.
    Find the shortest path in $\Theta^c(T_0)$ and provision connection on this path.
  end if
else
  Network upgrade, i.e., adding bandwidth to the network, is required.
end if

Fig. 5 *Provisioning connection $c = <s, d, h_c, A_c>$ given $G(V, E)$*

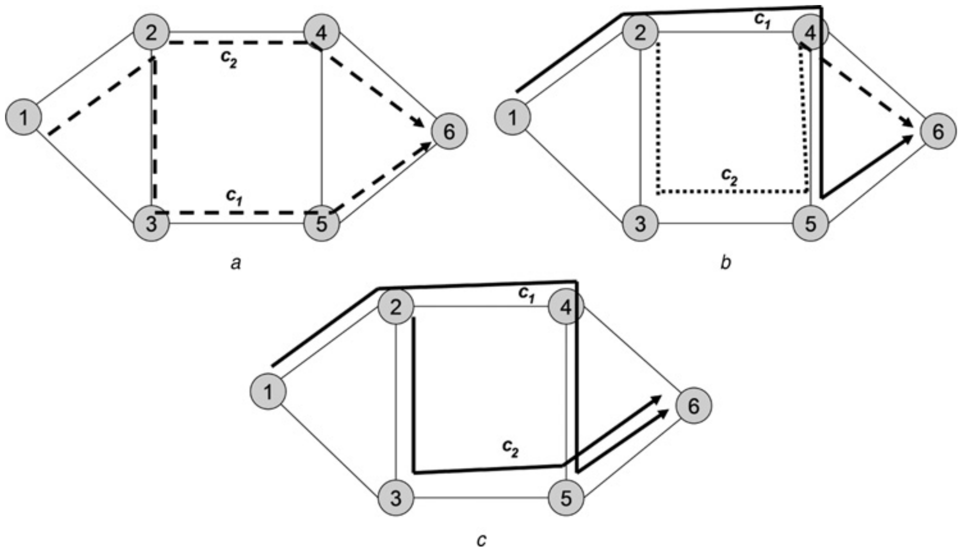

Fig. 6 *Sample reprovisioning scenario*

a Existing connections
b Reprovisioning c_1
c Reprovisioning c_2

connection c cannot afford any failures and its UL depends on its RHT and (12c) shows that connection c's SLA is already violated and urgency depends on how much SLA is violated and the RHT of the connection.

After ordering connections with respect to their ULs, our approach avoids disruption of connections during reprovisioning by using proposed non-disruptive reprovisioning techniques (e.g. 'bridge and roll' [23]). Fig. 6 demonstrates reprovisioning of two connections: c_1 and c_2, which are provisioned on paths (1–2–3–5–6) and (2–4–6), respectively (Fig. 6*a*). Let us assume $\text{UL}_1 > \text{UL}_2$, so we first reprovision c_1. The new paths in the next period for c_1 and c_2 are (1–2–4–5–6) and (2–3–5–6), respectively; and link (2–4) does not have any free wavelength. To avoid service disruption, first the subpath (2–4–5) of the new path of c_1 has to be provisioned (i.e. node 2 sends signals of c_1 to both nodes 3 and 4), then the subpath (2–3–5) of the existing path of c_1 can be removed. By using this approach, there is no disruption for c_1. However, in our example, link (2–4) does not have a free wavelength. Thus, our approach first provisions a backup path for link (2–4), temporarily reprovisions c_2 and sends signals of c_2 on this path [Note that this new path is temporary for c_2, because it is not reprovisioned yet. In our approach, we do not reroute connections if they are already reprovisioned for the period.], frees wavelength on link (2–4), which is used by c_2, and finally provisions c_1 on subpath (2–4–5) (Fig. 6*b*). After reprovisioning c_1, we can reprovision c_2 with the same non-disruptive method (Fig. 6*c*). Note that, if it is not possible to reprovision the connection without disrupting any other connection, our approach cancels the reprovisioning of the connection and keeps the current path of it.

Our reprovisioning approach updates link costs by the following function for each connection c (see (13))

where C_{rp} is the set of connections which are not reprovisioned and ε is a small number. To minimise the number of temporary reprovisioning, the cost assignment in (13) encourages connections to be reprovisioned on links, which have free wavelengths. Algorithm 2 (see Fig. 7) shows our reprovisioning approach for a given $G(V, E, C)$ for time period T_i, where C is set of existing connections. The complexity of Yen's k-shortest path algorithm is $O(k|V|^4)$ [16]. Reprovisioning process requires us to run the k-shortest path algorithm for each connection. Thus, the complexity of Algorithm 2 is $O(k|C||V|^4)$.

4 Illustrative numerical examples

4.1 Topology

We conduct numerical studies on a 24-node US topology with 32 wavelengths/link in each direction and with wavelength conversion (e.g. optical switches with O/E/O conversion). To model how fibre links are affected by dig-ups in urban areas, the information of which locations the fibre links traverse is required. Hence, we assume that fibre links are close to highways/railroads since they have to be accessible in case of a failure. Thus, we match the topology with the US transportation map, and we mark the locations of nodes and the major urban locations (e.g. population is > 80 000) where the fibre links traverse. Fig. 8 shows the topology and physical routes of fibre links with traversed locations.

We consider an upgrade model according to which are overbuilt individual fibre links when wavelength fill exceeds 60% at the end of each upgrade period (e.g. 1 year) [Upgrade is done by adding bundles of eight wavelengths in each direction with the assumption of minimum one and maximum four bundles per upgrade, depending on the link's maximum utilisation during the

$$C(e) = \begin{cases} \varepsilon \times -\log\big(A_e(T_i)\big), & \text{if } F(e) > 0 \\ -\log\big(A_e(T_i)\big), & \text{if } F(e) = 0 \text{ and } \exists c' \in \big\{C_{\text{rp}} - \{c\}\big\}: e \in E_{\theta^{c'}(T_{i-1})} \\ \infty, & \text{o.w.} \end{cases} \tag{13}$$

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Algorithm 2

1: Set $C_{rp} = C$.
2: Take the first connection c in C_{rp}, estimate the availability of each link for period T_i, $A_e(T_i)$, by Eqn. (9) and update link costs by Eqn. (13).
3: Find initial k-shortest-paths' set from node s to d, $\bar{\Theta}^c(T_i)$, where $|\bar{\Theta}^c(T_i)| = k'$ and $0 \leq k' \leq k$.
4: **if** $k' > 0$, **then**
5: Compute each path's availability and add paths to reliable paths' set, $\Theta^c(T_i)$, if $A_{\theta_j^c(T_i)} \geq A_c$.
6: **if** $|\Theta(T_i)| = 0$, **then**
7: Find the shortest path $(\theta^c(T_i))$ in $\bar{\Theta}^c(T_i)$ and go to Step 12.
8: **else**
9: Update link costs as follows: $C(e) = 1 + \epsilon \times (W(e) - F(e) - \epsilon \times S(e))$, where $S(e)$ is the number of wavelengths used by connections in C_{rp} on link e.
10: Find the shortest path $(\theta^c(T_i))$ in $\Theta^c(T_i)$ based on link-cost update in Step 9 and go to Step 12.
11: **end if**
12: Compare $\theta^c(T_{i-1})$ and $\theta^c(T_i)$.
13: **for** each link $e' \in E_{\theta^c(T_i)}$ **do**
14: **if** $e' \in \{E_{\theta^c(T_{i-1})} \cup E_{\theta^c(T_i)}\}$, **then**
15: Keep connection on the wavelength of link e' on which it is provisioned in the previous period
16: **else if** $e' \in \{E_{\theta^c(T_i)} - E_{\theta^c(T_{i-1})}\}$ **then**
17: **if** $F(e') > 0$, **then**
18: Take a free wavelength w_0 on link $e'$and add it to set W_c.
19: **else**
20: Take the wavelength $w_{c_{min}}$ used by c_{min}, the connection has the minimum UL among the connections, which are in C_{rp} and traverse link e'.
21: **if** a backup path exists for link e' such that there is at least one free wavelength on each link of backup path, **then**
22: Provision a lightpath on backup path for c_{min}, free $w_{c_{min}}$, and add it to W_c.
23: **else**
24: **if** $|\Theta^c(T_i)| = 0$, **then** go to Step 34, **else** clear W_c, remove $\theta^c(i)$ from $\Theta^c(i)$, and go to Step 7.
25: **end if**
26: Provision connection on the wavelengths in W_c.
27: Free wavelengths occupied by c on links which are in $\{E_{\theta^c(T_{i-1})} - E_{\theta^c(T_i)}\}$ and go to Step 34.
28: **end if**
29: **end if**
30: **end for**
31: **else**
32: Keep the current path $\theta^c(T_{i-1})$ as connection's path and go Step 34.
33: **end if**
34: Remove c from C_{rp}.
35: **if** $|C_{rp}| \neq 0$, **then** go to Step 2, **else** terminate algorithm.

Fig. 7 *Reprovisioning connections for period T_i given G(V, E, C)*

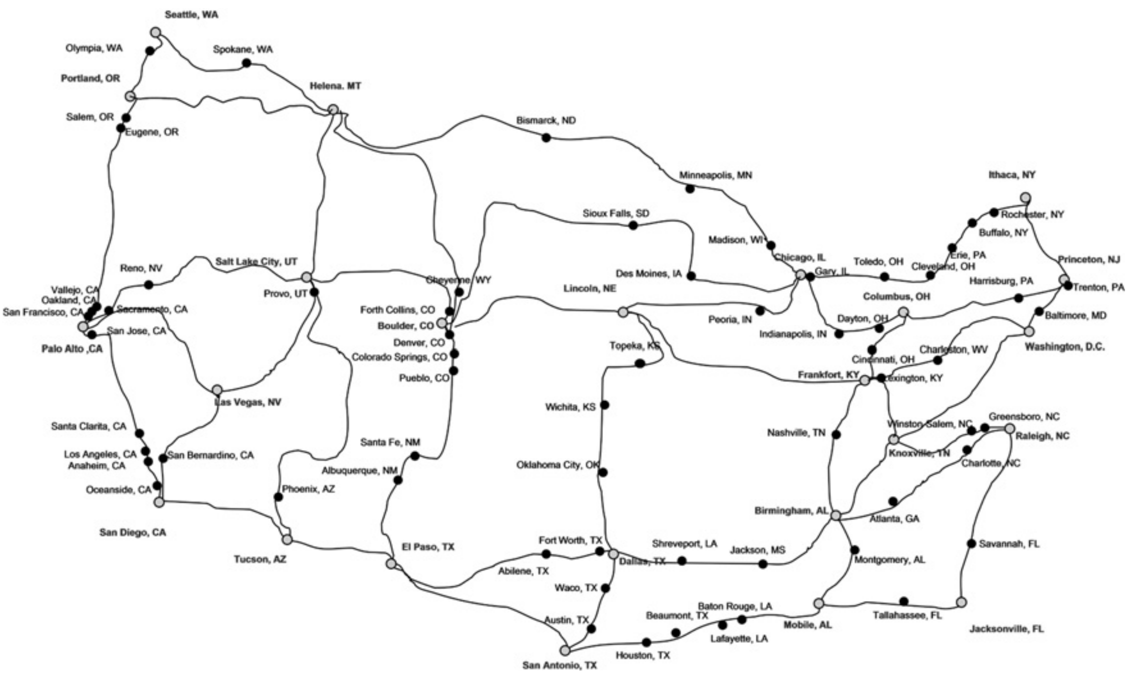

Fig. 8 *US-wide topology*

previous upgrade period.]. Indeed, NO do not want to turn away customers (i.e. reject connection requests) because of capacity exhaustion which would be an unrealistic mode of operation [24]. Hence, our model considers a growing traffic model together with an 'as-needed' upgrade of network capacity.

4.2 Collection of construction data

Moselhi *et al.* [4], El-Rayes and Moselhi [5] and Apipattanavis *et al.* [6] suggest some weather thresholds to determine if the weather is acceptable for construction/maintenance works. We apply these thresholds to our study to determine the probability of a dig-up. It [8] provides mean number of days, in which weather conditions do not provide safe working environment (work-unavailable days), because of rain (precipitation is equal or more than 0.01 inches), snow (including ice pellets), very high (above 90°F) or low (below 32°F) temperature, for each month at each location over 60 years [Number of years varies by the location depending on when the weather station initiated on that location. A 60-year interval is the average.]. We assume time unit (t) is 1 day. For each month, we determine $P^{\mathrm{u}}_{t,x}$ and $P^{\mathrm{a}}_{t,x}$ [used in (1) and (5)] as the ratio of number of work-available days and unavailable days to total days in that month, respectively. Fig. 9 shows the probability of work-available days for each month in different locations. We assume that the probability of a dig-up work on a work-available day is ten times of the probability of dig-up on a work-unavailable day ($P_{\mathrm{a}} = 10P_{\mathrm{u}}$) so that we can quantify the probability of failure in terms of $P_{\mathrm{f}}P_{\mathrm{u}}$. In our numerical examples, for evaluation purposes, we consider this product is equal to 0.05 to make links very fragile such that SLA violation penalties can be compared even for low network loads.

We use Weibull distributions shown in Fig. 4 to estimate repair time. By using (4) [We assume that time to detect failure (F) is negligible relative to other factors, the average speed of repair team $v = 90$ km/h, and there is a repair team ready at each node's location.] and (1), we can obtain the link availabilities for each time period T [(9)].

4.3 Traffic

We consider dynamic traffic where connections arrive, hold for a while, and terminate. Connection arrivals are scheduled for the first day of each month and holding time is one of the following options: 1, 3, 6, 12, 36 months, which follows the distribution: 50: 30: 15: 5: 1, respectively. We consider an exponential traffic growth model [25], where traffic is proportional to the population served by source and destination nodes of connections [26]. This aggressive traffic growth model helps us to compare upgrade costs even for low network loads. We conduct numerical examples for different network loads vary between 100 and 1000 Erlangs. We run our approaches ten times for each load and our results show the average.

4.4 Connection profile

We define five different types of connection requests targeting different availabilities (see Table 1). The number of requests in different types follows the distribution very important profile (VIP): platinum: gold: silver: bronze = 1: 5: 15: 30: 50. We define the penalty period the same as the connection's holding time.

4.5 Failure profile

Each urban location on each link experiences failures independently. We generate failures with probability $P_{\mathrm{f}}(x,$

Table 1 Customer profile

Type	VIP	Platinum	Gold	Silver	Bronze
availability	0.9999	0.9995	0.999	0.99	0.95

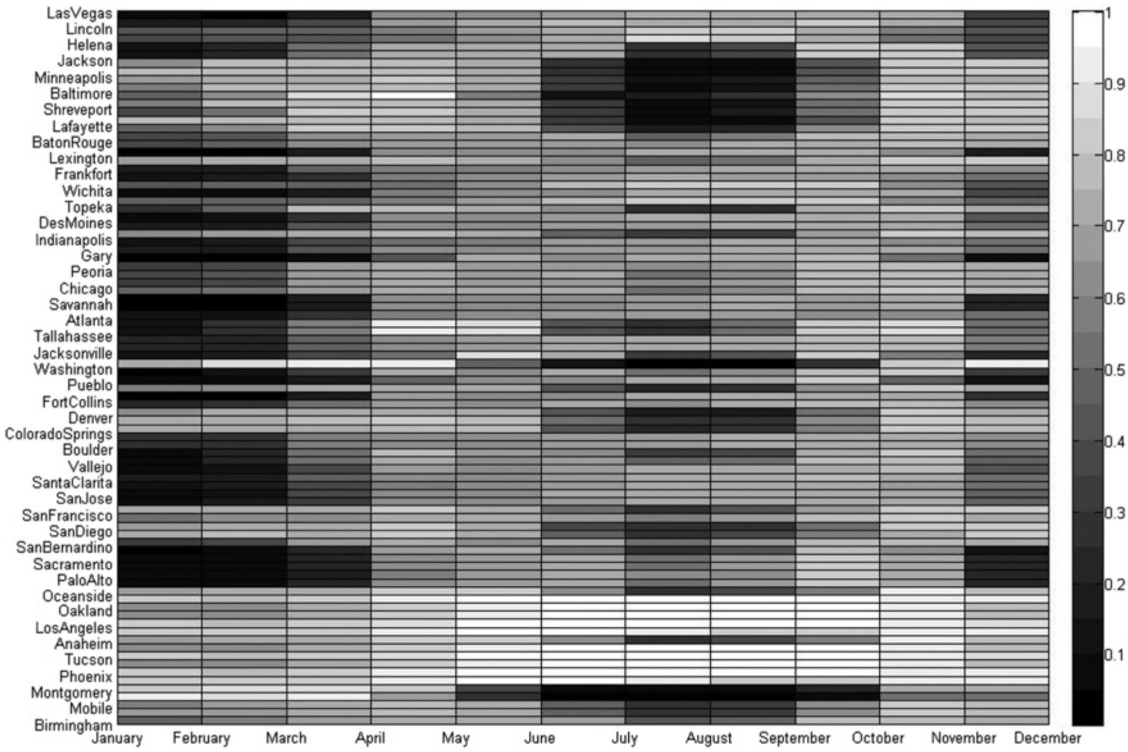

Fig. 9 *Probabilities of work-available days for each month in different locations*

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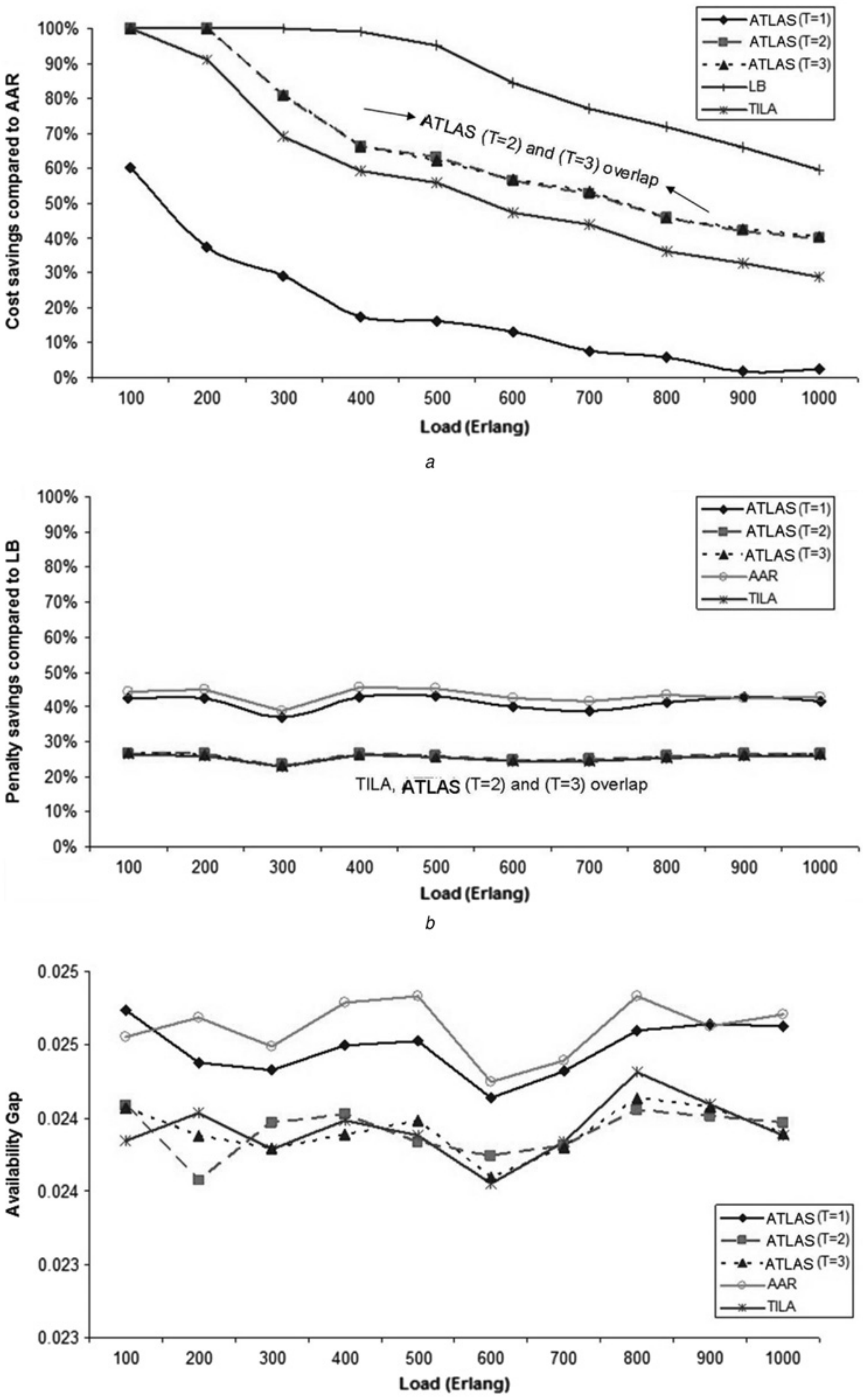

Fig. 10 *Comparison of*

a Upgrade-cost savings compared with AAR
b Penalty savings compared with LB
c Availablity gap

$t)(1+\zeta)$, where $P_f(x, t)$ is computed by (1) and ζ is a slack variable to account for the effects of deviations of weather conditions from average. In our numerical examples, we consider ζ is uniformly distributed between -0.01 and 0.01.

4.6 Comparison

We conduct numerical examples for our approach (ATLAS) for different reprovisioning period; $T = 1$, 2 and 3 months [We estimate link availabilities to provision/reprovision each connection for the time interval min(T, RHT_c).] and we compare it to (i) AAR [11], where availabilities of links are estimated by historical data of a large time interval (e.g. 60 years), (ii) TILA, which is similar to ATLAS, but availabilities of links are estimated only for holding time of each connection (i.e. there is no reprovisioning) and (iii) load-balancing (LB) approach, where connections are routed preferably on less-utilised links to avoid capacity exhaustion. We compare these approach in terms of upgrade cost (how much additional bandwidth required to be able to accept all requested connections), SLA violation penalty [22] (down time exceeding allowed down time specified in SLA) and availability gap between connections' actual and target availabilities.

Note that AAR shows the highest upgrade cost compared with the other approaches, because it targets to offer higher availability than needed, whereas LB shows the highest SLA violation penalty, because it is not aware of SLA requirements. Thus, we show cost savings normalised to upgrade cost in AAR (Fig. 10*a*) and penalty savings normalised to penalty in LB (Fig. 10*b*). Availability gap results are shown in Fig. 10*c*.

ATLAS with $T = 1$ month provides upto 60% upgrade-cost savings for low traffic loads, and upgrade-cost savings decreases with increase in load. Penalty savings are very close to those of AAR, since ATLAS with $T = 1$ provides availability closer to the target availability than AAR. When a link's time- and location-aware availability is estimated for a month, it is higher than a long-term statistical availability. Hence, ATLAS can find shorter paths which satisfy a connection's requirements. Cost savings can be increased if the availability gap is smaller, however this situation increases risk of SLA violation. For instance, ATLAS with longer reprovisioning periods ($T = 2$ or 3 months) or TILA can provide smaller availability gaps and high-cost savings, but this small gap will result in penalty increasing. LB can provide high upgrade-cost savings, because it selects a path which is unaware of availability requirements. Thus, it suffers in terms of SLA violation penalty. Availability gap of LB (not shown in Fig. 10*c*) is very low (around 0.02), which causes a connection's actual availability to be very close to the target availability. AAR, on the other hand, decreases SLA violation penalty, however it increases the upgrade costs. Our approach shows significant improvements on upgrade-cost savings while decreasing SLA violations.

Fig. 11 shows the average penalty savings compared with LB (over different network loads) for different (*a*) holding times and (*b*) connection types. For 1-month connections, penalty savings of all approaches are very close to each other. Note that these connections are not reprovisioned in ATLAS since the smallest reprovisioning period considered here is 1 month. However, for longer holding times, the smaller reprovisioning period provides just the right availability for the connections. Longer reprovisioning periods (ATLAS with $T = 2$ or 3 months) or lack of

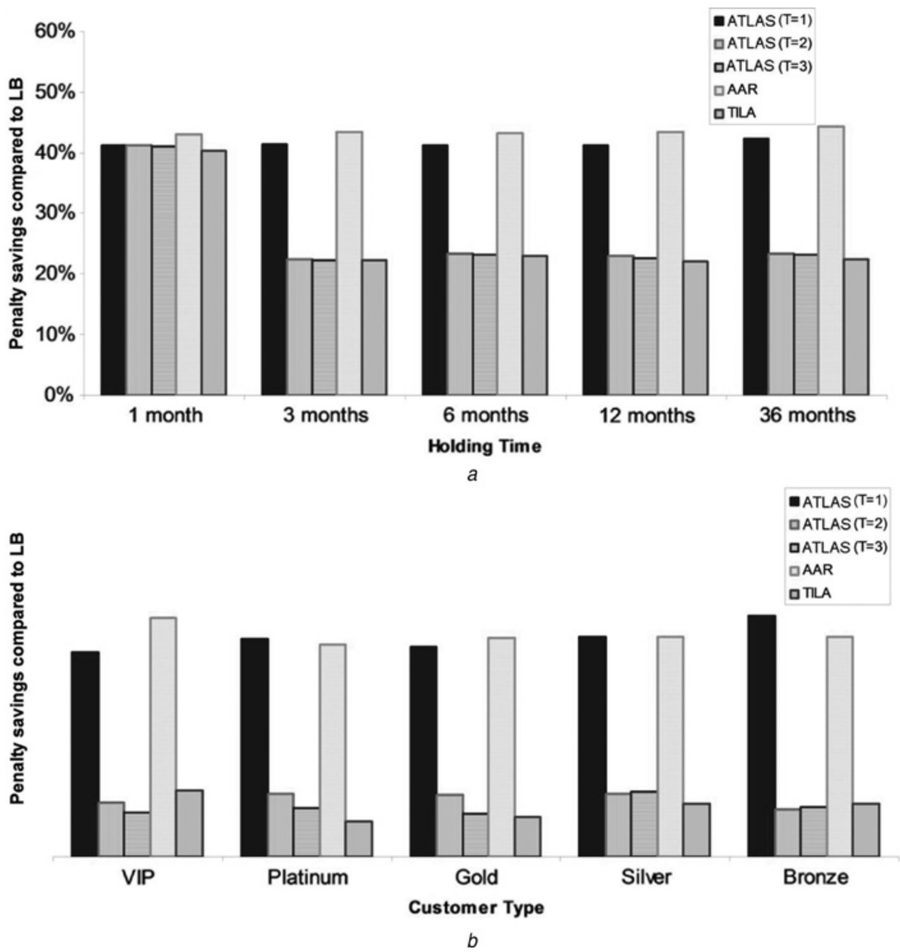

Fig. 11 *Penalty savings for different holding times and customer types*

a Penalty savings for different holding times
b Penalty savings for different customer types

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reprovisioning (TILA) causes SLA violations. ATLAS decreases SLA violations more than AAR when the availability requirements are less. For instance, AAR causes less penalties for VIP connections, but for bronze connections, ATLAS causes less penalty than AAR. Fig. 11*b* also shows that the shorter the reprovisioning period is, the more chance for penalty savings for high availability connections. The lack of reprovisioning as in TILA introduces more penalty for those connections.

5 Conclusion

In this study, we investigated the relationship between dig-up works and link failures, and explored the effect of time and location on the failures caused by dig-up. We discussed that there is a strong correlation between dig-up works and weather conditions, such that, for different locations and different times, we investigated time- and location-dependent failure rate and repair time characteristics. By exploiting this information, we proposed ATLAS, which provisions connections by estimating availabilities depending on when and at which locations connections are routed, and reprovisions them based on changing availability conditions of links. By numerical examples, we showed that our approach decreases upgrade costs without introducing additional SLA violations compared with traditional AAR.

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