Resource Re-Allocation for Pre-Planned Power Outages in Optical Networks

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Abstract: We quantitatively evaluate disruption of services under pre-planned power outages in optical networks. Considering batteries for bypassing and re-routing, the rejection rate is reduced by 33% with less than 1% service degradation.

1. Introduction

Optical networks are essential societal infrastructures that must guarantee continuous (ideally uninterrupted) service operation. Recently, service continuity in optical networks is challenged by an increased risk of power outages [1]. In fact, while power outages have been traditionally triggered by various reasons such as natural disasters, maintenance procedures, targeted attacks, lately new threats are emerging related to the *sudden energy shortages* due to international political crisis. For instance, South Africa has experienced recurring national power blackouts (named "load sheddings") since 2007. As a more recent example, during last winter (2022), both France and the United Kingdom had to face high risk of power cuts (lasting up to few hours) due to the energy crisis exacerbated by the joint effect of high winter energy demand and of supply disruptions caused by war [2]. Power outages typically result in the loss of functionality for geographically-adjacent nodes that accommodate network devices for optical switching and IP routing. This can trigger substantial network disruptions, which motivated us to investigate how to mitigate network disruptions, and maximize service continuity, under power outages. As this type of *pre-planned power outages* is usually announced several hours or even days in advance, we can devise proactive network-reconfiguration strategies that can use this early-warning time to reduce service disruption. In particular, the availability of batteries at selected nodes represents a game changer to achieve successful service preservation.

Some preliminary investigation has already separately investigated the energy-efficiency [3, 4] and disaster resiliency [5] of optical networks, but very limited attention has been devoted to the *optical-network resilience under power outages* [1]. The only existing work [1] considers a limited scenario where only one node fails, and does not investigate possible combinations of optical and IP-layer re-routing. Our work aims to address more realistic scenarios where multiple nodes are affected by power outages, and where different combinations of IP layer and/or optical layer re-routing are admitted. Moreover, our research takes into account the opportunity to use a given small amount of batteries to preserve at least the optical bypassing functionality, thereby minimizing service disruption. The idea of equipping selected nodes with emergency batteries for optical switching is underpinned by the observation that optical switching exhibits notably lower power consumption compared to that for transponders and IP routers [4]. Moreover, we extend our analysis to quantify both the decrease in rejection rate and the incurred cost associated with handling degraded requests when service degradation is permitted.

In the next sections, we first classify the proposed approaches for proactive resource re-allocation in case of pre-planned power outages, and provide an illustrative example. Then we propose novel resource re-allocation algorithm for connection re-routing (considering possible changes in modulation format and wavelength assignment). Finally, we provide a numerical evaluation of the rejection rate and degradation rate of different approaches.

2. Proactive Resource Re-Allocation in Response to a Pre-planned Power Outage

2.1. Classification of Re-Allocation Approaches for Pre-planned Power Outage

We consider 6 different proactive approaches to re-allocate resources for power outages. These approaches can be classified into two categories, (*i*) *without battery* and (*ii*) *with battery* (for bypassing in nodes with power outages). These two categories can be further divided into six different approaches according to different re-routing constraints. 1) *No Battery and Fixed Routing* (*NB-Fix*): nodes with power outages do not have batteries, and the routing of requests is fixed. 2) *No Battery and IP layer Re-Routing* (*NB-IP*): nodes do not have batteries, and IP layer re-routing is allowed. 3) *No Battery and IP&Optical Re-Routing* (*NB-IP&O*): nodes do not have batteries, and both IP and optical re-routing are allowed to re-route the requests. 4) *With Battery and Fixed Routing* (*B-Fix*): nodes with power outages can perform bypassing using batteries, and the routing of requests is fixed. 5) *With Battery and IP Re-Routing* (*B-IP*): nodes with power outages have batteries, and IP layer re-routing is allowed.

6) *With Battery and IP&Optical Re-Routing* (*B-IP&O*): nodes are equipped with batteries, and re-routing can be performed in both IP and optical layer. Note that we exclude the scenario where re-routing is exclusively permitted in the optical layer as it has no practical significance since optical layer re-routing has much higher operational complexity compared to the IP layer. Therefore, we consider that when re-routing in the optical layer is allowed, re-routing in the IP layer is also permitted. This encompasses both *NB-IP&O* and *B-IP&O*.

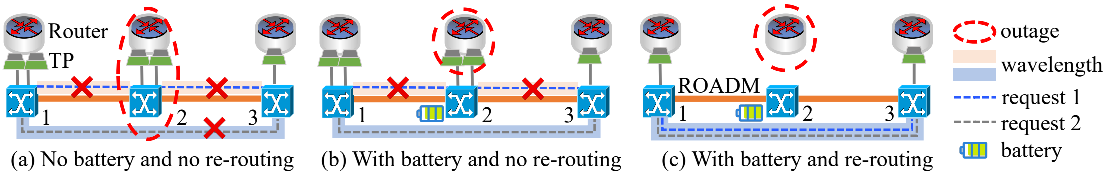

Fig. 1: Illustration of pre-planned power outage using batteries and re-routing.

2.2. *An Illustrative Example of Resource Re-Allocation of Pre-Planned Power Outage*

We demonstrate resource re-allocation for pre-planned power outage using batteries and re-routing with a three-node topology as shown in Fig. 1. Suppose that we have two requests between node pair (1,3). Request 1 is served with the orange wavelength and regenerated in the IP router of node 2, and request 2 is served with the blue wavelength by bypassing node 2. Assume that node 2 has a power outage. Fig. 1(a) shows the case where nodes are not equipped with batteries and re-routing is not allowed. In this case, since node 2 does not have batteries for both switching and IP router, the two requests are rejected. Fig. 1(b) shows the case with battery and no re-routing, where request 2 is served with optical switching. Moreover, Fig. 1(c) shows how to further accommodate more requests with both battery and re-routing in the IP layer. In this case, request 2 is groomed to the wavelength for request 1 if the residual capacity of the wavelength is greater than the requested data rate of request 1.

3. Reassignment of Routing, Modulation Format and Wavelength Assignment w/o Service Degradation

The resource re-allocation problem for pre-planned power outage can be stated as follows: **Given** a network topology, a set of nodes affected by power outages, a set of traffic requests, and a reach table, **decide** the re-routing, modulation format, wavelength, grooming, and service degradation of requests, **constrained** to bypassing constraints of nodes with power outages (w/o batteries), reaches and data capacity of different modulation formats, the maximum number of wavelengths, the data rate of traffic requests. The **primary objective** is to minimize the rejection rate, with a **secondary objective** to minimize the degradation rate (percentage of degraded requests).

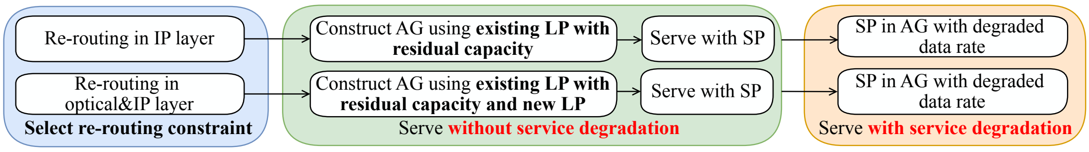

Fig. 2: Illustration of heuristic algorithm for resource re-allocation for pre-planned power outage.

We designed a scalable "battery-aware" auxiliary-graph-based heuristic algorithm extensible to all the compared approaches. For *NB-Fix* and *B-Fix*, we do not do any re-routing. The rejected requests in *B-Fix* are only the requests with the end nodes affected by power outages or nodes where requests are regenerated in the IP layer. Instead, in *NB-Fix*, once the path for a request traverses a node with power outages, the request is rejected since optical switching is also not allowed. The resource re-allocation of all the other approaches is shown in Fig. 2 with different re-routing constraints, namely, re-routing in the IP layer and re-routing in the optical&IP layer. The algorithm first serves requests without service degradation. Specifically, for the approaches allowing IP layer re-routing, we construct an auxiliary graph (AG) where an edge is created between two nodes if an existing light path (LP) has enough residual capacity to serve the request. Instead, for approaches allowing both IP and optical layer re-routing, edges are created using existing LP with residual capacity and new LP. Note that when nodes do not have batteries, LP traverses nodes with power outages can not be used. Instead, when nodes have batteries, LP can not be used only when one of the end nodes of LP are nodes with power outages. Then, requests are served if a shortest path (SP) can be found. After trying to serve requests without service degradation, if the re-allocation fails, the algorithm applies service degradation by reducing the requested data rate and re-runs the same procedures used for the case without service degradation.

4. Case Studies and Results

We compared the 6 resource re-allocation approaches on Japan topology [6] with 14 nodes and 22 links, each operating on a 6-THz C-band. We considered two different network scenarios, namely, a small-power-outage scenario where only one node has power outages (the cases without and with service degradation are named as *S-ND* and *S-D*, respectively), and a large-power-outage scenario where three nodes have power outages (the cases without and with service degradation are named as *L-ND* and *L-D*, respectively). The nodes with power outages are nodes in the center of the network to evaluate the capability of different approaches to mitigate significant disruptions.

We consider bidirectional traffic requests randomly generated between all node pairs, and the requested data rates are randomly generated among 100, 200, 300, and 400 Gbit/s. We increase the number of requests in the network until 1% of requests is rejected. The requested data rate can be reduced by up to 50% when service degradation is allowed. We evaluate the rejection rate and degradation rate with ZR/ZR+ [4] and long-haul transponders under different scenarios with all the proposed approaches. Results are averaged across 10 traffic matrices.

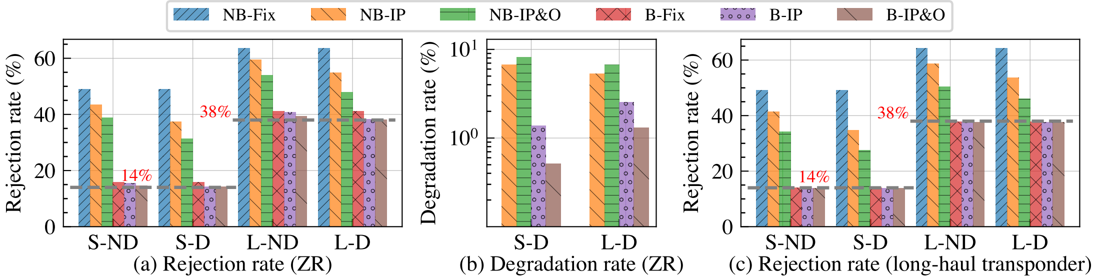

Fig. 3: Evaluation of rejection rate when end nodes are not nodes with power outages and degradation rate.

We first discuss the results obtained in the small-power-outage scenario without service degradation (*S-ND*). Note that requests with end nodes affected by power outages cannot be accommodated by any re-routing configurations due to the lack of power supply for IP routers. As shown in Fig. 3(a), for both *S-ND* and *S-D*, 14% of requests are always rejected since their end nodes are affected by power outages, as indicated by the grey dotted line in Fig. 3(a). As shown in Fig. 3(a), the rejection rate of *NB-IP* and *NB-IP&O* is about 5.6% and 10.1% lower with respect to *NB-Fix*. When nodes have batteries, the rejection rate decreases by up to 33.1%, as observed in the comparison between *NB-Fix* and *B-Fix*. Furthermore, the rejection rate for requests with end nodes unaffected by power outages decreases from 1.9% in *NB-Fix* to 1.5% and 0.7% in *NB-IP* and *NB-IP&O*, respectively. When introducing service degradation (*S-D*), the rejection rate of *NB-Fix* remains the same since no re-routing is performed. Instead, the rejection rate of *NB-IP* and *NB-IP&O* in *S-D* reduce by around 6% and 7%, respectively compared to that in *S-ND* due to degraded data rate. This reduction is obtained by paying off up to around 8% of degradation rate as shown in Fig. 3(b). Moreover, when nodes are equipped with batteries, the rejection rate is significantly reduced. For instance, rejection rate of *B-IP* reaches approximately 15.5%. This indicates that only 1.5% of requests with end nodes unaffected by power outages (note that 14% of requests rejected due to power outages in end nodes) are rejected, which is achieved with only around 1% of degradation rate as shown in Fig. 3(b). Note that the results reported so far are obtained assuming the transponder reaches compatible with ZR/ZR+ technology. We also repeated this analysis for long-haul transponders, the rejection rate and degradation rate show a similar trend as for ZR/ZR+. The difference is that as in Fig. 3(c), for long-haul transponders, with batteries and re-routing (i.e., *B-IP* and *B-IP&O*), less than 0.2% of requests where the end nodes remain unaffected by power outages are rejected thanks to the longer reach of long-haul transponders, paying off less than 0.3% of degradation rate (the degradation rate with long-haul transponders is not shown in Fig. 3 due to space limitation).

We now evaluate the large-power-outage scenario, where different approaches perform similarly to the case with the small-power-outage scenario. Note that the rejection rate due to end nodes with power outages increases from 14% to 38%. Different from the small-power-outage scenario, the absence of batteries results in more LPs affected by power outages, reducing the LPs available to serve degraded requests. Hence, the degradation rate of *NB-IP* and *NB-IP&O* reduces 1.4% in *L-D* compared to that in *S-D* as in Fig. 3(b). Instead, with batteries, LPs affected by power outages are reduced, and more requests need to be accommodated due to larger power outages, leading to increasing degradation rate of 1.2% and 0.8% in *B-IP* and *B-IP&O*, respectively, as in Fig. 3(b).

5. Conclusion

We investigated resource re-allocation in optical networks for pre-planned power outages, comparing six approaches, i.e., adopting IP layer and/or optical layer re-routing, and w/o batteries for bypassing. Results show that with IP layer and optical layer re-routing, the rejection rate can be decreased by up to 33%, paying off only around 1% of degradation rate. Moreover, we observed that with batteries, less than 1.4% of requests, involving end nodes unaffected by power outages, were rejected, showing that bypassing can significantly reduce service disruption.

Acknowledgements: This work was supported by the Italian Ministry of University and Research (MUR) and the European Union (EU) under the PON/REACT project.

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