Flow Availability Analysis in Two-Layer Networks with Dedicated Path Protection at the Upper Layer

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***Abstract*—We propose an analytical model that computes availability of upper-layer flows in two-layer networks with dedicated path protection deployed at the upper layer. Our proposed model reduces overestimation of the existing model caused by the ignorance of upper-layer failure correlations. We compute the flow availability by properly taking into account such correlation, and tracing upper-layer failures to lower-layer root causes. Our simulation results show that our proposed model reduces overestimation on upper-layer flow unavailability by about 30%, and thus significantly relaxes unnecessary high-availability requirements on lower-layer links without compromising the availability of upper-layer flows.**

I. Introduction

Backbone networks evolve into a two-layer architecture with the upper layer providing service to fine-granularity flows, and the lower layer providing high-bandwidth circuits. IP over optical networks adopt such a two-layer architecture, where a link at the IP layer (i.e., the upper layer), is laid out as a wavelength connection at the optical layer (i.e., the lower layer). For simplicity, in this paper we use term "flow" to refer to an upper-layer flow.

In two-layer networks, service protection for flows can be achieved by using path-oriented protection schemes at the lower or the upper layer [1], [2]. Protection is a proactive recovery procedure, where spare capacity is reserved during the request setup to tolerate a limited set of failure scenarios, e.g., against single fiber link failures in [1], [2]. When a failure occurs within the pre-defined set of failure scenarios, the flow is fully protected by switching over to its backup path, i.e., the flow maintains 100% availability. However, it is impractical to protect against all possible failures, and thus when a failure occurs outside of the pre-defined set of failure scenarios, the flow becomes out of service. A quantitative assessment of how well a flow is protected in all failure scenarios (both within and outside of the pre-defined set) is the "flow availability" metric, defined as a ratio of the accumulated operating time of a flow over its lifespan.

Different models were proposed to compute the availability of wavelength connections in optical networks, or generally, the availability of lower-layer connections in two-layer networks. These models employ either a serial-parallel reliability block diagram method [3] or a network-wise Markov state-space method [4], which all assume that failures of lower-layer links occur independently. Since a fiber link carries multiple wavelength connections by employing the Wavelength Division Multiplexing (WDM) technology, a single fiber link failure leads to multiple upper-layer link failures, causing a failure propagation issue in layered networks [5]. Therefore, the analytical model with an assumption of failure independence of upper-layer links [6]–[8] produces inaccurate results. Specifically, the seemingly independent upper-layer links may be closely associated with the same lower-layer links, leading to a failure correlation of upper-layer links.

We propose an analytical model to compute flow availability in two-layer networks to address the challenges arising from the fundamental differences between link failures at upper and lower layers. The key principle in tackling failure correlation is to compute flow availability at the lower layer, where lower-layer link failures are mutually independent in our assumption. Our model only requires upper-layer topology layout information, i.e., the mapping of upper-layer links onto lower-layer links. We consider dedicated path protection deployed at the upper layer as today's carrier networks rely on the upper layer to provide protection services [9]. The analytical results using our model match simulation results closer than the results using existing model [6]–[8]. Specifically, by treating the correlated upper-layer link failures as independent, the current flow availability model exaggerates flow unavailability, imposing unnecessarily high-availability requirements on lower-layer links to satisfy a given flow availability. In our simulation examples, existing model overestimates flow unavailability by 30% in average.

A good estimation of flow availability provides a significant saving in network resources. Flow availability is a key network quality of service (QoS) specification in the service level agreement (SLA), which is a formal contract between a service provider and a customer [10]. Flow availability in an SLA is the maximum accumulated service outage time a customer would expect over service duration. Violations of flow availability in SLAs result in financial penalties to service providers, and have negative impacts on customer relation. Note that in SLA-based provisioning, flow unavailability overestimation means additional network costs in terms of resource allocations and/or high-availability equipments for service guarantee.

Apart from the previous works in [6]–[8], the work in [11] discussed minimum failure-probability routing on a special correlated link failure model, where in face of a shared risk link group (SRLG) failure, the links associated with the SRLG fail independently with some probability (less than one). Also, the SRLG events are assumed to be mutually exclusive in the sense that only one SRLG failure can occur and exist in the network at a time. In the context of two-layer networks, the notion of an SRLG, however, is deterministic. In the event of a lower-layer link failure, all the lightpaths that traverse the lower-layer link fail. In addition, we do not make any specific assumptions on the lower-layer link failure scenarios that can occur. The work in [12] studied availability of logical topology in terms of connectivity while our focus is on the availability of upper-layer flows.

The remainder of this paper is organized as follows. We propose an analytical model for flow availability in Section II, followed by numerical results in Section III. We conclude this paper in Section IV.

II. Flow Availability Model

We propose a flow availability model when protection is performed at the upper layer.

The lower-layer topology is represented by an undirected graph $G_l = (\mathcal{N}_l, \mathcal{L}_l)$, where $\mathcal{N}_l$ is the node set, and $\mathcal{L}_l$ is the link set. The links are numbered from 1 to $|\mathcal{L}_l|$. Similarly, the upper-layer topology is modeled as $G_u = (\mathcal{N}_u, \mathcal{L}_u)$. $\mathcal{N}_u \subseteq \mathcal{N}_l$. When protection is deployed at the upper layer, each upper-layer link j is laid out as one lightpath $\boldsymbol{\theta}_j$ at the lower layer. The complete upper-layer topology layout information is captured by the interlayer link mapping matrix $\boldsymbol{\Theta} = \{\boldsymbol{\theta}_j\}_{|\mathcal{L}_u|\times 1} = \{\theta_{ji}\}_{|\mathcal{L}_u|\times|\mathcal{L}_l|}$. Binary element θ_{ji} takes the value of one if upper-layer link j uses lower-layer link i; zero otherwise. Given the upper-layer and lower-layer topologies, the link mapping matrix should guarantee that each upper-layer node pair has at least two paths that are not only link-disjoint at the upper layer but also link-disjoint at the lower layer. Such a survivable mapping matrix can normally[1] be found through the design principle proposed in [13].

Let $\mathcal{D}_u$ be the static upper-layer flow set. Each flow $s \in \mathcal{D}_u$ maintains on the logical topology a working path $\boldsymbol{\sigma}^s = \left\{\sigma_j^s\right\}_{1\times|\mathcal{L}_u|}$ and a backup path $\boldsymbol{\tau}^s = \left\{\tau_j^s\right\}_{1\times|\mathcal{L}_u|}$. The j-th element of the vectors takes the value of one if the corresponding path traverses upper-layer link j; zero, otherwise. Let binary row vectors $\boldsymbol{\rho}^s = \{\rho_i^s\}_{1\times|\mathcal{L}_l|}$ and $\boldsymbol{\varsigma}^s = \{\varsigma_i^s\}_{1\times|\mathcal{L}_l|}$ denote the physical layout of working path $\boldsymbol{\sigma}^s$ and backup path $\boldsymbol{\tau}^s$, respectively. Element ρ_i^s (ς_i^s) equals one if the working (backup) path traverses lower-layer link i; zero, otherwise. Element ρ_i^s and ς_i^s can be computed through $\rho_i^s = u\left(\sum_{j\in\mathcal{L}_u}\sigma_j^s\theta_{ji}\right)$ and $\varsigma_i^s = u\left(\sum_{j\in\mathcal{L}_u}\tau_j^s\theta_{ji}\right)$, respectively, where $\sum_{j\in\mathcal{L}_u}\sigma_j^s\theta_{ji}$ and $\sum_{j\in\mathcal{L}_u}\tau_j^s\theta_{ji}$ calculate the number of times the corresponding path traverses link i,

[1]While the work in [14] shows that the guarantee of logical topology connectivity in face of a single lower-layer link failure as in [13] does not guarantee the existence of physically link-disjoint path pairs for a logical node pair, design instances as in [1], [15] (and our practice) indicate that the latter property is well satisfied with the principle in [13].

and $u(x)$ is the Heaviside unit step function defined as

$$u(x) = \begin{cases} 1 & \text{if } x \geq 1, \\ 0 & \text{if } x < 1. \end{cases} \tag{1}$$

The working and the backup paths of flow s are physically link-disjoint to tolerate single fiber link failures, i.e., $\rho_i^s + \varsigma_i^s \leq 1, \forall\, i \in \mathcal{L}_l, s \in \mathcal{D}_u$.

Each lower-layer link i has a steady-state availability value A_i^l, independent of all the other links. The value of A_i^l is found through the mean failure rate λ_i and the mean time to repair $MTTR_i$ of link i as $A_i^l = (1/\lambda_i)/(1/\lambda_i + MTTR_i)$. Link unavailability $U_i^l \equiv 1 - A_i^l \ll 1$. Given A_i^l, the availability of upper-layer link j is calculated as

$$A_j^u = \prod_{i\in\mathcal{L}_l} A_i^{l\,\theta_{ji}}, \qquad \forall j \in \mathcal{L}_u. \tag{2}$$

If upper-layer link failures are treated as mutually independent events [6]–[8], the serial-parallel method can be applied to upper-layer paths. This enables simple availability formulations for working path $\boldsymbol{\sigma}^s$ and backup path $\boldsymbol{\tau}^s$ as in (3) and (4), respectively.

$$\widetilde{A}_s^{u,w} = \prod_{j\in\mathcal{L}_u} A_j^{u\,\sigma_j^s}, \qquad \forall s \in \mathcal{D}_u \tag{3}$$

$$\widetilde{A}_s^{u,p} = \prod_{j\in\mathcal{L}_u} A_j^{u\,\tau_j^s}, \qquad \forall s \in \mathcal{D}_u \tag{4}$$

Next, we show how the independence treatment affects the accuracy of the availability model. Introducing (2) in working path formulation (3) yields

$$\begin{aligned} \widetilde{A}_s^{u,w} &= \prod_{j\in\mathcal{L}_u} A_j^{u\,\sigma_j^s} \\ &= \prod_{j\in\mathcal{L}_u}\left(\prod_{i\in\mathcal{L}_l} A_i^{l\,\theta_{ji}}\right)^{\sigma_j^s} \\ &= \prod_{j\in\mathcal{L}_u}\left(\prod_{i\in\mathcal{L}_l} A_i^{l\,\theta_{ji}\sigma_j^s}\right) \\ &= \prod_{i\in\mathcal{L}_l}\left(\prod_{j\in\mathcal{L}_u} A_i^{l\,\theta_{ji}\sigma_j^s}\right) \\ &= \prod_{i\in\mathcal{L}_l} A_i^{l\left(\sum\limits_{j\in\mathcal{L}_u}\sigma_j^s\theta_{ji}\right)}. \end{aligned} \tag{5}$$

Equation (5) states that if an upper-layer path traverses a lower-layer link multiple times (as different upper-layer links can share the same lower-layer link), the availability of the lower-layer link is counted the same number of times in the availability model, and thus degrades the path availability in calculation. Similar derivation and statement can be made for backup path formulation in (4). Consequently, flow unavailability as a product of working and backup path unavailability is overestimated when any of its two paths traverses a lower-layer link more than once.

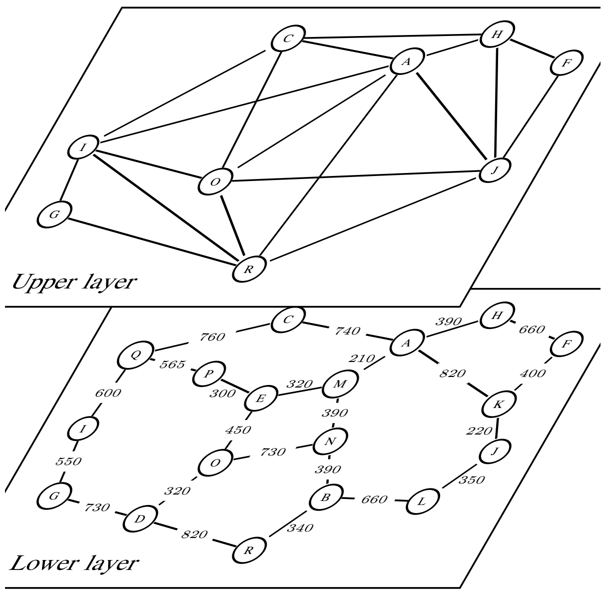

Fig. 1. Network topology with fiber length (in km) on physical links ($|\mathcal{N}_u| = 9, |\mathcal{L}_u| = 19, |\mathcal{N}_l| = 18, |\mathcal{L}_l| = 23$).

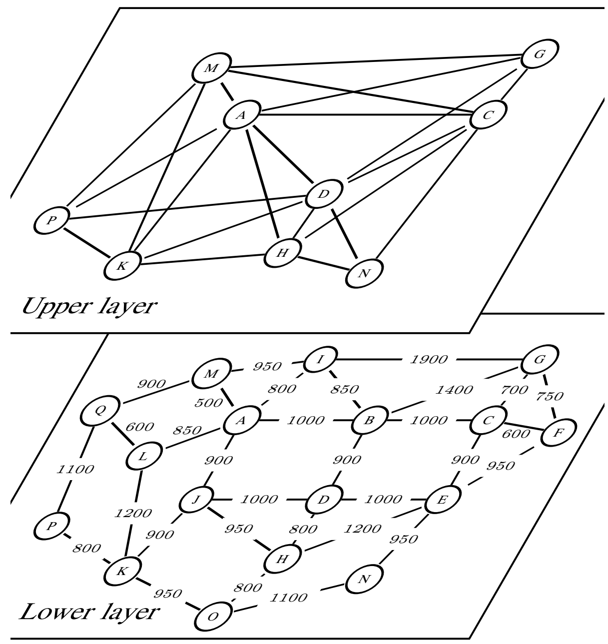

Fig. 2. Network topology with fiber length (in km) on physical links ($|\mathcal{N}_u| = 9, |\mathcal{L}_u| = 23, |\mathcal{N}_l| = 17, |\mathcal{L}_l| = 31$).

As indicated above, if path availability is calculated at the upper layer, where link failures are correlated, formulas based on the independent failure assumptions can cause unavailability overbuild. Alternately, as link failures are decorrelated at the lower layer, we propose to project the upper-layer paths onto the physical topology (i.e., find out the set of lower-layer links a path traverses), and build the flow availability model accurately at the lower layer. As a result, availability of working and backup paths of flow s is calculated as

$$A_s^{u,w} = \prod_{i\in\mathcal{L}_l} A_i^{l\,u\left(\sum_{j\in\mathcal{L}_u} \sigma_j^s \theta_{ji}\right)} = \prod_{i\in\mathcal{L}_l} A_i^{l\,\rho_i^s}, \qquad \forall s \in \mathcal{D}_u \quad (6)$$

$$A_s^{u,p} = \prod_{i\in\mathcal{L}_l} A_i^{l\,u\left(\sum_{j\in\mathcal{L}_u} \tau_j^s \theta_{ji}\right)} = \prod_{i\in\mathcal{L}_l} A_i^{l\,\varsigma_i^s}, \qquad \forall s \in \mathcal{D}_u. \quad (7)$$

Then, unavailability of flow s is given by

$$U_s^{u,f} = (1 - A_s^{u,w})\,(1 - A_s^{u,p})\,, \qquad \forall s \in \mathcal{D}_u. \quad (8)$$

III. Numerical Results

The comparative study is carried out on the network topologies in Figs. 1 and 2. The fiber lengths (in km) are marked on the physical topologies. The time to failure and the failure repair time of each lower-layer link follow negative exponential distributions. The mean failure rate of a link is measured in FIT/km, where 1 FIT (failure in time) refers to 1 failure in 10^9 hours. The mean time to failure of the network[2] is 170.72 hr and 68.49 hr for the network in Fig. 1 and Fig. 2, respectively, when the link failure rate is 500 FIT/km. The mean time to repair of a link is assumed to be 12 hr. The unavailability of a flow is calculated as the outage time divided by the total simulation time, which is 100 years. The results are averaged over 20 runs.

We use the path-flow/link-path version[3] of the integer linear programming model in [13] to design the survivable logical topology layout. Based on the survivable mapping, we generate the static flows for study. For each logical node pair, 5 working paths and 5 physically link-disjoint backup paths associated with each working path are calculated on the logical topologies, if they exist, by using the K shortest path algorithm. The physical hop counts of upper-layer links are used as link costs on the logical topologies. The total number of flows calculated is 601, i.e. $|\mathcal{D}_u| = 601$, for the network in Fig. 1, and 821, i.e. $|\mathcal{D}_u| = 821$, for the network in Fig. 2. Among them, we identify the flows that have any of its two paths traversing a lower-layer link multiple (≥ 2) times by set

$$\mathcal{M}_u = \left\{ s\in\mathcal{D}_u \;\middle|\; \exists\, i\in\mathcal{L}_l: \sum_{j\in\mathcal{L}_u} \sigma_j^s \theta_{ji} > 1 \vee \sum_{j\in\mathcal{L}_u} \tau_j^s \theta_{ji} > 1 \right\}. \quad (9)$$

The size of set $\mathcal{M}_u$ is found to be 400 (which is around 66.56% of the total flows) for the network in Fig. 1, and 257 (which is around 31.30% of the total flows) for the network in Fig. 2. As the calculations for the rest of the flows (i.e., $s \in \mathcal{D}_u \setminus \mathcal{M}_u$) are the same with different models, we focus on the flows in set $\mathcal{M}_u$ to compare the availability models.

Fig. 3 and Fig. 4 show (on the left axis) the average unavailability taken over all the flows in set $\mathcal{M}_u$ for the

[2] The mean time to failure is defined as the reciprocal of the mean failure rate. As the link failure arrivals are independent Poisson processes, considering the superposition property of independent Poisson processes, the mean failure rate of a network is thus calculated as the sum of the mean failure rates of all the links.

[3] 50 paths are pre-calculated for each upper-layer link, if they exist, by using the K shortest path algorithm with hop count metric.

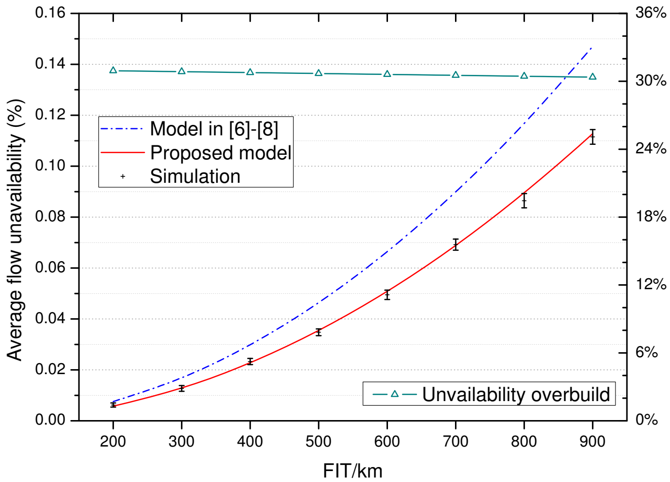

Fig. 3. Average unavailability taken over flows in set $\mathcal{M}_u$ on the network topology in Fig. 1. Simulation results are with 95% confidence interval.

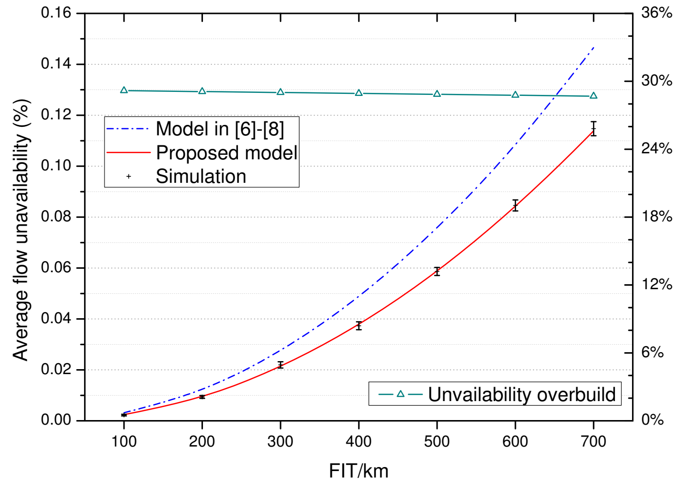

Fig. 4. Average unavailability taken over flows in set $\mathcal{M}_u$ on the network topology in Fig. 2. Simulation results are with 95% confidence interval.

network in Fig. 1 and Fig. 2, respectively. We compare under different link failure rates the proposed model, the model in [6]–[8], and the simulation results with a confidence level of 95%. We observe that the proposed analytical model fits well with the simulation results: nearly all the results fall into the 95% confidence interval for the network in Fig. 1; and all the results are within the interval for the network in Fig. 2. In contrast, the model in [6]–[8] gives much higher average values than the simulation results for both networks. This accords with our discussions in Section II that unavailability for flows in set $\mathcal{M}_u$ is overestimated by the model in [6]–[8].

As a measure to compare the proposed model with the model in [6]–[8], we define the unavailability overbuild of flow s as $\left(\widetilde{U}_s^{u,f} - U_s^{u,f}\right)/U_s^{u,f}$. Fig. 3 and Fig. 4 show (on the right axis) the average unavailability overbuild taken over all the flows in set $\mathcal{M}_u$ for the corresponding networks. We observe that for all the link failure rates studied, the average overbuild is above 30% on the network in Fig. 3, and is above 28% on the network in Fig. 4. The average overbuild decreases slightly with the increase of the link failure rates on both networks.

Fig. 5 takes a snapshot of the unavailability for each individual flow in set $\mathcal{M}_u$ on the network in Fig. 1. The failure rate is set to 600 FIT/km. We count the number of flows that is below, within, and above the 95% range, respectively, for both models. The comparative results between the proposed model and the model in [6]–[8] are 2 vs. 0 for below the range, 374 vs. 36 for within the range, and 24 vs. 364 for above the range, respectively.

Fig. 6 takes a snapshot of the flow unavailability in set $\mathcal{M}_u$ on the network in Fig. 2. The link failure rate is 400 FIT/km. We observe that using the proposed model, unavailability of 249 flows (96.89% of the flows in set $\mathcal{M}_u$) falls within the confidence interval, and only 8 flows (3.11% of the flows in set $\mathcal{M}_u$) fall above the confidence range. In contrast, with the model in [6]–[8], only 6 flows (2.33% in set $\mathcal{M}_u$) are within the confidence interval while the majority 251 flows (97.67% in set $\mathcal{M}_u$) are out of the range with higher unavailability values.

Results in Figs. 5 and 6 further show that the proposed model achieves much better accuracy than the model in [6]–[8].

IV. Conclusions

We studied the analytical model for flow availability in two-layer networks with dedicated path protection at the upper layer. We showed that if flow availability is calculated at the upper layer, where link failures are correlated, existing model that assumes failure independence significantly overestimates the flow unavailability. We proposed a new model that builds the flow unavailability at the lower layer so that redundant calculation is removed. Numerical results show that the existing model gives unavailability overestimation for a large portion of the flows while the new model achieves good accuracy in contrast.

V. Acknowledgement

Dr. Ni is highly indebted to Prof.-Dr. D. A. A. Mello for his help in understanding his work and the availability topic in general, and to Prof.-Dr. M. Tornatore for discussions on his work. Dr. Wu acknowledges the research support from the State Key Laboratory of Advanced Optical Communication Systems and Networks, Shanghai Jiao Tong University, China.

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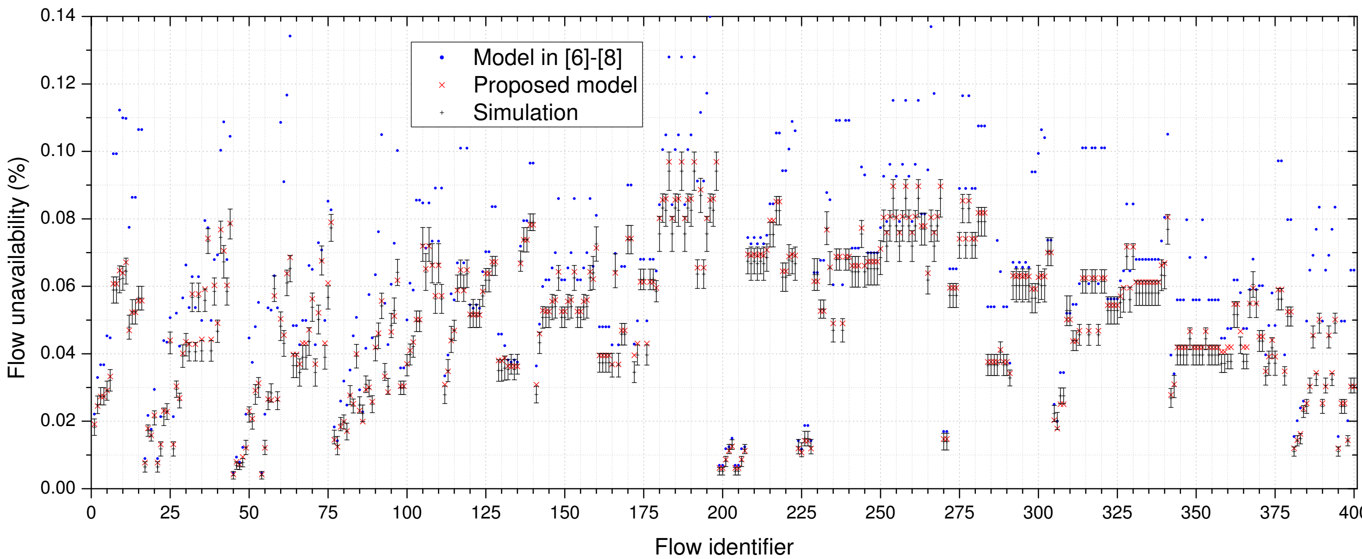

Fig. 5. Unavailability of flows in set $\mathcal{M}_u$ on the network topology in Fig. 1 when the link failure rate is 600 FIT/km. Simulation results are with confidence interval at 95% confidence level.

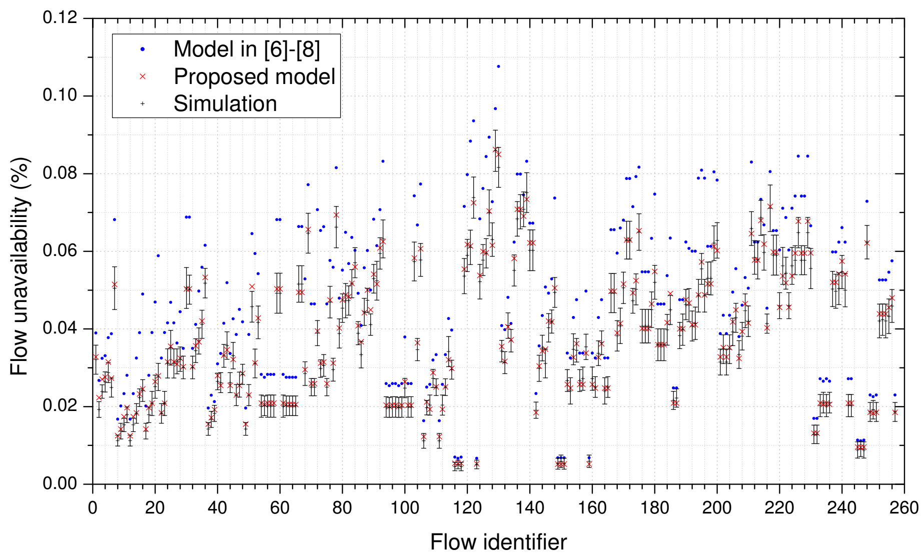

Fig. 6. Unavailability of flows in set $\mathcal{M}_u$ on the network topology in Fig. 2 when the link failure rate is 400 FIT/km. Simulation results are with confidence interval at 95% confidence level.

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