LIGHTPATH ROUTING FOR DISASTER SURVIVABILITY IN OPTICAL NETWORKS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

School of Electrical Engineering
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DECEMBER 2019

To my beloved parents and siblings

ACKNOWLEDGEMENT

In the Name of Allah, Most Gracious, Most Merciful

All praises to Allah s.w.t, whom we worship and from Whom we seek help and guidance. Without His blessings, I would not have been able to successfully complete this research work. It is His blessing that he gave me strength and patience to keep on working towards my goal and finally achieve my objectives successfully.

After this, I would first like to acknowledge the support and guidance of my PhD supervisors Prof. Ir. Dr. Sevia Mahdaliza Idrus for her constant support during this study. Her counselling always reenergized me whenever I faced a difficult time during my research. I would also like to express my gratitude to my co-supervisor Dr. Muhammad Al Farabi Bin Muhammad Iqbal for sparing his valuable time to guide me on many technical aspects of my research work. Through the expert guidance of my supervisors, I have been able to overcome all the hurdles in the course of research and move steadily towards my research goals.

I am also indebted to my parent university; Bahauddin Zakariya University, Multan, Pakistan for providing me scholarship to pursuing PhD degree at Universiti Teknologi Malaysia.

Finally, I would like to acknowledge the contributions of my beloved parents and siblings who have always been praying for my success and supported me in my difficult times of research work.

ABSTRACT

Optical network serves as a core network with huge capacity and a multitude of high-speed data transmission. Natural disasters and physical attacks showed significant impacts on the optical networks such as damages the network nodes and optical links. This thesis aims to investigate and develop algorithms for the provisioning of risk-averse lightpaths to combat disastrous events or intentional attacks. Generally, network survivability is obtained by computing the backup path such that the nodes and the lightpaths are disjoint without considering how optical fiber cables are deployed within the physical plane. In contrast to many previous works, this research work has considered lightpaths, established over the fiber cables, as a series of line segments and not just a single line segment because real-world fiber paths are not always laid out as direct paths between cities or countries or even across the oceans. In this work, two novel disaster-resilient heuristic algorithms are proposed. First algorithm finds a pair of lightpaths with a maximum value of minimum spatial distance in order to enhance network survivability against spatial-based concurrent fiber failures, while second algorithm finds a pair of lightpaths in which length of primary lightpath is minimized but constrained by minimum spatial distance. Capacity exhaustion problem in post-disaster scenario is also addressed as a reactive compensation. In this regard, another novel congestion-aware lightpath routing algorithm is developed to tackle the provisioning and restoration of disrupted lightpaths in a post-disaster scenario. Selection of alternative lightpath is based on a criteria parameter for a lightpath to be least loaded and constrained by either the length or the spatial distance between primary and alternative lightpaths. The spatial distance between lightpaths enables to re-establish the disrupted connection request away from disaster proximity. Extensive simulations are performed to evaluate our proposed algorithms for several parameters like blocking probability, network resource utilization, connection success rate and minimum spatial distance, and compared with existing techniques proposed in the literature. Simulation results of proposed algorithms show an improvement through 50% reduced computation time by lowering blocking probabilities of lightpaths up to 10% and 3% to 21% enhanced capacity utilization. Moreover, 100% connection success rate is achieved for modest network load.

ABSTRAK

Rangkaian optik bertindak sebagai rangkaian teras dengan kapasiti yang besar dan pelbagai penghantaran data berkelajuan tinggi. Bencana alam dan serangan fizikal memberi kesan yang ketara pada rangkaian optik iaitu dengan merosakkan nod rangkaian dan pautan optik. Tesis ini bertujuan untuk menyiasat dan membangunkan algoritma untuk penyediaan jalur cahaya berisiko rendah dalam mengatasi kejadian bencana atau serangan yang disengajakan. Secara amnya, keselamatan rangkaian diperolehi dengan mengira laluan sandaran sehinggakan nod dan jalur cahaya terpisah tanpa mengambil kira bagaimana kabel fiber optik digunakan dalam satah fizikal. Berbeza dengan kerja sebelum ini, penyelidikan ini menganggap bahawa jalur cahaya, dihasilkan melalui kabel gentian yang dianggap sebagai satu siri daripada segmen garisan dan bukan hanya satu segmen garisan tunggal kerana laluan fiber dalam dunia sebenar adalah tidak sentiasa diletakkan sebagai satu laluan terus antara bandar atau negara mahupun merentasi lautan. Dalam kerja ini, dua algoritma heuristik berdaya tahan bencana yang baharu telah dicadangkan. Algoritma pertama menemukan sepasang jalur cahaya dengan nilai maksima bagi jarak ruang yang minima bertujuan meningkatkan rangkaian keselamatan terhadap kegagalan berasaskan ruang gentian serentak, manakala algoritma yang kedua menemukan sepasang jalur cahaya dengan panjang yang minima tetapi dihalang oleh jarak ruang yang minima. Masalah kekurangan keupayaan dalam situasi pasca bencana juga ditangani sebagai pampasan yang reaktif. Dalam hal ini, satu lagi algoritma jalur cahaya baharu yang mempunyai keupayaan mengesan kesesakan dibangunkan untuk mengatasi masalah pembekalan dan pemulihan jalur cahaya yang terjejas dalam senario pasca bencana. Pemilihan jalur cahaya secara alternatif adalah berdasarkan kepada parameter kriteria untuk jalur cahaya iaitu kurang beban muatan dan kekangan oleh panjang atau jarak ruang antara jalur cahaya utama dan alternatif. Jarak ruang antara satu jalur cahaya dengan jalur cahaya yang lain membolehkan pembentukan semula sambungan yang terganggu jauh dari kawasan bencana. Simulasi yang ekstensif dilakukan untuk menilai algoritma yang dicadangkan bagi beberapa parameter seperti menyekat kebarangkalian, penggunaan sumber rangkaian, kadar kejayaan sambungan dan jarak ruang yang minima dan dibandingkan dengan teknik-teknik sedia ada yang dicadangkan dalam literatur. Hasil simulasi algoritma yang dicadangkan menunjukkan penambahbaikan dengan mengurangkan masa pengiraan sebanyak 50% dengan mengurangkan kebarangkalian jalur cahaya disekat sehingga 10% dan 3% hingga 21% seterusnya meningkatkan kapasiti pengeluaran. Selain itu, kadar kejayaan sambungan mencapai 100% bagi rangkaian yang mempunyai beban sederhana.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

ASR	-	Availability Satisfaction Ratio
ATM	-	Asynchronous Transfer Mode
BTS	-	Base Transceiver Station
CASPaR	-	Congestion Avoidance Shortest Path Routing
COs	-	Central Offices
cTGGD	-	Compensated Total Geographical Graph Diversity
DLA	-	Distributed Lightpath Allocation
DLBSPP	-	Dynamic Load Balancing Shared Path Protection
DRG	-	Distinct Risk Groups
DWDM	-	Dense Wavelength Division Multiplexing
EMP	-	Electromagnetic Pulse
FTBCP	-	Fault Tolerance Method Based on Cheapest Paths
GeoDivRP	-	Geodiversed Routing Protocol
GIS	-	Geographic Information System
GMPLS	-	Generalized Multi-Protocol Label Switching
HCA	-	Hybrid Connection Algorithm
ICT	-	Information Communication Technology
ILP	-	Integer Linear Programming
IP Layer	-	Internet Protocol Layer
ISIS	-	Intermediate System to Intermediate System
kNN	-	k-nearest neighbour search algorithms
kD	-	k-dimensional tree (kD-tree)
LC-DAL	-	Least-Congested Distributed Lightpath Allocation
MILP	-	Mixed Integer Linear Programming
MPLS	-	Multi-Protocol Label Switching
MSD	-	Minimum Spatial Distance
MSCs	-	Mobile Switching Centers

OSPF	-	Open Shortest Path First
OXCs	-	Optical Cross-Connects
PCE	-	Path Computation Element
PDP	-	Packet Delivery Probability
PoP	-	Point of Presence
QoS	-	Quality of Service
QoT	-	Quality of Transmission
RECODIS	-	Resilient Communication services protecting end-user applications from Disaster-based failures
RWA	-	Routing and Wavelength Assignment
SDH	-	Synchronous Digital Hierarchy
SDON	-	Software-Defined Optical Networking
SFPP	-	Short Full Path Protection
SLA	-	Service Level Agreement
SONET	-	Synchronous Optical Network
SPPP	-	Shortest Path Pair Protection
STAR	-	Self-Tuned Adaptive Routing
WDM	-	Wavelength Division Multiplexing
WMD	-	Weapon of Mass Destruction
WRT	-	Wavelength Retuning

LIST OF SYMBOLS

δ - Exclusion distance

. - Separation Distance

K - Total No of Shortest Lightpath (K)

T - Distance (Threshold Value)

$\mathcal{G}$ - Graph / Network

N - Set of Nodes

L - Set of Links

P - Set of candidates shortest lightpaths

d_s - Spatial distance

$\boldsymbol{s}$ - Source Node

$\boldsymbol{d}$ - Destination Node

(s, d) - A connection request from source node s to target node d such that $\forall\ s, d \epsilon N$ and $s \neq d$

$l_{ij}^{(s,d)}$ - A subset of engaged links by the connection request (s, d)

$\omega_{ij}^{(s,d)}$ - A subset of lengths of engaged links $l_{ij}^{(s,d)}$

t_0 - The time instant at which no connection is served by the network i.e. network is in an idle state

t - The time instant at which any number of connections are served by the network

$\mathcal{S}_{ij}^{(s,d)}$ - A subset of the number of spectrum slots available over engaged links $l_{ij}^{(s,d)}$

$\mathcal{L}$ - Set of number of spectrum slots where $\mathcal{L} = \{\mathcal{S}_{ij} \mid \forall\ l_{ij} \in L\}$ also known as the indexed list of spectrum slots

P_k - The k^{th} lightpath where $P = \{P_1, P_2, P_3, \cdots, P_k\}$

(P_u, P_v) - A pair of primary and alternate ligthpath for a connection request

σ_k - The minimum number of slots over the constituting links of k^{th} lightpath enables to find least loaded lightpath

W_k - The length of k^{th} lightpath where $W = \{W_1, W_2, W_3, \cdots, W_k\}$

β - Lightpath blocking probability

$\rho(t)$ - Network spectrum utilization ratio at any time instant

K - Required number of alternate lightpaths which is taken as

1000

γ - The conditional parameter to controls the provisioning of optimal alternate lightpath.

X - Set of unestablished connection requests as $X = \{(s, d) | \ s \neq d\}$

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Background

Optical networks serve as backhaul to all modern telecommunication networks and offer reliable transmission of data in huge volumes over long distances. Optical networks are much faster with low attenuation compared to other technologies like copper-based digital subscriber line (DSL) and wireless networks. Figure 1.1 shows the map of undersea optical fiber cable network that traverses through the globe and comprises of 366 cables with 1.2 million kilometres length and 1,006 landing stations [1]. These cables provide nationwide connectivity between the dense wavelength division multiplexing (DWDM) gateway nodes over very long distances such as the Asia-America gateway (AAG) cable system is 20,000 kilometer long [2]. The shortest link is 131 kilometer long i.e. the CeltixConnect connecting UK and Ireland [3]. These optical links carry huge amount of traffic especially the newer cables (made of new fiber materials installed with newly developed amplifiers) can carry Tbps of data as compared to older cables. For instance a MAREA cable [4] can carry 160 Tbps. It is estimated that about 99% of the international internet traffic is carried by these cables [5] which includes voice and data. Due to enormous increase in internet traffic and mobile subscriptions, the International traffic carried by these under-sea optical cables is continuously increasing as shown in Figure 1.2. According to IEEE comprehensive report bandwidth demand is growing at a very fast pace compared to its delivering capacity [6], which will lead to further expansion of under-sea network.

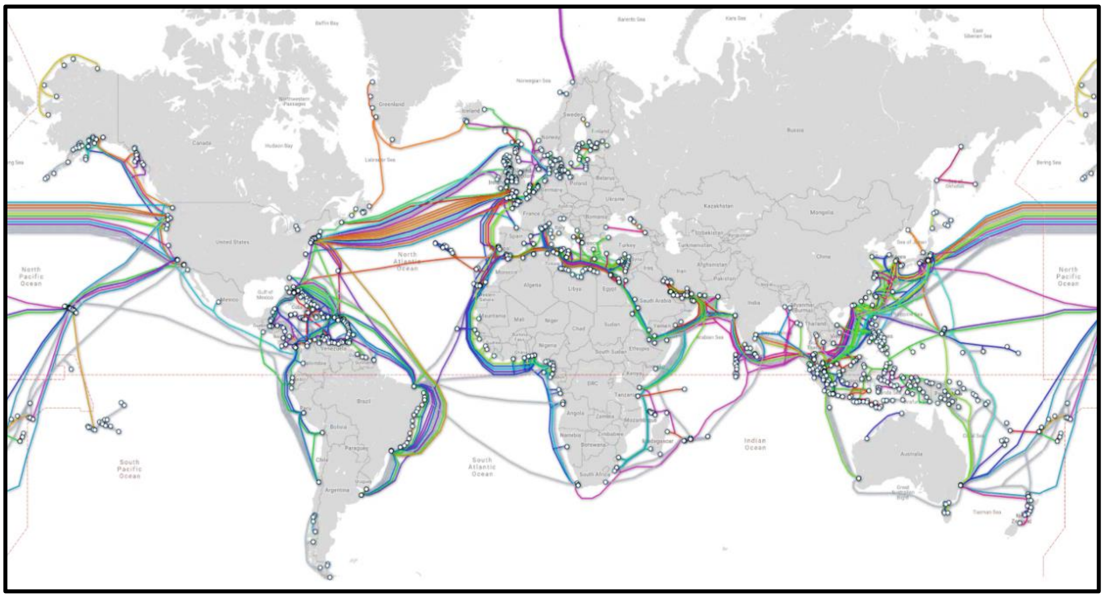

Figure 1.1 International Undersea Optical Fiber Map [1]

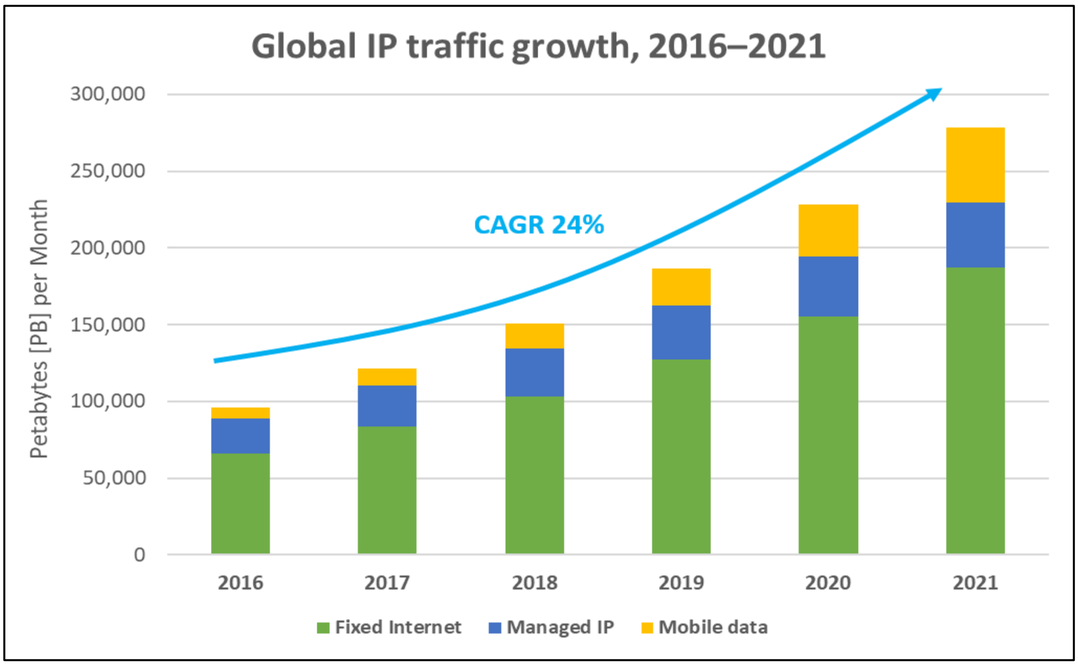

Figure 1.2 International Traffic Growth, Source: Cisco VNI, 2017

The main drivers of this rapid growth in worldwide connectivity and the proliferation of Internet-connected devices are the increasing trends of cloud computing and emerging social IT needs e.g. social media apps, video streaming, changing business conducts etc. This revolution has led to the immense growth of global IP traffic. Forecasted global IP traffic growth [7] from 2016 to 2021 is shown in Figure 1.2. It is estimated that annual global IP traffic will be 3.3 ZB at a Compound Annual Growth Rate (CAGR) of 24% from 2016 to 2021 which is nearly threefold in five years. Projected values of the world population that will be using internet and monthly internet traffic data per user will be 58% and 61 GB respectively by 2021. It is anticipated that eighty percent of the internet traffic will be video streaming with average broadband speed of 53 Mbps.

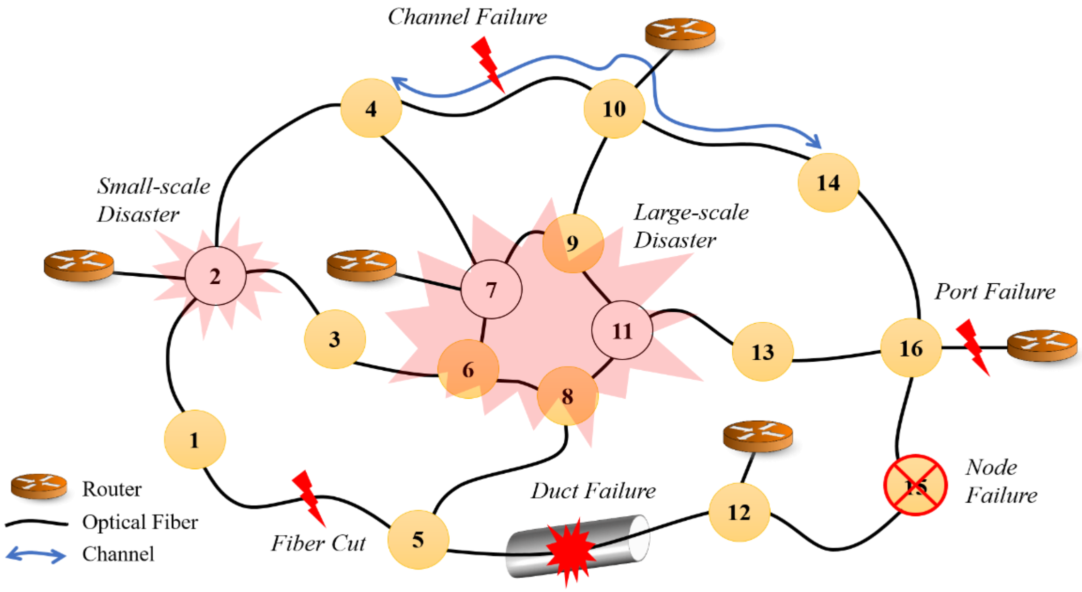

Figure 1.3 Types of Network Failures

The wide span and huge traffic carrying capacity of the optical networks significantly increases the operational importance of the optical links. The cause of the failure of an optical link is not only limited to a physical cable cut or damage. An optical link comprises of many interconnected hardware components such as routers and switches. Any failure of a hardware component may also cause a network failure and may lead to severe service outages. The time period for which a network fails to provide its services, is known as network downtime. Network failure could be complete or partial failure of any number of network components. When a network attempts to deliver uninterrupted services in case of a network failure, it is called network survivability. Network survivability requires physical redundancy and restoration protocols. The degree of survivability can be defined from the capability of a network to be resilient against single or multiple failures. Figure 1.3 shows several types of network failures usually occur within the network.

Statistics implicating cable damage for smaller outages that occur nationwide are not exactly available. However, hundreds of cables cut related network outage notifications will be returned if a phrase "cable cut" is searched through any internet search engine. Network outages due to fiber cut reported to Federal Communications Commission (FCC) from 1993 to 2001 were estimated to be 386 or 25% of all network outages. The outage for 30 minutes or more may affect over 30,000 customers [8]. Optical fiber cables, where each cable may carry hundreds of fiber strands made of doped glass, are enfolded with multiple layers of insulations. Fiber cables are laid down in bundles swathed by a duct between nodes (i.e. network equipment or part of equipment which serve different functions such as routing, switching and traffic grooming). Fiber cut occurs when a duct is cut due to fishing, anchoring, mudslide, earthquakes etc. All the lightpaths that traverse a failed fiber will be disrupted. A fiber cut or a duct cut can lead to tremendous data loss.

To meet the challenges posed by the ever-increasing demands for bandwidth, the accessible bandwidth on a fiber is divided into multiple channels of non-overlapping wavelengths. Each channel may have a capacity of 100 Gigabits per second or higher and collectively turns in Terabits per second data rate over these channels [9]. Channel failures are caused by the failure of transmitting/receiving devices operating on the channel in dense wavelength division multiplexing (DWDM) networks. Channel failure can be handled either by prompt switching to another idle channel or by treating it as a link failure in absence of idle channel [10].

A catastrophic event such as fire or flood can fail the central offices where Optical Cross-Connects (OXCs) are located. This can be referred to as node failure. Node failures are rare as compared to other types of failures described above but impose devastating impacts on the network. Node failures can also be referred to as router’s experience when it suddenly losses its connectivity while other connecting devices are working properly. This could be the result of bad port or port failure. The remedy of this problem is to try another port or replace the router.

Disaster-based failures may devastatingly impact the physical topology of an optical network by making its services unavailable [11]. Disasters can be natural (adverse events resulting from natural processes of the earth) or intentional (man-made or technological). Examples of natural disasters may include hurricanes & tropical storms, tornadoes, earthquakes, landslides, avalanches, tsunamis, floods, wildfires, animal bites etc., and power service disruption & blackouts, human negligence or errors, anchor drag/drops, electromagnetic pulse (EMP) attacks, nuclear explosion, sabotage, anti-corporate attacks, cyber-attacks, terrorist attacks or vandalism may be known as man-made or technological disasters.

Figure 1.4 shows the statistics for the year of 2016 of top ten countries with natural disasters categorized by type [12]. Total economic losses which also include network outage from natural and man-made disasters in 2017 are estimated to be a total of 306 billion USD which exceeds 63% of loss value of 2016 and far higher than average over the last 10 years [13]. Some disasters may be forecasted before their occurrence by assessing their atmospheric and environmental characteristics using modern scientific techniques, known as predictable disasters. Earthquakes and power outages due to technical faults are examples of unpredictable disasters. A large-scale disaster could affect multiple nodes and links, which do not only affect the optical layer but could also cause failure in the upper layers. Disaster-based failures can be correlated or cascading and can trigger the failures horizontally or vertically within the network [11]. For example, optical layer in WDM networks provides services to the upper layers (e.g., ATM, SONET-SDH, MPLS, IP), and lack restoration of optical layer may vertically disrupt the services of the upper layers. Today’s intelligent networks are managed through software designs. The complexity level of these software designs is increasing over the time. Software bugs could lead to unstable network states. For example, in 2012, a routine update of load balancing software on a Gmail server caused a partial loss of 40% of services for 18 minutes [14] because this update contained a faulty logic. A single node was fully updated to recover this cascading error instead of partially updating all failed nodes at a time.

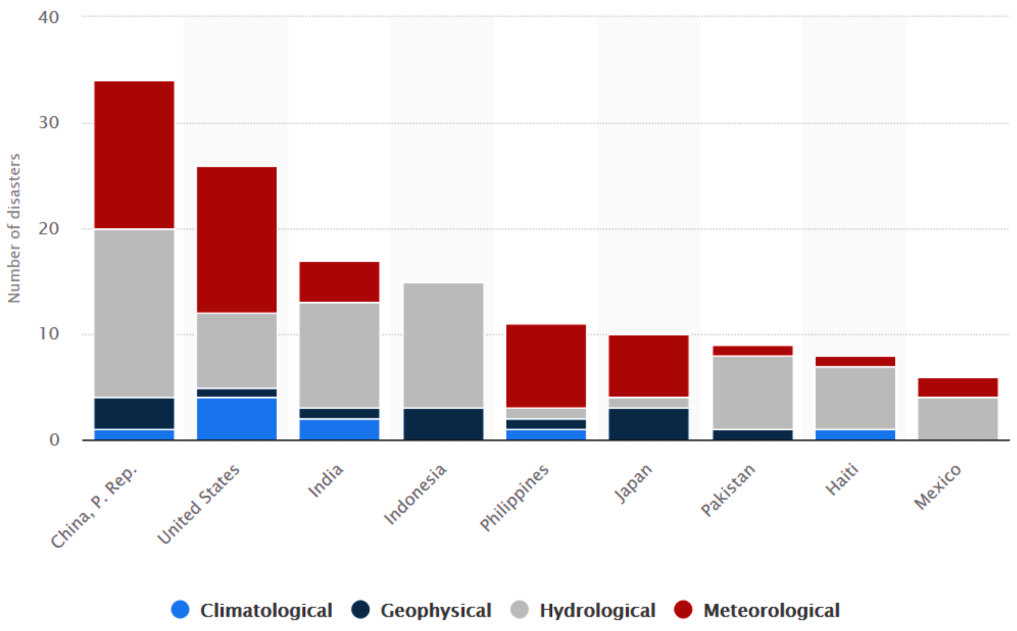

Figure 1.4 Ten Countries with Natural Disaster by Type in 2016 [12]

Provision of network services are supposed to be continuous even during a crisis, which can be achieved by making nodes and interconnecting survivable links. Network components (nodes and links) eventually malfunctioned and cease to function, particularly in disaster occurrence regardless of the preventative protection measures taken. Natural disasters and intentional attacks show that optical fibers are vulnerable to failures and affect many applications and services supported by the optical layer. Hence, it is essential to recognize the exposure of fiber networks to disasters so that survivable light path routing is made possible.

1.2 Motivation

Modern telecommunication networks are running on top of optical network to provide high-speed network services to their consumers. Government, academic and research institutions, cellular network operators, Telecom companies, multinational corporations and service providers all rely on optical networks to send data around the world. Cable faults are very common, 100 per year on average as shown in Figure 1.5, but rarely noticed because most of the companies reserve backup cables so that network runs without interruption even if one cable is broken or cut [15]. Natural disasters are critical threats to submarine cables. For example, Taiwan earthquake of magnitude-7.1 in 2006 catastrophically disrupted the internet services between China, South East Asia and Hong Kong by damaging eight submarine cables [16]. A more recent incident of an earthquake of magnitude 7.1 struck central Mexico on 19 September 2017, causing 355 fatalities, 6100 injuries and collapsed nearly 44000 buildings. It also severely damaged the underground optical fiber and telecom infrastructure [17]. Network damages caused by Intentional attacks could be physical and effect the neighboring components as well. Motivations of intentional attacks cannot be discerned easily. Other than that, an occurrence at the bank of Egypt in March 2013, three men went scuba diving down to cut off the undersea optical fiber [18]. This incident slowed down 60% of internet speed. Many specialists feel that deliberate damage of submarine cables is unrealistic or impossible. However, undersea-cable bottlenecks have the potential for serious interruptions is causing network providers to search for the alternative paths to connect the continents. Similarly, in 2015, an attacker tries to slice a series of cables which carry billions of bits of data [19]. A brief summary of network damages due to disasters and intentional attacks are given Table 1.1.

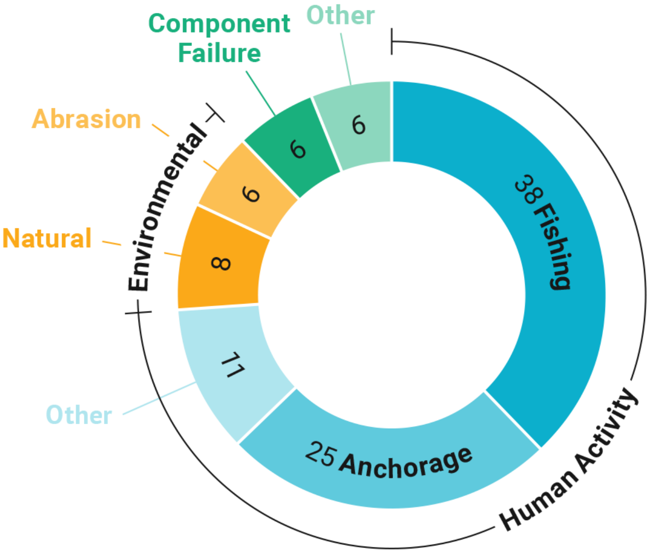

Figure 1.5 Cable Faults [15]

Table 1.1 Network Damages Caused by Recent Disasters

Year	Nature of Disaster	Damage & Network Availability	Reference
2017	Mexico Earthquake of magnitude 7.1	Caused 355 fatalities, 6100 injuries and collapsed nearly 44000 buildings. It also severely damaged the underground optical fiber and telecom infrastructure.	[17]
2015	Earthquake-affected the Rural Information and Communication Technology (ICT) Infrastructure and Services in Nepal	Collapsing the houses, schools, ICT access centres, BTS, transmission towers, fiber backhaul, microwave links were damaged.	[20, 21]
2013	Cutting off fiber cables at the bank of Egypt	Slowed down 60% of internet speed	[18]
2011	Mainshock and aftershocks of Great East Japan Earthquake & Tsunami	1,500 telecom buildings by the main shock & 700 telecom buildings experienced power outages	[22]
2008	Mediterranean Sea Fiber Cuts by Ship Anchors	Loss of 70% of Egypt's connection to the outside world and 50% to 60% of India's network outbound connectivity on the westbound route.	[23]
2008	Sichuan Province Earthquake	Around 30,000 km of optical fiber cable & 4,000 telecom offices were damaged.	[24]
2006	Earthquake in Taiwan cut fibers connecting Asia and North America.	Reduced Hong Kong and China internet capacity by 100% to 74% respectively.	[16]
2005	Hurricane Katrina struck United States Gulf Coast	Power outage and floods reduced telecom network availability from 99% to 85%.	[25]

Overloading of network resources is known as network congestion. It means available capacity of the network cannot fulfil the total demand or connection requests. Congestion occurs due to several reasons like low bandwidth, multicasting, bad configuration, too many hosts in the broadcast domain or broadcast storm (can be a busy day for e-commerce or Black Friday sales) etc. Generally, congestion can be avoided by network segmentation, backpressure routing and prioritizing the network traffic. Congestion control techniques reduce or ease capacity overloading. The critical issue which is also in focus is the traffic congestion due to re-routing after a disaster. Generally, optical networks have some unused capacity to exploit traffic fluctuations and capacity exhaustion problem [26]. The main reason behind the capacity exhaustion problem is post-disaster traffic floods. Most of the people use applications and services to investigate what is happening during disasters, as indicated in [27], which shows that two out of every three people use social media during a disaster and post-disaster. During a large-scale disaster, user behaviour is critically observed in [28] and authors showed that 76% of users post information on social media and 95% of users make phone calls. Furthermore, warnings and precautions are broadcasted through social media, government websites and news agencies which are also visited by the people. Sudden rise of real-time video traffic (TV breaking news) and user generated videos can also be observed [29]. Optical network serves as middleware between the access and the data centres and is responsible for delivering the data between them. In order to follow the Service Level Agreement (SLA), it is the core responsibility of these networks to provide continuous and uninterrupted services even in case of crisis. Since capacity of the network cannot be upgraded or enhanced by instantly installing new fibers, new techniques are required to handle such situations.

1.3 Problem Statement

Optical networks provide higher grade of service in terms of speed and data volumes in all telecommunication networks (wired or wireless) as the backbone network. The network survivability is mostly relying on the survivability of the nodes and links. Any failure of links and/or nodes within a network may cause connection failures, data losses, service outage, service downtime, and revenue losses. Even a single fiber failure can be disastrous to the network operation [30]. It has been assessed in [31] that losses due to service downtime can range between 25–150 thousand dollars per hour. The work had served as a guidance for network operators to identify network vulnerability (possibility of disruption) to disasters and design appropriate countermeasures. The ever-growing demand for bandwidth and high transmission speeds for mission-critical applications, as expected to realize in 5G [32, 33], can only be fulfilled through backhaul optical networks. Therefore, it is essential to investigate such techniques which make networks more reliable and as robust as possible in case of a disaster occurrence. From the discussion above, the following gaps are identified and opening new directions of research.

i. The occurrence of large-scale disasters may simultaneously damage multiple disjoint but spatially close lightpaths between two network nodes which leads to communication failure.
ii. After the event of a disaster, re-routing in the network may cause traffic congestion due to the inefficient utilization of network resources by the routing scheme, and the unavailability of multiple network components.

Hence, disaster-aware network resilience is a critical issue to future society. The focus of the research is to propose techniques and algorithms for network connections with most risk-averse reliable paths separated by maximum spatial distance and tackling the resulting network congestion. This research emphasizes the network survivability by handling single as well as multiple nodes and link failures using topologies of real-life networks and proposes a preventive as well as a reactive approach to enhance the network resilience against disasters.

1.4 Scope of Work

Disasters are inevitable and show effects on physical layout of optical fiber networks. For end-to-end communication, digital data is encoded into light pulses carried by optical fibers moving along specified nodes and links until reaching the destination. Formerly specified nodes and links carrying the light pulses was able to establish connections requests known as lightpaths. In case of a disaster, some nodes or links or both may be damaged and stop functioning which can be referred to as network outage. Maintaining connectivity and services provided by the network in the event of disaster is more important and critical to achieve network survivability. Techniques to assess and survive from disaster-based failures are categorized in Figure 1.6.

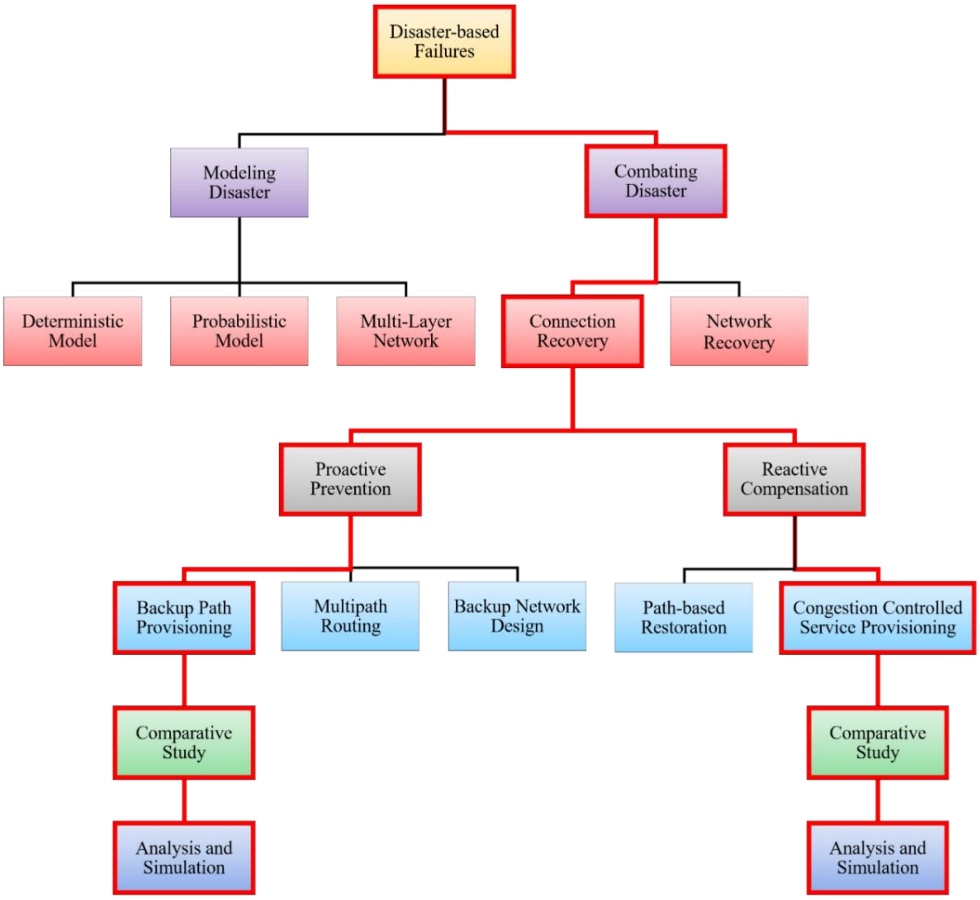

Figure 1.6 Modelling & Combating Disaster Survivability

Modelling disaster refers to estimating losses caused by a disaster incorporating disaster characteristics into computational risk model. It is implicitly account for the uncertainty associated with various model components and depending upon deterministic and probabilistic risk estimates. Disaster-based failures are considered as multiple failures which might be correlated or uncorrelated. Disaster failures could cause multi-domain multi-layer failures that span several network domains. For such failures, multi-layer modelling is used to assess the impacts of disasters. A disaster covering a large geographic area could interrupt the functioning of multiple nodes and links, which could result in multi-layer failures. To combat this type of failures, most existing works of disaster survivability focused on intelligent network provisioning to restore services with higher priority (i.e. connection recovery) and network recovery after failures. Generally, approaches for connection recovery falls into proactive prevention and reaction compensation considering the routing and capacity assignments. Protection of connections can be done either by proactively provisioning backups or by re-provisioning connections reactively after failure (path-based restoration).

The focus of this work is the survivable multipath routing because protecting a connection over multiple disjoint paths has the advantage of better fault tolerance. It is also emphasized on congestion control service provisioning (a basic reactive procedure) in which capacity is re-arranged and re-provisioned for existing connections during network operation. As this method adapts to dynamic network events, it can handle concurrent, cascading failures. Through reactive compensation, limited network resources can re-allocate (re-provision) multiple times for most effective usage.

1.5 Research Objectives

After an event of disaster, when some network components are failed, blocked or interrupted, traffic is re-routed on disjoint lightpaths to provide continuous services. However, provisioned disjoint lightpath for re-routing of such traffic may exist within the disaster proximity. Furthermore, re-routing may overload the capacity resource on the provisioned disjoint lightpath. Therefore, this work focusses on (1) developing routing algorithms for network survivability and (2) proposing the techniques to control the network congestion after re-routing in the event of a disaster. From above, clear objectives of this research study are as follows:

i. To develop a heuristic algorithm for provisioning the disjoint lightpaths between any two network nodes with maximized spatial distance between them, so that network survivability can be achieved.
ii. To propose a heuristic algorithm for re-provisioning the disrupted lightpaths after the event of disaster with minimal network congestion.
iii. To verify the proposed algorithms using real life network topologies through simulation.

The results of this research could serve as a guide to the network administrators to identify network vulnerability (possibility of disruption) of optical backbone networks to disasters and design appropriate countermeasures. Since proposed techniques include the geographical information of nodes and links, which make these algorithms practically adaptable by the network operators with no conversion or transformation.

1.6 Thesis Organization

Due to the importance of optical networks, this thesis mainly focusses on two research problems regarding disaster-aware routing techniques with controlled congestion. This chapter delivers the necessary background on what optical networks are and how disaster impacts them the chapter continues with the motivation of the research work, while providing corresponding problem statement, scope and research objectives. The chapter ends with thesis organization.

Chapter 2 builds a foundation for readers to understand routing, types of routing and elastic optical networking their role in disaster survivability. Chapter also provides a glimpse into the related work of disaster-aware routing with several perspectives. Separate reviews of related studies on disaster-aware lightpath routing and congestion-aware lightpath routing are presented. Finally, close comparison of the related work is given to identify the research gaps.

In Chapter 3, the research methodology is presented. First, the overall methodology to achieve the research objectives is described. Then the methodology and simulation setups to achieve the specific objective are explained in detail.

Chapter 4 starts with the introduction of spatially-close fibers and the scenarios in which optical fibers may be specially-close. As lightpaths are established over these fiber cables which redeem to spatially-disjoint lightpath routing for network survivability described in problem formulation Section. Then two polynomial-time algorithms are proposed as solution to this problem. At the end of the Chapter, simulation of proposed algorithms and illustrative results are discussed with the comparison of existing technique.

Chapter 5 starts with the discussion of capacity constraint for optical network which is huge but finite and may fluctuate drastically during a disastrous event. Then concept of least congested lightpath routing is addressed to mitigate the problem of network congestion in post-disaster scenarios. A capacity-constrained algorithm is proposed to provision optimal lightpaths for post-disaster routing. Illustrative simulation results describe the working of proposed technique with benchmarked technique.

Finally, in Chapter 6, concluding remarks and recommendations for future prospects of this work are given and the publications made during this research work are listed.

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LIST OF PUBLICATIONS

1. **M. Waqar Ashraf**, Sevia M. Idrus, Farabi Iqbal, and Rizwan Aslam Butt. "On spatially disjoint lightpaths in optical networks." *Photonic Network Communications* (2018): 1-15. (**Impact Factor = 1.2**)
2. **M. Waqar Ashraf,** Sevia M. Idrus, Farabi Iqbal, Rizwan Butt, and M. Faheem. "Disaster-Resilient Optical Network Survivability: A Comprehensive Survey." In *Photonics*, vol. 5, no. 4, p. 35. Multidisciplinary Digital Publishing Institute, 2018. (**ISI Indexed**)
3. **M. Waqar Ashraf,** Sevia M. Idrus, R. Aslam, and Farabi Iqbal. "Capacity-bounded Lightpath Routing in WDM Optical Networks." *Optical fiber Technology*, 2019. (**Impact Factor = 1.35**)
4. **M. Waqar Ashraf,** Sevia M. Idrus, and Farabi Iqbal. "Maximally Spatial-Disjoint Lightpaths in Optical Networks." *Indonesian Journal of Electrical Engineering and Computer Science* 10, no. 2 (2018): 733-740. (**Scopus**)
5. **M. Waqar Ashraf,** Sevia M. Idrus, Farabi Iqbal, Rizwan Butt. "Post-Disaster Least Loaded Lightpath Routing in Elastic Optical Networks." *International Journal of Communication Systems*, 2019. (**Impact Factor = 1.71**)