SAKARYA UNIVERSITY
INSTITUTE OF SCIENCE AND TECHNOLOGY

SURVIVABLE AND DISASTER-RESILIENT SUBMARINE OPTICAL-FIBER CABLE DEPLOYMENT

M.Sc. THESIS

Dawson Ladislaus MSONGALELI

Department	**:**	**COMPUTER AND INFORMATION ENGINEERING**
Field of Science	**:**	**COMPUTER AND INFORMATION ENGINEERING**
Supervisor	**:**	**Assist. Prof. Dr. Ferhat DIKBIYIK**

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This thesis has been accepted unanimously / with majority of votes by the examination committee on 05/06/2015

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Head of Jury	Jury Member	Jury Member

DECLARATION

I declare that all the data in this thesis was obtained by myself in academic rules, all visual and written information and results were presented in accordance with academic and ethical rules, there is no distortion in the presented data, in case of utilizing other people's works they were referred properly to scientific norms, the data presented in this thesis has not been used in any other thesis in this University or in any other University.

Dawson Ladislaus Msongaleli

05.06.2015

PREFACE

I would like to express my sincere appreciation to my Supervisor Assist. Prof. Dr. Ferhat Dikbiyik, for his benevolent support during my studies. His is a good listener, with huge patient and sanity judgement when discussing research problems. He was full committed and he devoted much of his time to this research. Without him I could hardly make it.

Prof. Moshe Zukerman of City University of Honk Kong is another significant person in my research career. Thanks for accepting me to be part of the “Cost Effective and Survivable Wide-area Topology of Telecommunication Cabling” project. Thanks to this particular experience I could learn from the wealth of his experience in conducting research.

I would like to extend my appreciation to Prof. Biswanath Mukherjee of The University of California Davis, USA. He provided invaluable contributions as well as necessary guideline and comments whenever needed.

Moreover, I am immensely grateful to the government of The Republic of Turkey for giving me an opportunity to study in Turkey and support my study. Studying abroad has allowed me to grow in many more ways, learning new cultures, and broaden my horizon.

Last but not least, I would like acknowledge my parents Ladislaus Msongaleli and Anna William who raised me as a free spirit and encouraged me to learn. I also appreciate my cousin Deonatus Fortunatus, my sister Happiness Ladislaus, my love Jacqueline Rogath and other members of family as well as my relatives. Their spiritual guideline and moral support to me during this research is indispensable.

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LIST OF SYMBOLS AND ABBREVIATIONS

BU	: Branching Unit
CPU	: Central Processing Unit
ECC	: Expected Cruising Cost
ECL	: Expected Capacity Loss
ERC	: Expected Repair Cost
FTTx	: Fiber to the x
GB	: Gigabyte
GHZ	: Giga Hertz
ILP	: Integer Linear Programming
NME	: Network Management Equipment
PFE	: Power Feeding Equipment
RAM	: Random Access Memory
SLTE	: Submarine Line Terminal Equipment
SD	: Source Destination
SLA	: Service Level Agreement
Tbps	: Terabytes per second
WDM	: Wavelength Division Multiplexing

LIST OF FIGURES

SUMMARY

Keywords: Submarine Optical-Fiber Cable, Natural Disasters, Disaster-Resiliency, Network-Design Optimization.

With the existing profoundly social and economic reliance on the Internet and the significant reparation cost associated with service interruption, network survivability is an important element in telecommunication network design nowadays. Moreover, the fact that submarine optical-fiber cables are susceptible to man-made or natural disasters such as earthquakes is well recognized.

A disaster-resilient submarine cable deployment can save cost incurred by network operators such as the capacity-loss cost, the cruising cost, and the repair cost of the damaged cables, in order to restore network service when cables break due to a disaster. In this study, we investigate disaster-aware submarine fiber-optic cable deployment problem. While selecting a route/path for cables, our approach aims to minimize the total expected cost, considering that submarine optical-fiber cables may break because of natural disasters, subject to deployment budget and other constraints. In our approach, we assume disaster-unrelated failures are handled by providing a backup cable along with primary cable.

In the simple case, we consider a scenario with two nodes located on two different lands separated by a water body (sea/ocean). We then consider an elliptic cable shape to formulate the problem, which can be extended to other cable shapes, subject to avoiding deploying cable in disaster zones. Eventually, we provide an Integer Linear Programming formulation for the problem supported with illustrative numerical examples that show the potential benefit of our approach.

Furthermore, in order to make the problem more practical, we consider a mesh topology network with multiple nodes located on different sea/ocean, submarine optical- fiber cables of irregular shape, and the topography of undersea environment. Eventually, we provide an Integer Linear Programming to address the problem, together with illustrative numerical examples. Finally, we validate our approach by conducting a case study wherein we consider a practical submarine optical-fiber cable system susceptible to natural disasters. In this case, we compare our approach against the existing cable system in terms of deployment cost and reduction in expected cost. In either case results show that our approach can reduce expected cost from 90% to 100% at a slight increase of 2% to 11% in deployment cost of disaster-unaware approach.

KALIMLI VE FELAKETE DAYANIKLI DENİZALTI OPTİK FİBER KABLO YERLEŞTİRİLMESİ

ÖZET

Anahtar kelimeler: Denizaltı Optik Fiber Kablo, Doğal Felaketler, Felaket Dayanıklılığı, Bilgisayar Ağı Tasarım Optimizasyonu.

1988 den beri Britanya, Amerika Birleşik Devletleri ve Fransa' ya bağlı ilk okyanus aşırı fiber optik kablo yerleştirildiği zaman Dünya çok büyük bir iletişim devrimi yaşamıştır. Bu teknolojinin itme ve talebin çekme gücünün bir sonucudur. Bugünlerde ağ bağlantısı çoğunlukla denizaltı fiber optik ağa bağlıdır.

Akıllı telefonlar ve datacenterlar gibi yeni cihazlar ve uygulamaların keşfedilmesinden dolayı son zamanlarda dünya, bandgenişliği talebinde etkili bir artış yaşamıştır. Cisco ya göre 2003'teki internet trafiğinin miktarı 667 exabayta ulaştı. İlginç bir şekilde, IDC/EMC 2015' te insanoğlunun 7910 exabayt internet trafiği yaratacağını tahmin ediyor.

Bu artış ağ operatörlerinin sürekli ve zamanında servis kalitesini sağlayarak pazar talebini tatmin etmek zorunda olduğu yükü beraberinde getirecektir. Bu bağlamda ağ altyapısını değiştirmek ya da geliştirmek büyüyen bir endişedir. Fiber optik ağ bugünlerde artan bandgenişliği talebi için saniyede terabayt veriyi iletebilen umut vadeden bir teknolojidir. Büyük bandgenişliği, düşük sinyal zayıflaması (0.2 dB/km), düşük güç ihtiyacı, elektromanyetik karışımlara karşı korunması gibi sebeplerden ötürü diğer ağ teknolojilerini geçerek ilerlemiştir.

Doğal afetler meydana gelmiş ve denizaltı fiber optik kablolarına çok fazla zarar vermiş durumdadır. Doğal afetler tarafından meydana gelen denizaltı fiber optik kablolarındaki kırılmalar önemli bir ekonomik kayıp meydana getirmiştir. (Swiss Federal institute of technology ETH Zurich) İsviçre Federal Teknoloji kurumu tarafından 2015'te yapılan bir araştırmaya göre İsviçrenin tümünde bir internet kesintisi meydana gelirse ülkenin Gayrisafi Yurt İçi Hasılasında (GDP) %1.2 nin üzerinde maddi kayıp yaşayacaktır.

İnternete olan mevcut sosyal ve ekonomik bağlılık ve servis kesintileri nedeni ile oluşan önemli miktardaki tamir masrafları ile ağ kalımlılığı günümüzde telekomünikasyon ağ dizaynının önemli bir parçası olmuştur. Ayrıca, denizaltı fiber

optik kabloların depremler gibi doğal afetlere veya insan-yapımı afetlere karşı zayıf olduğu da herkesçe kabul edilmiş bir gerçektir.

Bugünlerde iletişim sistemlerinin günlük yaşamımızdaki vazgeçilmez rolü nedeniyle ağ tasarımı ilk aşamalarda en kötü senaryoyu düşünmelidir. Öyle ki ağ arızaları kısa zamanda ve ağ operatörlerine ve müşterilerine büyük ekonomik kayıp yaşatmadan kolayca azaltılabilir. Düğüm ve bağlantılar gibi ağ donanımdaki arızalar doğal afetler, kötü amaçlı saldırılar ve insanların faaliyetlerinden meydana gelir.

Afete dayanıklı bir denizaltı kablo yerleştirilmesi, bir ya da daha fazla kablo afet nedeni ile koptuğunda ağ servislerini yeniden eski haline getirmek için ağ operatörünün maliyetlerini (yolculuk maliyeti, kapasite kayıp maliyeti ve hasar gören kablonun tamir maliyeti) azaltabilir.

Bu çalışmada afet-farkındalığı denizaltı fiber optik kabloları yerleştirme problemini araştırdık. Kablolar için bir yol/rota seçerken yaklaşımımız toplam beklenen kayıp maliyetini, denizaltı fiber kabloların afetler nedeni ile zarar görebileceğini de düşünerek, bütçe ve diğer kısıtlamalar altında minimize etmeyi hedefledik. Yaklaşımımızda afetle ilişkisiz arızaların ana kablonun yanında bir de yedek kablo sağlanarak üstesinden gelindiğini varsaydık.

Önce basitçe bir su kütlesi (deniz/okyanus) tarafından ayrılmış iki kara parçası üzerine yerleştirilmiş iki düğümün olduğu bir senaryoyu düşündük. Daha sonra problemi formüle edebilmek için afet bölgelerinden sakınacak şekilde eliptik kablo şeklini dikkate aldık. En nihayetinde problem için, bu durumda yaklaşımımızın potansiyel faydalarını gösteren sayısal örneklerle desteklediğimiz bir Tam sayılı Lineer Programlama formülasyonu ürettik.

Bu bilgiyi kullanarak, doğal afetten dolayı kablo kırılırsa ağ operatörü tarafından karşılanması beklenilen masrafın sayısal değerini elde ettik. Beklenen masraf beklenilen onarma maliyeti, beklenilen yolculuk maliyeti, ve beklenilen kapasite kayıp maliyeti toplamıdır.

Ağ operatörleri tarafından karşılanacak beklenilen masrafı azaltmak için aşağıdaki metriklere bağlı aday yollardan seçilen yollarda kalımlı ve felaket bilinçli denizaltı fiber optik kablo yerleştirme yaklaşımını araştırdık. Bu metrikler yerleştirme bütçe kısıtı, yol benzersizlik kısıtı, düzenli koruma kısıtı, eliptik şekil kısıtı, ve doğrusallaştırma kısıtıdır.

Kalımlı ve felaket bilinçli denizaltı fiber optik ağ sorununu irdelemek için Tam sayılı Lineer Programlama (ILP) formülasyonunu geliştirdik. Bu doğal afetlerin fiziksel konumu, doğal afetlerin yarıçaplarını, denizaltı fiber optik kabloların fiziksel konumunu, kabloların şeklini ve doğal afetlerin merkez üssünden uzaklığını hesaba katar.

Bu durumda amaç doğal afetler tarafından meydana gelen zarardan dolayı onarma faaliyetleri için denizaltı fiber optik kablo sahipleri tarafından karşılanacak maliyeti minimize etmektir. Bu maliyet beklenilen onarılma maliyeti, beklenilen yolculuk maliyeti ve beklenilen kapasite kaybı maliyetinin toplamıdır. Kısıtlar aşağıdaki gibidir.

Yerleştirme maliyeti beklenilen maliyete ters orantılıdır. Bu çalışmada beklenilen maliyeti azaltırken yerleştirme maliyetinin bütçe planını aşmamasını sağladık.

Bu kısıtlar her bir ana ve yedek kablo için benzersiz yol olmasını sağlar. Aynı yolun hem ana hem de yedek kablo için seçilmesi ihtimaline karşı ana ve yedek kabloların aynı alana yerleştirilmemesini sağlar.

Ana ve yedek kabloyu aynı çevreye yerleştirmek ardışık kablo arızalarına neden olur. Bu durumdan kaçınmak için ana ve yedek kablolar ardışık kablo arızalarından kaçınacak en az uzaklık kadar birbirinden ayrılmalıdır.

Elips kablo şekli varsaydığımız için yedek eksen değeri sıfırdan büyük olmalıdır. Öyle ki asal eksen aday yollar arasında olmayacaktır.

Açıklayıcı sayısal örnekler ile desteklenen bu sorunu irdelemek için tam sayılı lineer programlama formülasyonunu geliştirdik. Buna göre, yaklaşımımızın sonuçlarından yerleştirme maliyeti masrafında beklenen maliyeti önemli derecede azalttığını görebiliyoruz.

Simülasyonumuzu intel i3 2.4 GHZ CPU, 4 GB DDR3 RAM ve 64 bit Microsoft Windows 8.1 işletim sistemli bilgisayar ile 50 defa çalıştırdık. Yalnızca düzenli arızaları dikkate alan felaket bilinçli olmayan yaklaşımla yaklaşımımızı karşılaştırdık. Felaket bilinçsiz yaklaşımla karşılaştırıldığında beklenilen maliyetteki azalma ve yerleştirme maliyetindeki artış yönünden sonuçları bildirdik.

Bu durumda sayısal sonuçlar yerleştirme maliyetindeki artışın masrafındaki beklenilen maliyeti önemli biçimde azalttığını ortaya çıkartmıştır. Dahası yaklaşımımız iki düğüm arasındaki ayrılmanın uzaklığı çok geniş olduğu zaman umut vadeden sonuçlar ortaya çıkarır.

Deniz yatağının engebesi, denizaltı vadisi, ve deniz derinliği gibi (i)coğrafi kısıtlar doğrusal, halka ve mesh topoloji ağ şekillendirmek için ikiden daha fazla düğüm içeren denizaltı fiber optik kablo sistemleri(ii) 3 boyutlu uzayda kabloların şeklinin belirlenmesinde ana etkendir.

Buna göre bu noktada üç boyutlu uzayda düzensiz şekilli kabloları kullanarak mesh ağ topolojisinin çoklu düğümlerini bağlama sorununu dikkate alarak yaklaşımımızı genişlettik. Mesh ağ topolojisini G(V,E) olarak düşündük. V düğümleri, E ise heterojen bandgenişlikli bağlantıları gösterir.

Topoloji adaları ve kıtaları bağlayan fiber optik kablo olarak düşünülebilir. Ek olarak her bir komşu düğüm çifti düzensiz şekilli ana ve yedek kablo tarafından bağlanmıştır.

Bu bağlamda ana ve yedek kablolar ardışık kablo arızalarından kaçınmak için farklı yolları kullanmak zorundadır.

Düğümlerin iletişimini ayıran su kütlesi tahmin edilebilir ve tahmin edilemez doğal felaketlere duyarlıdır. Her bir iletişim düğümü için kabloları yerleştirebilmek için kullanılacak muhtemel aday yollar vardır. Bu yollar diğer coğrafi kısıtlar kadar denizaltı çevresinin topografisi dikkate alır.

Bununla birlikte problemi daha pratik hale getirmek için, farklı kara parçalarına yerleşmiş çoklu düğümlerin örgüsel bir ağ topolojisini, düzenli şekillere sahip olmayan kabloları, deniz altındaki ortamın topografisini de dikkate aldık. Bu problemi de ifade etmek için sayısal örneklere birlikte bir Tamsayı Lineer Programlama sunduk.

Aynı şekilde bu durumda amaç takip eden kısıtlara bağlı olan doğal afetlerin tekrarlanması dikkate alınarak beklenilen onarılma maliyeti, beklenilen yolculuk maliyeti ve ağın beklenilen kapasite kaybının toplamı olan toplam beklenilen maliyeti minimize etmektir.

Yerleştirme ve koruma maliyeti bütçe planını aşmamalıdır. Yaklaşımımız beklenilen toplam maliyeti minimum yapmayı sağlayan verilmiş aday doğal felaket alanından geçerek bir yol seçebilir. Bu durumda bu bölüm korunmasız olacaktır. Tüm denizaltı fiber optik kablo sistemini korumak uygun maliyetli olmadığından yaklaşımımız aday doğal felaket alanlarından geçen denizaltı fiber optik kablonun kısımlarını koruyarak minimum bağlanabilirliği garanti eder. Diğer kısıtlar benzersiz yol kısıtı, ayrık yol kısıtı, ağ bağlanabilirlik kısıtı ve lineere bağlı kısıtları içerir. Sayısal örnekler tarafından desteklenen bu sorunu irdeleyen Tam sayılı lineer programlama formülü geliştirdik. Buna göre yaklaşımımızdaki sonuçlardan yerleştirmedeki artışın masrafında beklenilen maliyeti önemli bir şekilde azalttığını görebiliriz.

MedNautilus denizaltı fiber optik kablo sistemini dikkate alarak yaklaşımımızın kullanışlı uygulanabilirliğini değerlendirmek için vaka çalışması yürüttük. Bu sistem toplam 7000 km uzunluğundadır ve 7 kara istasyonunu bağlar: Atina (Yunanistan), Catania (İtalya), Chania (Yunanistan), Haifa (İsrail), İstanbul (Türkiye), Pentaskhinos (Kıbrıs) ve Tel Aviv (İsrail).

Akdeniz denizaltı fiber optik altyapısına zarar veren ve yüzlerce insanı öldüren deprem ve tsunami gibi çok sayıda doğal afetlere elverişlidir. Bununla birlikte bu bölge Doğu Akdeniz , Batı Avrupa, Kuzey Afrika ve Asya ülkeleri için hayati önem taşır. Denizaltı kablo etkileşimli haritaya göre yaklaşık olarak 13 denizaltı fiber optik kablo sistemleri Akdeniz bölgesinden geçer.

Derin denizde meydana gelen ve denizaltı fiber optik kablolara zarar veren belirli doğal afetleri dikkate alarak çalışmamızı genişlettik. Bu çalışmamızın amacı derin denizde doğal afetler tarafından sonuçlanan denizaltı fiber optik kablo arızalarını irdelemektir.

Bu durumda akdenizin derinlerinde meydana gelen doğal afetleri dikkate aldık. Once again numerical results in this case reveal that our approach perform better for any clustering coefficient. Özet olarak bizim yaklaşımımız felaket bilinçsiz yaklaşımla karşılaştırıldığında umut vadeden sonuçlar gösterir.

Sonuç olarak, pratik durumu düşünerek bir örnek durum incelemesi üzerinde yaklaşımımızı mevcut kablolama sistemleri ile kıyaslayarak teyit ettik. İki durumda da, sonuçlar bize %2-%11 oranında bir yerleştirme maliyeti artışı karşılığında beklenen maliyeti %90-%100 arasında azaltabileceğimizi gösterdi.

CHAPTER 1. INTRODUCTION

A network is a set of autonomous terminals or nodes that can communicate using a set of protocols and interconnected by a transmission medium. There are two categories of transmission mediums viz: guided or unguided medium [1]. Guided mediums also known as wired mediums transmit signal from the sender to the receiver using a determined physical device such as twisted pair, coaxial cable and optical-fiber. In contrary, unguided mediums also referred to as wireless medium carry electromagnetic waves from the sender to the destination through undetermined physical path. Signal transmission in unguided mediums involve propagating signal through air, water, sea-water as well as vacuum. Communicating terminals or nodes can exchange information if and only if they are equipped with transmitter and receiver.

An optical network consists of communicating nodes such as switches interconnected by optical-fiber cables. However, in this context communicating devices could be electrical, optical, or hybrid [2]. Advancement in information and communication technology shows that optics is tremendous for signal transmission due to the fact that (i) signals are transmitted at a speed light (ii) optical amplifiers are capable of simultaneously amplifying all signal on more than 160 wavelength channels on a single optical-fiber. Nevertheless, optical nodes technology is still pre-mature. Authors in [3] reveal that optical nodes are too expensive, complex, inflexible, and unreliable. In a nutshell, an optical network certainly consists of optical transmission albeit communicating nodes can be optical, electrical or hybrid.

Recently the world has experienced a drastic increase in bandwidth demand due to the invention of new devices and applications such as smartphones and datacenters. According to Cisco, in 2003 the amount of Internet traffic reached 667 exabytes [4]. Interestingly, IDC/EMC estimate that in 2015 mankind will generate 7910 exabytes of Internet traffic, a remarkable increase [4]. This increase comes with burden as network operators need to satisfy the market demand by delivering quality service consistently and timely. In this context, changing or upgrading network infrastructure is a growing concern. Optical-fiber network is a promising technology to the ever increasing bandwidth demand nowadays, capable of transmitting terabytes of data per second. Certainly, huge bandwidth, low signal attenuation (0.2 dB/km), low power requirement, immunity to electromagnetic interference among others, are reasons as to why optical-fiber network leapfrogged other networking technologies. Hitherto, optical-fiber networks played a significant role in long-haul communication, however, with the emergency of FTTx technologies, optical-fiber network is available in abundancy for last mile networks.

1.1. Submarine Optical-Fiber Network

Since 1988 when the first transoceanic optical-fiber cable was laid, which connected Britain, United States of America, and France, the world has experienced a tremendous communication revolution. This was a result of acutely technology push and market pull. Hitherto, continental and international telecommunications relied on satellites, however, interference, propagation delay, large investment capital, frequency congestion among others are motivations for the existing profound development of submarine optical-networks [5] and [6]. Nowadays, network connectivity heavily relies on submarine optical-fiber networks, which have become more essential in our lives, given our social and economic reliance on the Internet. A comparison of satellites and optical-fiber communications is presented in [7] and the numerical values discussed thereof as shown in Table 1.1 reveal the better performance of optical-fiber over satellite communication.

Table 1.1. A Comparison of satellite versus submarine optical-fiber communication.

Comparison Factors	Satellite	Submarine optical-fiber
Latency	250 milliseconds	50 milliseconds
Design life	10-15 years	25 years
Capacity	48,000 channels	160,000,000 channels
Unit cost of Mbps Capacity	$ 737,316 US	$ 14,327 US
Share of traffic: 2005	50%	50%
Share of traffic: 2008	3%	97%

Generally, submarine optical-fiber network consists of multiple landing stations interconnected by submarine optical-fiber cables. Landing stations are located on different continents or countries, and the distance separating two landing stations is usually very large (thousands of km) as indicated in Fig. 1.1. Furthermore, communicating nodes (land stations) are separated by water bodies such as sea or oceans that are susceptible to natural catastrophes such as earthquakes, tsunami, and hurricane among.

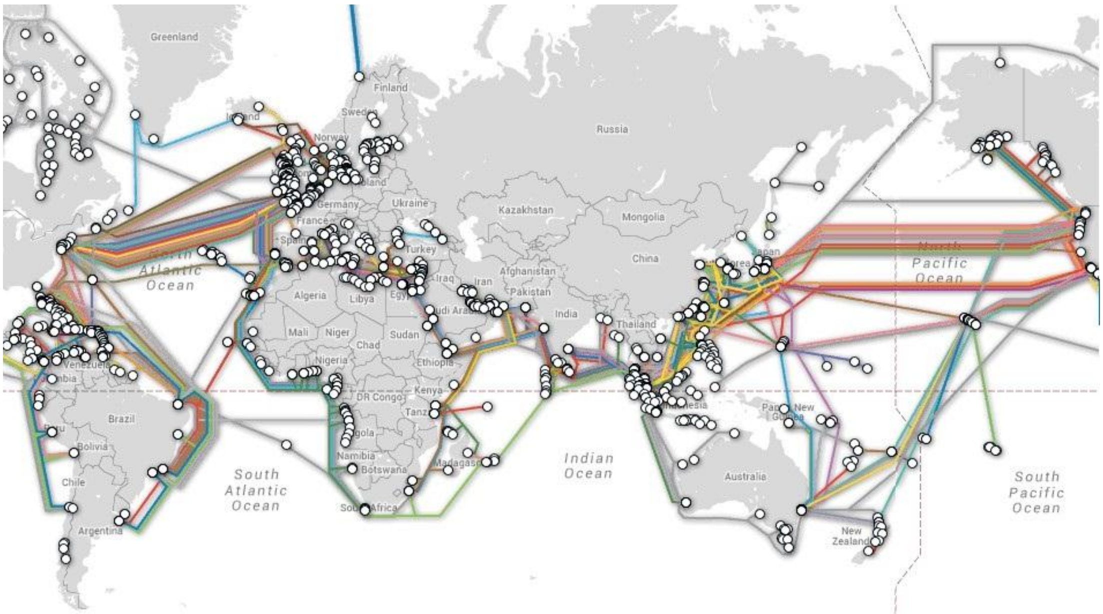

Figure 1.1. The global submarine optical-fiber cable map depicting active and planned submarine optical-fiber cable systems and their landing stations as of 2015 (Adopted from [8]).

1.1.1. Historical growth of submarine optical-fiber networks

In the past three centuries the world has experienced different technological advancements. The 18th century is part of the so called “The Age of Enlightenment”, this is the historical period in which there was a change from traditional religious authority towards science and rational thought. Due to new inventions, modern manufacturing engines began to replace manual labor in this period. Essentially, the 18th century was characterized by new achievements in mechanical systems which stimulated Industrial Revolution.

The 19th century marked the second Industrial revolution era. It is during this epoch when useable electricity, steel, as well as petroleum products were inverted. This prompted growth of transport systems such as railways and steam ships. During the 20th century technological inventions progressed at a high rate ranging from airplanes, automobiles, radio, computers and Internet. However, communication was the key technological achievements in this era. New means of information gathering, processing as well as distribution were inverted. This includes installation of worldwide telephone networks, invention of radio and television, deployment of submarine communication cables, launching of communication satellites and the beginning the computer and Internet industry.

The history of transcontinental communication falls into thee epochs: the telegraph cables epoch (1850-1960), the coaxial telephone cables epoch (1959 – 1990) and the optical-fiber cable epoch (1988 to present). The invention of electric telegraphic is one of the marvelous innovation of the mid-nineteenth century as it dramatically changed the nature of communication. The first successful attempt of deploying submarine telecommunication system was done in 1849 using a ship to shore wire, through which messages were exchanged from London to a vessel in the England channel. The wire was insulated with latex substance from trees called gutta percha [9]. Eventually, in 1850 the first submarine cable was laid connecting France and England, however, messages were garbled and the cable failed within twenty four hours.

In 1851 a second cable which was insulated by tarred hemp and galvanized iron wires with a covering of gutta percha was successful laid. In the following years, there was numerous submarine cable deployed viz.: in 1871 Great Northern Telegraph Company from Denmark laid two submarine cables, in 1872 Japanese government built the first submarine cable in Kanmon Straits, etc. Following telephone invention in 1876, the first submarine cable for telephone was built in 1891. For almost 75 years submarine cables systems were the major means of international communications, until 1920s when radio technology was inverted [10]. The invention of radio communication necessitated the shift of means of communication. Consequently, radio technology dominated communications industry for almost 30 years. Nevertheless, its limited capacity and atmospheric conditions were challenging factors that necessitated invention of alternative means of communication. Between 1955 and 1959 two submarine coaxial cable were installed, these cables connected Scotland and Newfoundland [11]. Along this technological achievement, comes the design of boosting repeaters for amplification of signals.

In 1979, the first trial of submarine optical-fiber cable installation was conducted [12]. Later, in 1986, the first international optical-fiber cable system was installed linking UK and Belgium, and subsequently in 1988 the first trans-oceanic optical-fiber cable was installed connecting UK, USA, and France [11]. Technological advancements in optical communication industry have stimulated dominance of optical components in communication industry nowadays. Submarine optical-fiber cables and their terrestrial counterpart act as a conduit of local and global communication. Huge bandwidth, high speed of signal transmission, and low signal attenuation among others, are factors that aided submarine optical-fiber cables leapfrog radio communication and coaxial cables. Currently submarine optical-fiber cables carry about 97% of the global Internet traffic, linking about 2.7 billion of Internet's users and carrying almost 30 trillion of bits per second. [13]. The existing ubiquitous access of Internet and mobile phones has increased our reliance on communication infrastructure in education, commerce and trade, entertainment etc. Unreliable communication infrastructures endanger public welfare, attract unstable economy, threaten national economy and leaves other critical sectors exposed.

1.1.2. Components of submarine optical-fiber networks

Repeaters, branching unit (BU), power feed equipment (PFE), submarine line terminal equipment (SLTE), network management equipment (NME), and optical cables are the primary components of submarine optical-fiber cable system. These components can be bifurcated into dry components and wet components depending on their physical location on the system. Dry components such as PFE, NME, and SLTE are found on terrestrial, whereas wet components such as BU, repeaters and optical cables are found undersea. In order to enhance bidirectional communication modern optical-fiber cables are designed on a fiber-pair basis. Existing technology allows a single cable to contain even eight optical-fiber pairs.

Considering inherent signal attenuation of about 0.2 dB/km, absorption loss, dispersion loss, and scattering loss of optical equipment, repeaters are deployed in optical communication systems. The principal function of repeaters is regeneration of signals, usually at regular intervals of approximately 50 to 110 km apart [14]. This enables a periodic compensation of attenuated signals within a submarine optical-fiber cable. Before, signals regeneration at the repeaters involved conversion of optical signals back to electric signals for regeneration then electric signals are converted back to optical domain before transmission to the destination, however, modern technology allows a direct regeneration of optical signals without conversion [10]. Branching units (BU) are wet components, these enable splitting of submarine optical-fiber cables interconnection. A single BU can provide up to three interconnection. The PFE play a significant role in submarine optical-fiber cable systems by supplying electrical power into the submarine optical-fiber cable. Electric current injected by PFE is used at the repeaters and BU for signal regeneration process. SLTE is a terrestrial component, this is responsible for processing, sending and receiving signals. Signal processing at SLTE includes multiplexing and de-multiplexing of signal across different channels on a single optical-fiber. Finally the NME facilitates monitoring, and control of a submarine optical-fiber cable system. Fig. 1.2 presents the existing interaction of these equipment.

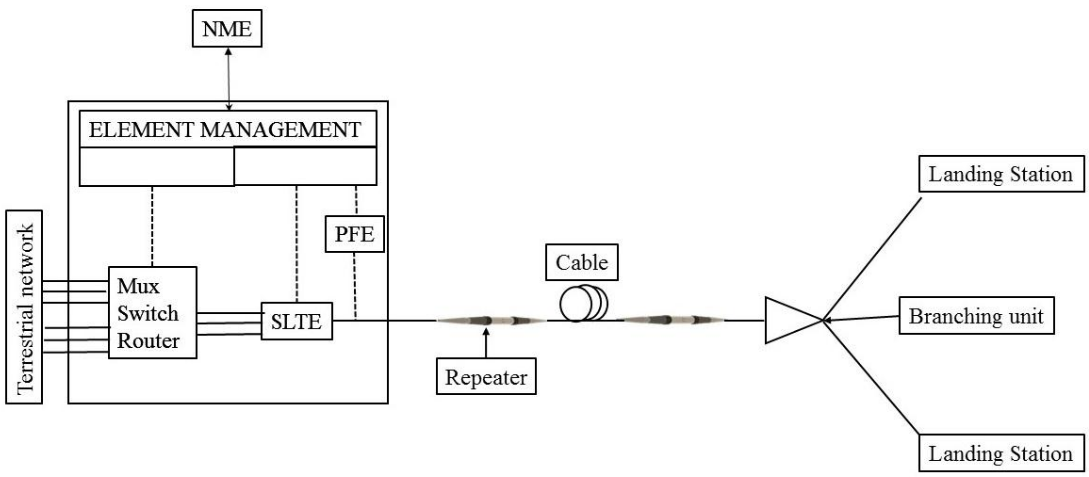

Figure 1.2. Primary components of a modern submarine optical-fiber cable system.

1.1.3. Submarine optic-fiber network topology

In computer networking, the term network topology refers to the schematic description of a network. It entails the arrangement of various components of a network such as nodes and links. The topology of a network is vital in determining the way nodes are connected and communicate with each other. Network topology falls into two categories viz: physical topology and logical topology. The physical topology of a network is the physical layout of communicating nodes and links, whilst logical topology refers to the flow of information between communicating nodes. There are five common network topologies viz: bus, mesh, ring, star and tree. In submarine optical-fiber networks the location of landing stations determines the physical topology of a given network. In Fig. 1.3 we present some of the existing submarine optical-fiber cable systems, which depicts different physical topologies of submarine optical-fiber cable systems viz: bus (East Africa Submarine System), ring (Azores Fiber Optic System), and mesh (FLAG North Asia Loop, and MedNautilus systems) topologies.

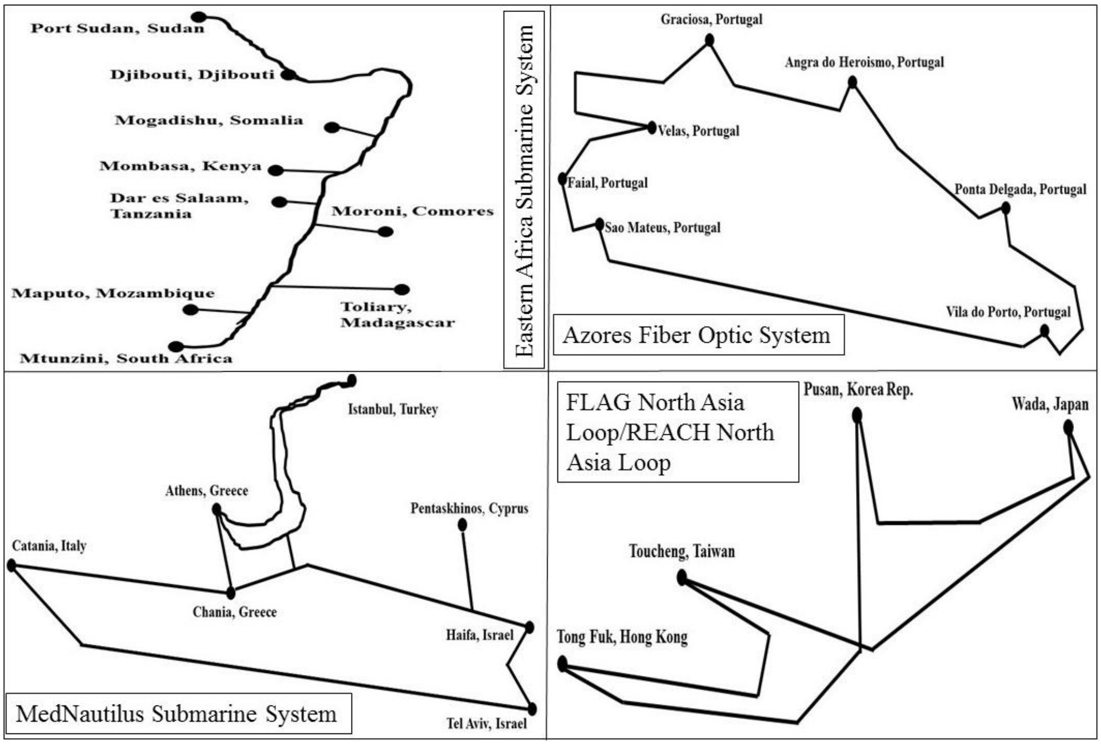

Figure 1.3. Physical topologies of submarine optical-fiber systems.

In contrast logical topology of a network describes the flow of data between communicating nodes. In submarine optical-fiber networks logical topology play a vital role in providing reliability, robustness, as well as low outage time of a network. In Fig. 1.4, we present a comparison of physical against logical topology of the East African Submarine System (EASSy). The logical topology of the systems is configured as a collapsed ring that provides internal protection routing [15].

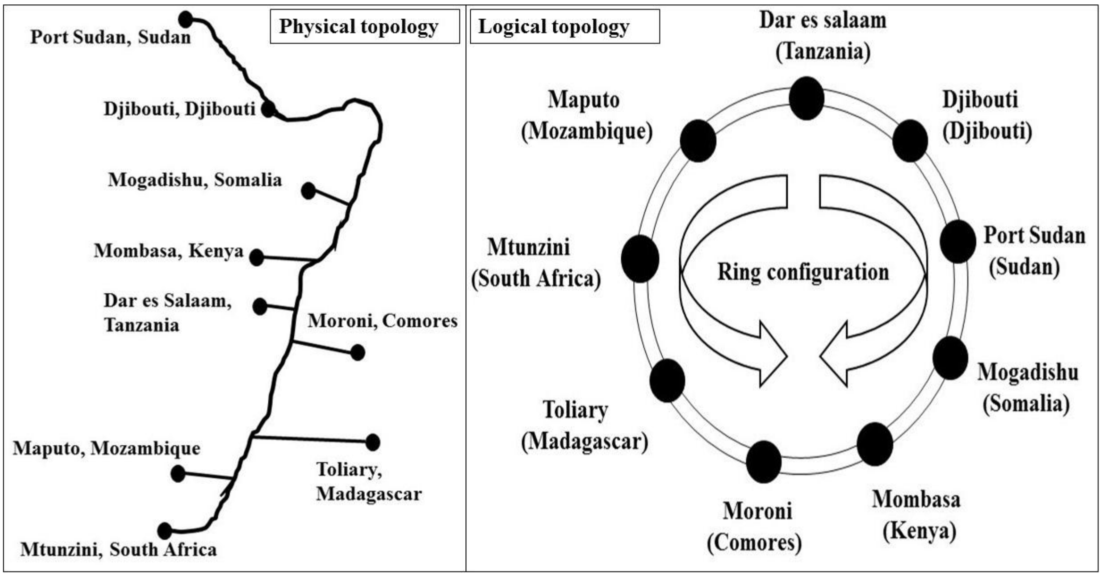

Figure 1.4. Physical and logical topology of East African Submarine System.

1.3. Effects of Natural Disasters on Submarine Optical-Fiber Networks

Despite the fact that, our lives heavily relies on submarine optical-fiber networks, this indispensable role is mainly recognized and appreciated when there are cable failures. The principal causes of submarine optical-fiber cable failures are external aggressions, which are bifurcated into human activities such as fishing, shipping, anchorage etc. and natural disasters such as earthquake, tsunami, hurricane etc. Statistics show that about 70% of total submarine optical-fiber cable faults are a result of external aggressions mainly associated with human activities (e.g., shipping, fishing, and anchorage). Moreover, 75% of all submarine optical-fiber cable faults occur in water depths shallower than 200 m, because of fishing and shipping activities [11]. The conventional approach of reducing this type of failures involves provision of additional protective materials or burying cables underground Zhang *et al.* [16].

Despite the fact that failures caused by natural disasters are less than 10% of all failures (occurred both in deep and shallow water), when focusing on deep-water cables, at least 31% of submarine cable failures are prompted by natural disasters [11]. Considering the fact that natural disasters occur sporadically, efforts to address the problem of submarine cable failures have been focusing on eradicating faults resulting from human activities, while paying little attention to the remaining causes, which constitute 30% of cable breaks in deep water, perhaps, because we are often guided by heuristics and rules of thumb to address disaster planning.

Berger *et al*. [17] point out some useful lessons to guide us in making decision about disaster planning by distinguishing losses caused by natural disasters from occurrences of natural disasters. Although natural disasters occurs sporadically, and their percentage composition to submarine cable failures is very small e.g. 10%, they attribute acute economic loss to submarine optical-fiber cable owners and Internet subscribers. Accordingly, paying little attention to failures prompted by natural disasters is myopic disaster planning. Berger *et al*. [17] stipulate two components that lead to losses from a natural disaster: (1) whether or not a natural disaster occurs and (2) the size of the loss as a result of occurrence of a natural disaster. Consequently, loss distribution evaluation must involve two components: occurrence and magnitude. Additionally, the distinction between these two components is critical for optimal decision making [17].

Below we provide some facts and figures on the effects of submarine optical-fiber cable disruptions due to disasters and we can see that disaster-aware submarine cable deployment considering the loss in case of a disaster is a must to reduce (or even eliminate) such damages.

The 26th December 2004 Andaman-Sumatra earthquake of magnitude 9.0 earthquake prompted a tsunami in Indian Ocean that affected about 18 countries. This is known to be the most deadly and detrimental tsunami ever occurred. It is estimated that about 250,000 people died on a single day, and 1.7 million were left homeless [18]. Telecommunication industry in Thailand recorded a loss of about $ 20 million due to damage caused by this disaster [19]. Additionally, land-based telecommunications networks were damaged in coastal Malaysia and South Africa [11]. On 29th August of 2005, Hurricane Katrina made landfall in Louisiana State of USA. It is estimated that about 2.5 million of Post Switching Telephone Networks (PSTN) lines were damaged [20]. Additionally, following the flood, six telecommunication central office lost communication and power failure prompted loss of service to eighteen telecommunication central offices [20].

In 2006, the Pingtung (aka Hengchun) earthquake in Taiwan of a magnitude 7.0 earthquake prompted mud flows and submarine landslides that travelled over 246 km at a depth greater than 4 km, causing 22 submarine optical-fiber cables break [21]. Eventually, telephone systems, data and Internet traffic were extensively disrupted in China, Taiwan, Hong Kong, Macao, and other countries, and the process of repairing the affected cables took seven weeks.

In 2008, Hurricane Gustav prompted telephone outages of about 50,000 lines mainly due to power outages [22]. Moreover, on 13th September of 2008, Hurricane Ike prompted landfall in Galveston Island, eventually, telephone outages of about 340,000 was experienced [23]. The author in [20] reveals that AT&T (one of the largest telephone company in North America) lost service in five of its central offices, whilst one of them was severely destroyed.

A strong earthquake of about 8.8 earthquake affected the coastal region of Chile on 27th February of 2010. The country experienced network congestion following this disaster. Alongside network congestion, a significant telecommunication outage occurred mainly due to power insufficient [20]. An earthquake of magnitude 6.1 affected Christchurch, New Zealand on 22nd February of 2011. Likewise, network congestion and lack of power in telecommunication systems was observed [20].

The authors of [11] considered different natural disasters occurring in different regions together with their effects to submarine optical-fiber cables viz.: (i) The 2009 Typhoon Morakot in Taiwan prompted sediment laden flows that broke at least nine submarine optical-fiber cables. (ii) In 2003, the Boumerdes earthquake of magnitude 6.8 in Algeria triggered landslides and turbidity currents, which damaged six submarine optical-fiber cables, hence disrupted all submarine optical-fiber networks found in the Mediterranean region.

Furthermore, we learn from [24] that, The Great East Japan Earthquake of magnitude 9.0 earthquake off the coast of Japan that occurred on March 11, 2011, is the fourth strongest earthquake ever occurred in the world. This stringently affected telecommunication infrastructure, as the author of [24] reveals that, considering Nippon Telegraph and Telephone Corporation's (NTT) facilities, 2700 km of cables were swept away, 1.5 million circuits for fixed lines as well as 4900 mobile base stations were severely damaged. Additionally, six submarine optical-fiber cables systems were damaged and about 30% of Japan's international communications was knocked out [13].

Natural disasters that have occurred, and detrimentally affected submarine optical-fiber cables are countless. Submarine optical-fiber cable breaks caused by natural disasters has significant economic loss as a research conducted in 2005 by the Swiss Federal Institute of Technology (ETH) Zurich found that if there is an Internet blackout in the entire country of Switzerland that last for one week, the country will experience a monetary loss of over 1.2% of its GDP [25].

1.4. Survivable Network

With the indispensable role of communication systems to our daily lives nowadays, network design should consider the worst case scenario at its early stage such that network failures can be easily mitigated, within a short time, and without accumulating huge economic loss to network operators and their customers. Failures in network equipment such as nodes and links are caused by natural catastrophes, malicious attacks and other human activities.

Performance of communication systems has been described by using qualitative and quantitative terms such as dependability, fault-tolerance, reliability, security, resilient, as well as survivability [26-28]. Interestingly, the differences between these terms is subtle due to their overlapping meaning and ambiguity in their definition as pointed by Al-Kuwaiti *et al.* [27]. Survivability of a system refers to the ability of a system to accomplish its mission, on a timely manner in the presence of attacks or failures [27-29].

Existing research publication categorize survivability techniques into two paradigms viz: pre-assigned protection and dynamic restoration [29-31]. In pre-assigned protection scheme, backup resources are pre-provisioned along a primary path either during connection setup or during network design. Pre-assigned protection can be classified as link protection, sub-path, or path protection depending on what is protected. The classification of protection paradigm can further be known as dedicated-protection, if backup resource is not shared among multiple primary paths and shared-protection if backup resource is shared among multiple primary paths. In path protection, each primary path is pre-assigned a backup path so that once a primary path fails, then connection is re-established on backup path. In contrast, in link and sub-path protection schemes, a backup path is pre-assigned for each link or sub-path such if failure occurs then backup resources are used to establish connection as shown in Fig. 1.5. Failure recovery in this paradigm takes a very short time.

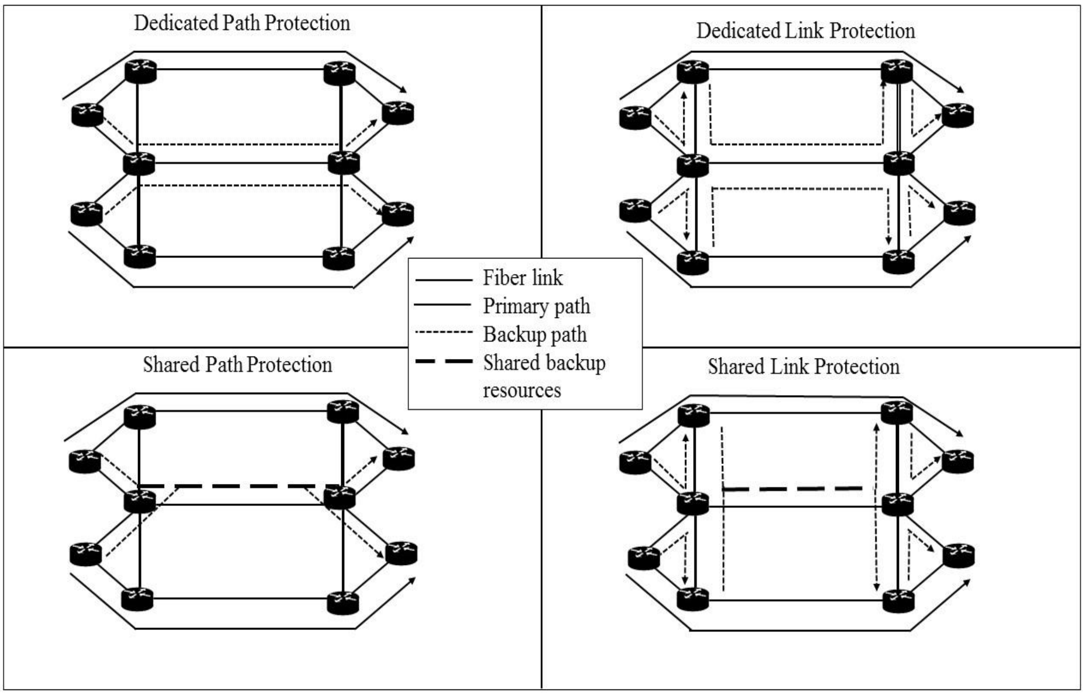

Figure 1.5. Protection schemes.

Nevertheless, in pre-assigned protection resources are under-utilized and it is suitable for recovering single point of failures. In dynamic restoration paradigm failures are recovered through discovering spare capacity after failure occurrence. Recovery time in dynamic restoration is longer, however, resources are well utilized and the approach performs better under multiple failures [32].

1.5. Literature Review

A survey on existing research publications associated with disaster survivability in optical networks is provided in [34], where authors classify disasters into three groups viz: predictable, non-predictable and intentional attack, based on their characteristics and impacts on networks. Additionally, in [34] disaster modelling approaches are classified into two categories, namely deterministic models and probabilistic models.

Deterministic model assumes that a network equipment such as link or node fails with probability 1 if it is located within a disaster zone and 0 otherwise. In contrast, in probabilistic model, a network equipment fails with a certain probability, which depends on factors such as its distance from the disaster epicenter, dimension of the equipment, specifications, etc. [34]. Our approach uses probabilistic model because there are many factors that may affect cable response to earthquake. Therefore, a probabilistic model is more appropriate and realistic than a deterministic approach.

There are some recent work that focus on disaster-resilient network design and traffic engineering, but mostly they focus on impacts of disasters to terrestrial networks and cables buried under ground as in [16], [35-39]. Cao *et al.* [40] investigate a disaster-resilient network design particularly in submarine environment. Authors' approach focuses on network survivability and cable-shape aspects in addressing the cost of network deployment without giving detailed results as to what monetary loss is associated with a given disaster.

In order to design a robust network against earthquake, Saito [38] proposes spatial network design rules, which include three components: (i) a shorter zigzag route which can reduce the probability of networks falling in disaster zones, (ii) additive performance metric, where repair cost and network's shape are independent if the length of the route is fixed and (iii) probability that all nodes intersect the disaster area is not reduced by additional of routes within a ring network. Saito [39] presents geometric model of a physical network affected by a disaster, which can be used in evaluating performance metrics of a network such as network connectivity.

Unlike [38] and [39] that consider survivability metrics such as network connectivity, we consider costs incurred by submarine optical-fiber cable owners, shape of the cable, topography of submarine environment, as well as probability of occurrence of a natural disaster considering cable break is prompted by occurrence of a natural disaster, particularly in submarine environments. To the best of our knowledge, this study addresses a unique concept from the existing research publication associated with disaster survivability of submarine optical-fiber cables.

We study a survivable and disaster-aware submarine optical-fiber cable deployment by using a probabilistic model. Our approach investigates the cost incurred by submarine optical-fiber cable owners to restore network service to a normal condition when submarine optical-fiber cables break as a result of natural disasters based on the probability of natural disaster occurrences as well as the probability of cable breaks. Thereafter, we evaluate the total cost that is a sum of cruising cost (cost of repair ship to arrive at a failure point from closest station), repairing cost, and penalty due to bandwidth loss. In a nutshell, our approach minimizes losses incurred by submarine optical-fiber cable owner following a cable break due to a disaster occurrence by applying a survivable and disaster-aware submarine optical-fiber cable deployment significantly with a slight increase in deployment cost.

CHAPTER 2. SURVIVABLE AND DISASTER-AWARE SUBMARINE OPTICAL-FIBER CABLE DEPLOYMENT FOR POINT TO POINT COMMUNICATION

In this chapter, we investigate the problem of connecting two continents or islands by submarine optical-fiber cables as shown in Fig. 2.1. Generally, the two land masses can be connected by one or more optical-fiber cables. When the two landmasses are connected by one submarine optical-fiber cable, a connection is not protected, hence, a connection failure will be experienced if cable break occurs. Ramamurthy and Mukherjee [41] studied protection in WDM networks using two paradigms, namely protection and restoration. Additionally, Spilios *et al.* [42] studied metrics for measuring the robustness of undersea cable infrastructure wherein resiliency is one of them.

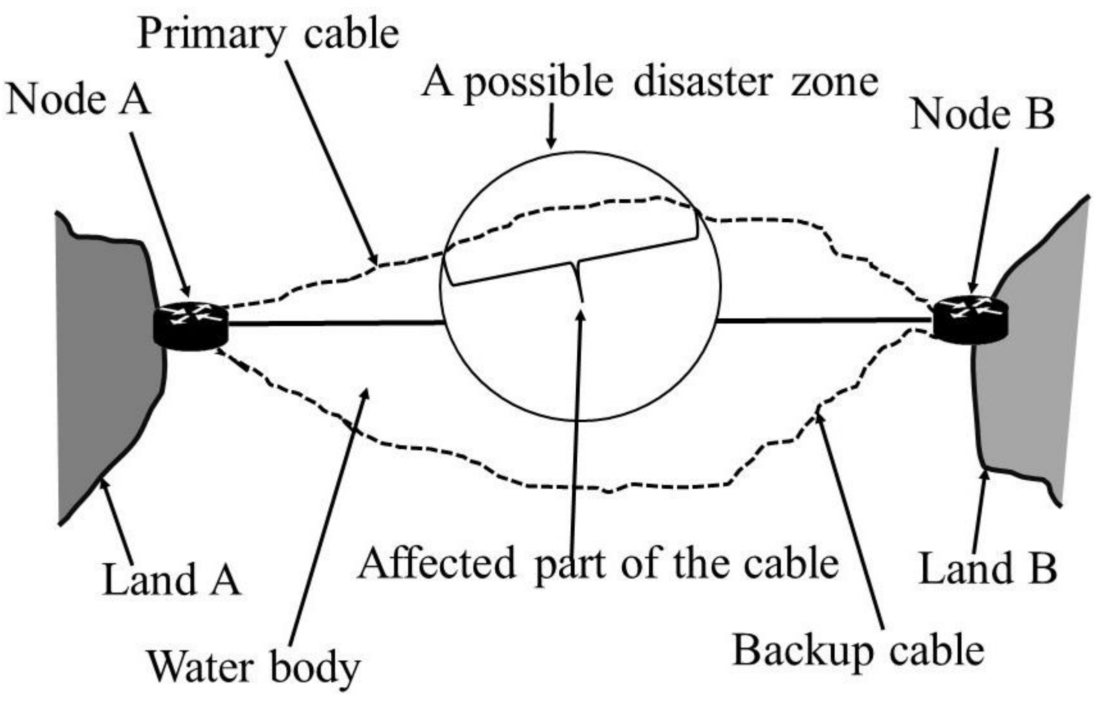

Figure 2.1 Two land-masses connected by one submarine optical-fiber cable.

Considering findings presented in [41] and [42], in this study, we provide a protected connection between the two landmasses by connecting them using by two submarine optical-fiber cables[1] denoted by $i = \{1, 2\}$ such that i is equal to 1 for primary cable and 2 for backup cable. Here, we assume that backup cable is provided mainly for disaster-unrelated failures. Whereby, the water body separating the two landmasses is susceptible to a number of possible natural disasters.

2.1. Problem Description and Assumptions

In particular, we consider the problem of the best way to connect the two nodes located on the beaches of the two continents/islands as shown in Fig. 2.2. The assumption that the two nodes are located on the beaches is made for simplicity and for ease of exposition. Allowing the nodes to be located inland will require considerations of different costs for laying and repairing cables in the sea and inland, which introduces additional complexity in the formulation. However, our solutions for the simpler case can be extended to the case where the nodes are located inland. Various topologies can be employed to provide connection between these two nodes, e.g., rectangular, circle/ring, triangular, etc.

Cao *et al.* [40] present topology optimization of undersea cables in which various cable shapes are considered including rhombus, rectangular, and a rectangle with round corners. Eventually, [40] focused on a rectangular topology in their study, aiming at minimizing the probability of simultaneous cable breaks considering natural disaster occurrences. In our approach, we focus on elliptic cable shape, which is more cost effective in terms of deployment cost.

Unfortunately, there is no simple closed-form formula for calculating perimeter of an ellipse, as there is for a circle, a rectangle, etc. Thus, even though there are simple equations, yet there is no simple and exact equation. The list of these equations includes; First Approximation, Second Approximation (Ramanujan), Infinite series 1, Infinite series 2, etc. Some studies (e.g., [43]) on the existing equations and their findings proved that Second Approximation by Ramanujan performs better than

[1] We can easily generalize our approach for any number of cables, but for simplicity (and as in typical practice), we keep the number of paths to two.

others. Hence, in this study, we apply this equation. The Second Approximation states that the perimeter of an ellipse is given by:

$$P = \pi(a+b)\times\left(1+\frac{3h}{10+\sqrt{4-3h}}\right), \tag{2.1}$$

where a is the major axis, b is the minor axis, and h is defined as $h=\frac{(a-b)^2}{(a+b)^2}$ that ranges from 0 for circles ($b = a$) to 1 for the degenerate ($b = 0$). Observe that, for submarine optical-fiber cables, the distance between two nodes is very large (about 5,000 km to 30,000 km), so $a >> b$, which approximates h to 1. Thus, equation (1) can be reduced to:

$$P = \pi(a+b)(14/11) \tag{2.2}$$

Therefore, given the cost of deployment per unit kilometer (C_d) and Eq. (2.2), the cost of deployment of a cable (that is half of the ellipse) is:

$$C = C_d \times \pi(a+b)(7/11) \tag{2.3}$$

Furthermore, deployment cost increases when the values of the major and minor axes of the ellipse increase. However, since major axis is a given parameter in our problem, we can optimize the minor axis such that expected total cost is minimized, subject to deployment budget constraint. The expected cost includes expected (i.e., probabilistic) cost incurred by the network operator to restore network connections due to a cable break. Clearly, the lower the probability of cable break, the lower is this expected repair cost.

We consider a set of candidate cable paths as shown in Fig. 2.2. Let Ω be a set of possible natural disasters wherein each natural disaster is assumed to be a circular disk, characterized by location, radius and strength. The epicenter of a natural disaster is assumed to be located near natural disaster's fault. For each $n \in \Omega$, let $P_{j,i}^{n}$ be the probability that, if natural disaster n occurs and if candidate path j is selected for cable

i, cable breaks. This probability depends on the distance of the cable from the natural disaster epicenter and follows a certain given function which decays as the distance of the cable from the epicenter increases [44] (e.g., following a Normal distribution).

Additionally, when a cable passes through a natural disaster zone and breaks as a result of that natural disaster, then a set of costs will be incurred by the network operator to restore the service; namely, cost of repair (C_r per km), cost of cruising to the cable-break location to do technical repair (C_t per km), and penalty (C_p per unit of bandwidth lost) due to breach of service level agreement (SLA). Effects of the natural disaster will damage length $L_{i,j}^{a,n}$ of cable i, if candidate path j is selected, passing through natural disaster n. We assume that one of the repair ships at the closest station will travel length $L_{i,j}^{u,n}$ to visit affected part for reparation activity. These lengths are shown in Fig. 2.2.

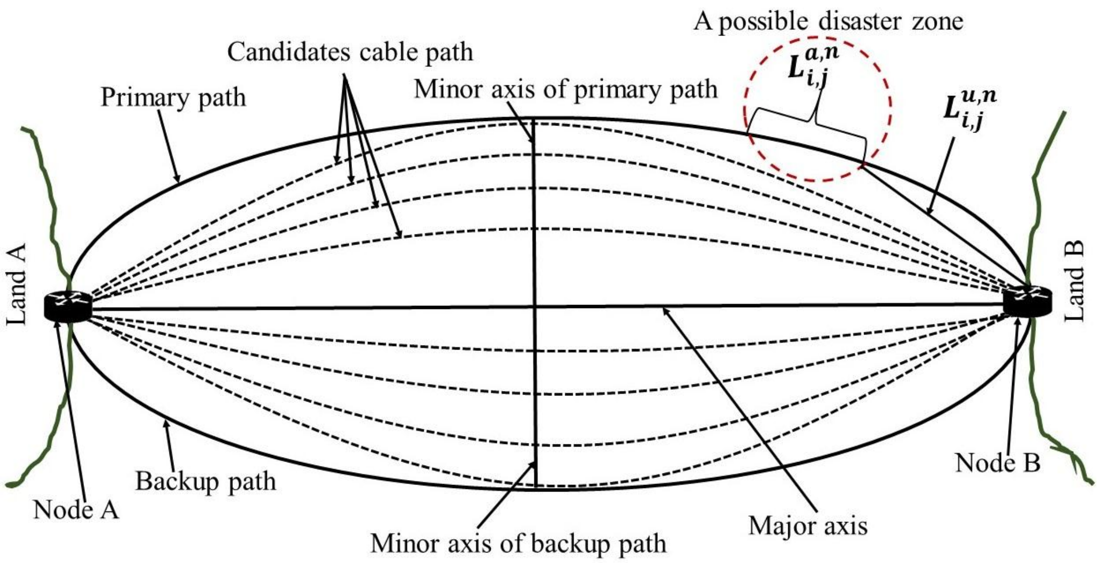

Figure 2.2 Elliptic shape candidate cable paths connecting two nodes located on two beaches.

2.2. Problem Formulation

In order to address the problem of survivable and disaster-aware submarine optical network, we develop an Integer Linear Programming (ILP) formulation that considers physical locations of natural disasters, radii of natural disasters, physical locations of submarine optical-fiber cables, shapes of the cables, and their distance from natural disasters' epicenters.

By exploiting this information, we obtain numerical values of the expected cost to be incurred by the network operator if a cable break due to a natural disaster. The expected cost is a summation of expected repair cost, expected cruising cost, and expected capacity loss penalty. We investigate a survivable and disaster-aware submarine optical-fiber cable deployment approach wherein a path is selected from the candidate paths based on these metrics in order to minimize expected cost to be incurred by network operators subject to deployment budget constraint, path uniqueness constraint, regular protection constraint, elliptic shape constraint, and constraint due to linearization.

Given:

a. M: Set of minor axes for each candidate cable path, V_j is the length of minor axis for j^{th} candidate cable path.

b. Ω: Set of possible natural disasters characterized by their location, radius and strength. Each natural disaster is assumed to be a circular disk of radius r.

c. C_d: Cost of cable deployment per km.

d. C_r: Cost of repair per km.

e. C_t: Cruising cost per km.

f. C_p**:** Penalty per bandwidth, per unit time due to breach of service level agreement (SLA).

g. N: Total capacity provided by the two cables.

h. γ : Deployment budget.

i. S: Acceptable minimum distance separating primary and backup cables to avoid losing both cables by a regular failure (e.g., cable cut due to anchoring).

j. $P_{j,i}^{n}$: Probability that, if natural disaster n occurs and if candidate path j is selected for cable i, cable breaks. This probability depends on the distance of the cable from the natural disaster epicenter's and follows a certain given function which decays as the distance of the cable from the epicenter increases [44] (e.g., following a Normal distribution).

k. $L_{i,j}^{a,n}$: Damaged length of cable i, if candidate path j is selected, passing through natural disaster n.

l. $L_{i,j}^{u,n}$: Cruising length from the closest station.

Variable:

a. $B_{i,j}$: a binary variable, such that:

$$B_{i,j} = \begin{cases} 1, \text{if } j\text{th candidate cable path is selected for cable } i \\ 0, \text{Otherwise} \end{cases}$$

Objective Function:

The objective of this study is minimizing cost incurred by submarine optical-fiber cable owners for reparation activities because of damage caused by natural disasters. This cost is the sum of expected repair cost, expected cruising cost, and expected capacity loss cost. Thus, given M and $\Omega,$ the repair cost (RC) of cable i with respect to damage caused by natural disaster $n \in \Omega$ can be defined as:

$$\text{RC} = \sum_{n \in \Omega} \sum_{i \in \{1,2\}} \sum_{j \in M} C_r \times L_{i,j}^{a,n} \times B_{i,j} \tag{2.4}$$

Moreover, we consider during reparation activity a cruising ship will cruise twice a distance $L_{i,j}^{u,n} + L_{i,j}^{a,n}$. Hence, cruising cost (CC) for reparation of cable i because of natural disaster n is evaluated as:

$$\text{CC} = \sum_{n \in \Omega} \sum_{i \in \{1,2\}} \sum_{j \in M} 2 \times C_t \times B_{i,j} \times \left(L_{i,j}^{u,n} + L_{i,j}^{a,n}\right) \tag{2.5}$$

Furthermore, given the total capacity provided by the two cables and a pre-computed value ($X_{n,i}^{j}$) such that:

$$X_{n,i}^{j} = \begin{cases} 1, \text{if cable } i \text{ is deployed on } jth \text{ candidate cable path} \\ \quad \text{and passes through disaster zone } n \\ 0, \text{ otherwise.} \end{cases}$$

Then, we define penalty due to capacity loss (CLP) by natural disaster n as:

$$\text{CLP} = \sum_{n \in \Omega} \sum_{k \in M} \sum_{j \in M} \boldsymbol{C_p} \times N \times X^{j}_{n,1} \times B_{1,j} \times X^{k}_{n,2} \times B_{2,k} \tag{2.6}$$

Recall that, in this study, we assume that the penalty is due when both primary and backup cables are damaged for capacity loss. Note that, in Eq. (2.6), the multiplication of two binary variables makes our formulation non-linear. To make it linear, we provide an auxiliary binary variable which is equal to logic AND operation of these two binary variables, i.e., if they are both 1, it is equal to 1, otherwise it is 0. Thus, it does not induce any error. Let $D_{j,k}$ be an auxiliary binary variable such that:

$$D_{j,k} = \begin{cases} 1, \text{ if } & B_{1,j} \times B_{2,k} = 1 \\ 0, & \text{Otherwise} \end{cases}$$

Subject to:

$D_{j,k} \leq B_{1,j}$,

$D_{j,k} \leq B_{2,k}$, and

$D_{j,k} \geq B_{1,j} + B_{2,k} - 1$.

Hence, (2.6) can be rewritten as:

$$\text{CPL} = \sum_{n \in \Omega} \sum_{k \in M} \sum_{j \in M} C_p \times N \times X^{j}_{n,1} \times X^{k}_{n,2} \times D_{j,k} \tag{2.7}$$

Then, the objective function can be written as follows:

$$\text{Min } \underbrace{\sum_{n \in \Omega}\left(\sum_{i \in \{1,2\}}\sum_{j \in M} C_r \times L_{i,j}^{a,n} \times B_{i,j}\right) \times P_{j,i}^{n}}_{\textit{Expected repair cost}}$$

$$+\underbrace{\sum_{n \in \Omega}\left(\sum_{i \in \{1,2\}}\sum_{j \in M} 2 \times C_t \times \left(L_{i,j}^{u,n} + L_{i,j}^{a,n}\right)\right) \times P_{j,i}^{n}}_{\textit{Expected cruising cost}}$$

$$+\underbrace{\sum_{n \in \Omega}\left(\sum_{k \in M}\sum_{j \in M} C_p \times N \times X_{n,1}^{j} \times D_{j,k} \times X_{n,2}^{k}\right) \times P_{j,1}^{n} P_{k,2}^{n}}_{\textit{Expected Capacity loss cost}} \tag{2.8}$$

Constraints:

a. Deployment budget constraint:

Deployment cost is inversely proportional to expected cost. This is due to the fact deploying submarine optical-fiber cable in a disaster free zone attracts increase in deployment cost, because of increase in the length of the route. In this study, while minimizing expected cost we ensure that deployment cost does not exceeds a certain budget (γ) by providing the following constraint.

$$\sum_{i \in \{1,2\}}\sum_{j \in M}\left(\pi \times C_d \times \left(a + V_j\right) \times B_{i,j}\right) \leq \gamma. \tag{2.9}$$

b. Path uniqueness constraint:

Following constraint ensures that there is a unique path for each primary and backup cable. This assures that primary and backup cable are not deployed in the same zone in case the same path is selected for both primary and backup cable. We define this constraint as follows.

$$\sum_{j \in M} B_{i,j} = 1 \qquad \forall i;\ i \in \{1,2\} \tag{2.10}$$

c. Regular protection constraint:

Deploying primary and backup cable in close proximity attracts simultaneous cable failures. In order to avoid this undesired situation, we ensure that primary and backup cables must be separated by at least a certain distance to avoid simultaneous cable failures (e.g., cable cut due to anchoring) by providing the following constraint.

$$\sum_{i\in\{1,2\}}\sum_{j\in M} B_{i,j} \times V_j \geq S \tag{2.11}$$

d. Elliptic shape constraint:

Since we assume elliptical cable shape, it follows that the value of the minor axes should be greater than zero such that the major axis will not be among candidate paths. We ensure this by providing the following constraint.

$$\sum_{j\in M}\left(V_j \times B_{i,j}\right) \geq 0 \qquad \forall i;\ i \geq 1 \tag{2.12}$$

e. Constraints due to linearization:

Recall that, in Eq. (2.6), the multiplication of two binary variables makes a non-linear equation. We linearize the equation by proving an auxiliary variable that necessitate the introduction of other constraints as follows.

$$D_{j,k} \leq B_{1,j} \qquad \forall j \in M, j \geq 1, \forall k \in M, k \geq 1 \tag{2.13}$$

$$D_{j,k} \leq B_{2,k} \qquad \forall j \in M, j \geq 1, \forall k \in M, k \geq 1 \tag{2.14}$$

$$D_{j,k} \geq B_{1,j} + B_{2,k} - 1 \qquad \forall j \in M, j \geq 1, \forall k \in M, k \geq 1 \tag{2.15}$$

Since for each cable i and each candidate path j, we have binary variable $B_{i,j}$ and for each pair of candidate cable path we have auxiliary binary variable $D_{j,k}$, the number of variables in the ILP is $I \times J + J^2$, where I is the number of cables (e.g., 2 in our examples) and J is the number of candidate path for each cable. Similarly, the number of constraints is $3(I + J^2) + 1$.

2.3. Illustrative Numerical Examples

In order to evaluate our approach, we present numerical examples using different dimension of major axis (5000 km, 10000 km, 15000 km, 20000 km, and 25000 km). We generate random natural disasters with different radii (10 km, 20 km, 30 km, 40 km, and 50 km), different interval of minor axes between consequent candidate cable paths (1 km, 2 km, 5 km, 10 km, and 20 km). The probability of cable failure depends on the distance of the cable from the natural disaster epicenter and follows a normal distribution, which decays as the distance of the cable from the epicenter increases. All cost parameters used in our simulation are determined by information from public sources such as [45] and [46]. These parameters are normalized as follows; deployment cost per km is normalized to 1, cruising cost per km is normalized to 0.4, repair cost per km is normalized to 0.6. Moreover, minimum cable separation distance (S) required to avoid regular failures is 10 km, penalty due to capacity loss is 100 per Tbps and the capacity of the two cables is 54 Tbps, 27 Tbps for each.

The author of [47] performed a study aiming at investigating the minimum distance at which an alternate facility should be placed, in which different categories of natural disasters such as hurricane, storm and snow, earthquake, volcano, tsunami, terrorism, etc. are considered. Records from this study show that hurricane recorded maximum distance of 105 miles whereas storm and snow, earthquake, volcano, and tsunami recorded 68, 60, 75, and 51 miles of minimum distance, respectively.

Considering findings from [47], we assume the maximum value of minor axis for each cable is 110 km, because this distance is sufficient to achieve a solution of higher precision. Moreover, if the selected interval between cables is 1 km, 2 km, 5 km, 10 km, or 20 km, we have 120, 60, 24, 12 or 6 potential solution paths, respectively. Note that the two paths will converge towards each other at the nodes, so it is not a factor that can be avoided. Besides, in this study we focus on the deep-water cable failures.

We rerun all our simulation 50 times on a computer with an Intel i3 2.4 GHZ CPU, 4 GB DDR3 RAM, and 64 bit Microsoft Window 8.1 operating system for each parameter set values and the results shown below are average of the results obtained.

Then we compare our approach with a disaster-unaware approach, which considers regular failures only. Finally we report the results in terms of reduction in expected cost (expected cost of repair, expected cost of cruising to the cable break location, and expected penalty due to bandwidth loss) and increase in deployment cost compared to disaster-unaware approach.

2.3.1. Major axis

A comparison of different major axis values is presented in Fig. 2.3. In this case, we consider a set of five natural disaster zones with radius of 30 km and a second set with ten natural disaster zones with radius of 50 km. The results show that our approach reduces expected cost significantly (between 75% and 97% depending on major axis) at a slight increase in deployment cost (around 18.1 %).

Moreover, Fig 2.3 shows that our approach performs better when the distance between landing stations is very large. Accordingly, our approach is suitable to long-haul networks such as submarine optical-fiber networks because of their long-range coverage, which spans over 30,000 km between two landing stations. Additionally, when there are more possible natural disasters, our approach may reduce the expected cost more, a practical advantage.

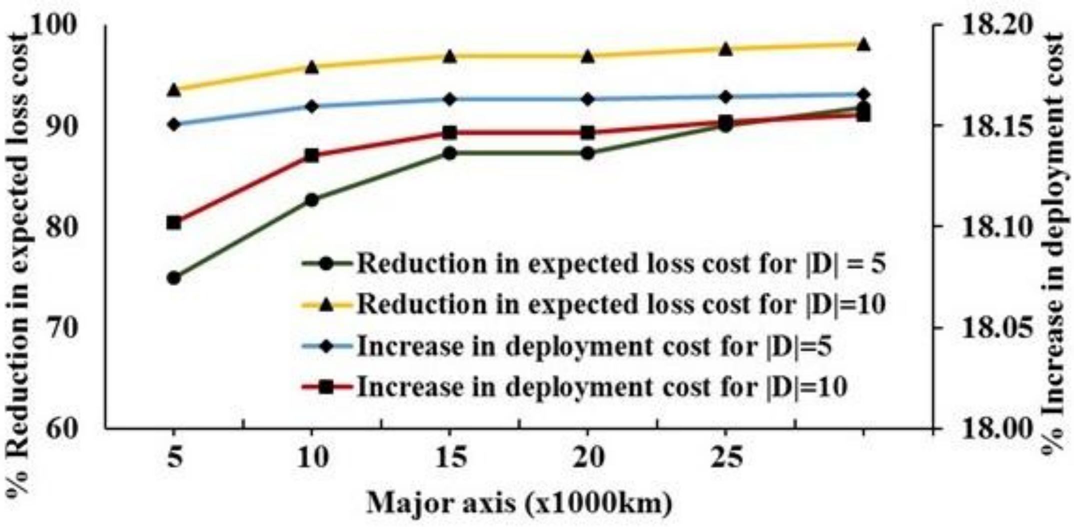

Figure 2.3 Reduction in expected cost and increase in deployment cost for different major axis length values.

2.3.2. Radius size

We conducted numerical examples using five natural disaster zones of variable radii, followed by another example which involved ten natural disaster zones, likewise, with variable size. Here, the major axis is 15,000 km. Results in Fig. 2.4 show that, the ability of our approach to reduce expected cost is limited by both the size of the natural disaster zones and the number of natural disaster zones.

Because under such circumstances it is more difficult to avoid passing through natural disaster zones. Nevertheless, our approach eventually chooses the no-risk or low-risk paths for primary and backup cables, so that it can still reduce the expected cost around 41% for large natural disaster zones.

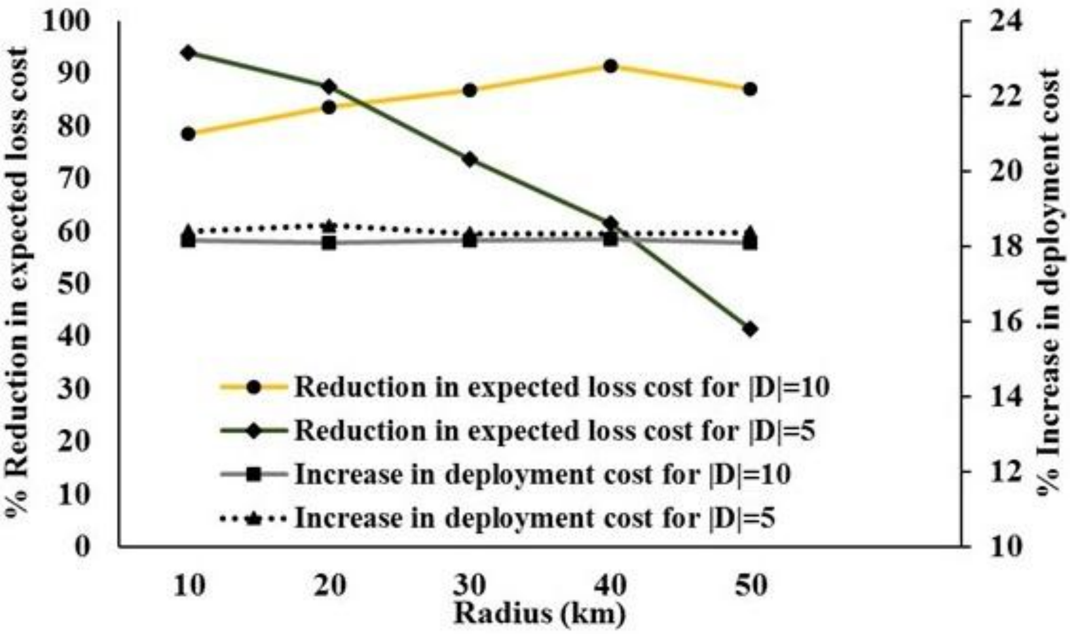

Figure 2.4 Radius size vs. costs.

2.3.3. Interval between minor axes

In Fig. 2.5 we present the results for different values of candidate paths, when we select them with minor axes 1 km, 2 km, 5 km, 10 km, or 20 km apart from each other.

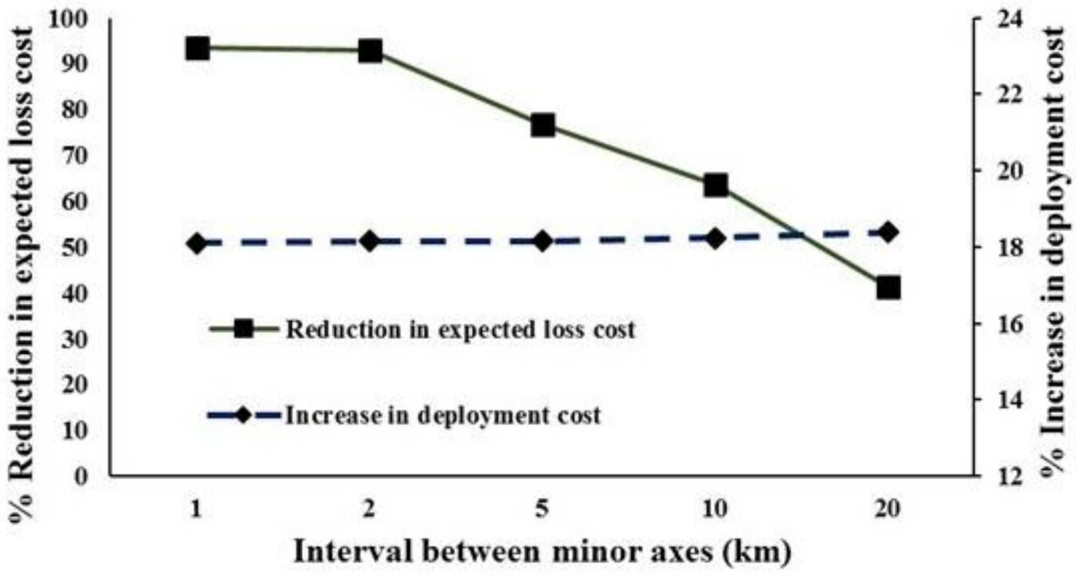

Figure 2.5 Reduction in expected cost and increase in deployment cost for different interval between minor axes.

The results show that we can improve the quality of the solution when the interval between candidate paths is small at the expense of execution time of the optimization, as indicated by Table 2.1. Because, when we have more candidate paths, it will increase the size of the problem as well as the number of potential solutions.

The execution times are shown in Table 2.1. When the interval is 1 km (which means that there are 120 candidate paths for each cable), it requires 1000 milliseconds to run vs. when the interval is 20 km (which means there are six candidate paths for each cable), it requires 15 milliseconds on a computer with an Intel i3 2.4 GHZ CPU, 4 GB DDR3 RAM, and 64 bit Microsoft Window 8.1 operating system.

Table 2.1. Interval Between Minor Axes vs. Execution Time

Interval between Minor Axes (km)	Execution time (msec)
1	1000
2	141
5	40
10	20
20	15

Figure 2.6 shows selected path for primary cable and path for backup cable, where the distance separating two landing stations is 20000 km.

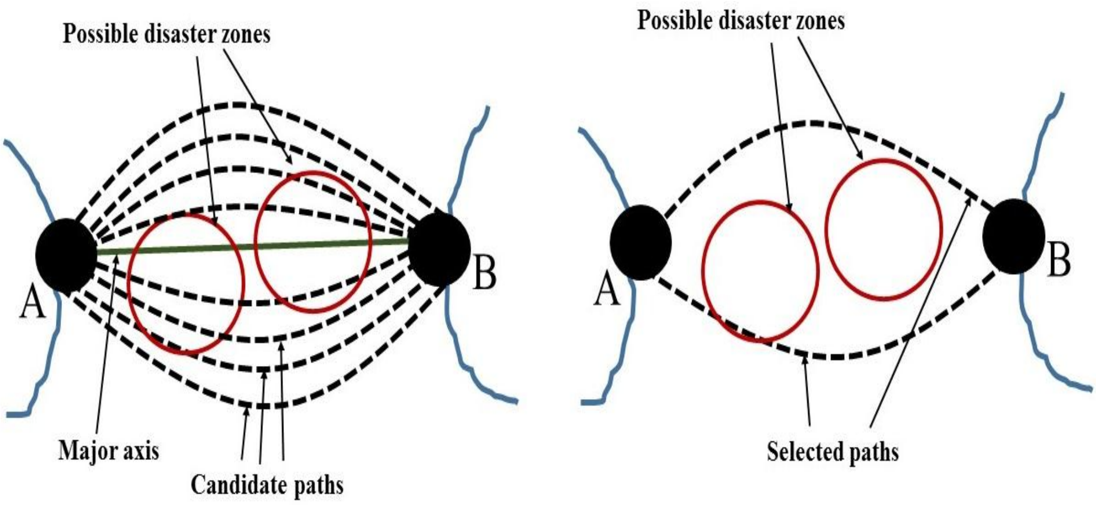

Figure 2.6 Actual path selected by our approach to connect two nodes.

2.4. Conclusion

In this chapter, we investigated the problem of minimizing expected cost incurred by submarine optical-fiber owners because of failures resulted by natural disasters. Expected cost is thought as the summation of expected cruising cost, expected reparation cost, and expected capacity loss cost. We apply survivable and disaster-aware submarine optical-fiber cable deployment approach to achieve this objective.

For simplicity we considered the problem of connecting a single pair of source and destination (SD) and elliptical cable shape. The two nodes are separated by water body that is susceptible to natural disasters such as earthquake, tsunami, and hurricane. Furthermore, we model the natural disaster as disc with a given radius wherein the epicenter of the natural disaster is at the center of the natural disaster. The challenge here to avoid deploying the cable in natural disaster zones by using optimal deployment budget.

We developed an Integer Linear Programming (ILP) formulation to address this problem and finally we presented numerical results that show the potential merits of our approach. Numerical results reveal that we can reduce expected cost significantly at the expense of a slight increase in deployment cost. Moreover, our approach reveals promising results when the distance of separation between the two nodes is very large, a practical advantage.

CHAPTER 3. SURVIVABLE AND DISASTER-AWARE SUBMARINE OPTICAL-FIBER CABLE DEPLOYMENT FOR MESH NETWORKS

3.1. Problem Description and Assumptions

In Chapter 2, we provided an Integer Linear Programming (ILP) formulation that provides an optimal solution to the problem of connecting two nodes using two cables of an elliptical shape. The ILP formulation provided in Chapter 2 does provide optimal solution, nevertheless, it is confined to elliptic shape of cables in a two-dimensional space. However, it should be designed in a three-dimensional space.

Practical experience shows that (i) geographical constraints such as roughness of seabed, undersea valleys, and sea depth are main determinants of shapes of the cables in a three-dimensional space, (ii) submarine optical-fiber cable systems consist of more than two nodes forming line, ring or mesh topology networks. Accordingly, we can achieve a solution of higher precision by taking into consideration these geographical information in our approach as well as network topology.

Consequently, our approach should incorporate both a three-dimensional space and multiple nodes. The determination of candidate irregular-shaped paths can be obtained through the use of commercial software such as Makai Plan [48], which gives the potential candidate paths with their irregular shapes in a three-dimensional space for each pair of communicating nodes as shown in Fig. 3.1.

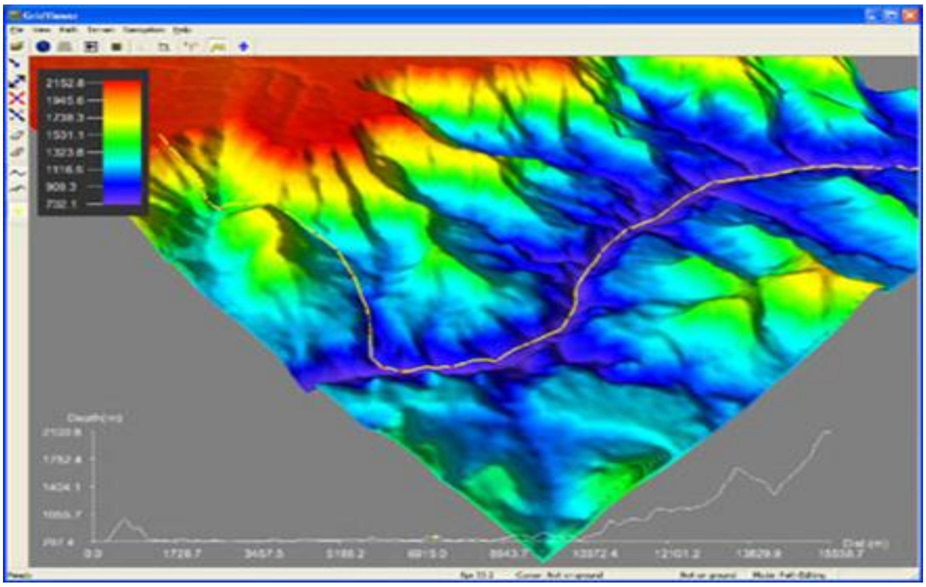

Figure 3.1 A possible cable path (a screenshot from Makai Digital Terrain Modeling Tools) [21].

Accordingly, in this chapter, we extend our approach wherein we consider the problem of connecting multiple nodes of a mesh network topology using irregular shapes of cables in three dimension space. We consider a mesh network topology $G\ (V, E)$ where V is the set of nodes and E is the set of links of heterogeneous bandwidth capacity denoted by N_e. The topology is thought of as optical-fiber cables connecting islands or continents. Additionally, each pair of adjacent nodes is connected by primary and backup cables of irregular shape. In this context, primary and backup cables must use different routes/paths in order to avoid simultaneous cable failures.

The water body separating communicating nodes is susceptible to predictable and non-predictable natural disasters. For each pair of communicating nodes there exists a set of possible candidates routes/paths that can used to deploy cables. These routes consider the topography of undersea environment as well as other geographical constraints. A sample mesh network topology with corresponding candidate cable paths as well as communicating nodes is shown below in Fig. 3.2.

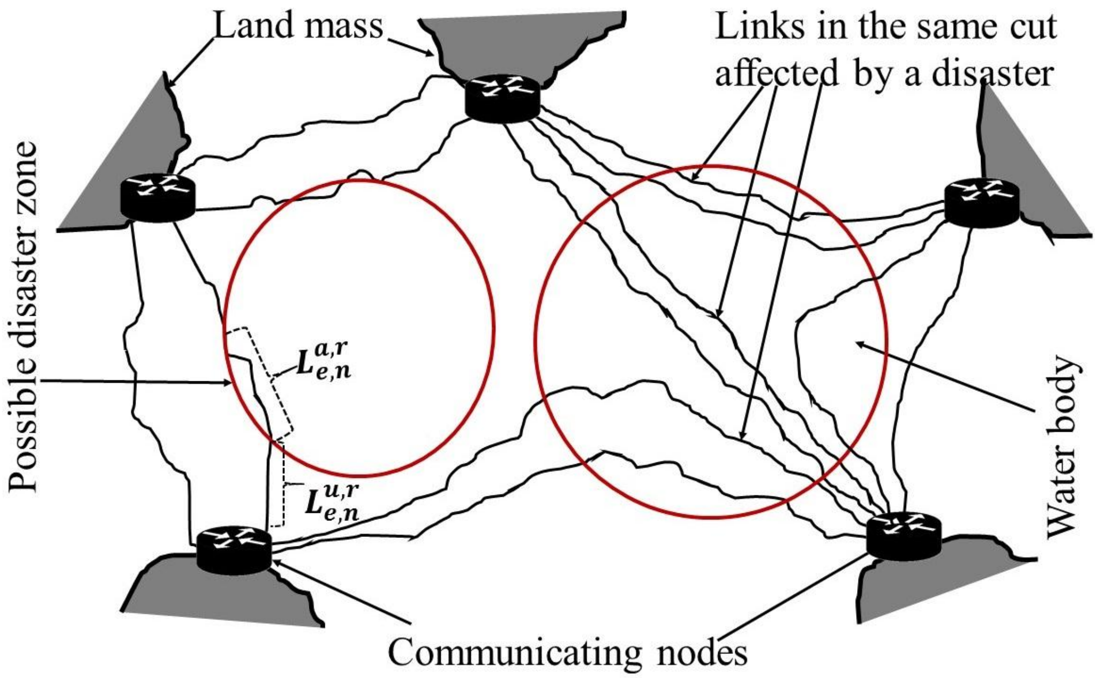

Figure 3.2 A sample mesh network topology.

3.2. Problem Formulation

Given:

a. *G (V, E)*: Mesh network topology where *V* is the set of nodes and *E* is the set of links that connect nodes. In this case, links in the network support heterogeneous bandwidth capacity denoted by N_e.

b. *i* = {*1, 2*}: Primary and backup cables which connect each pair of nodes in each link $e \in E$ such that: $i = \begin{cases} 1, \text{if it is a primary cable} \\ 0, \text{if it is a backup cable} \end{cases}$

c. Q_e {*1… r*}: Set of candidate routes for each link $e \in E$. which can be obtained by using intelligent software such as Makai Software [48]. These routes are of irregular shape considering the topography and geographical constraints of submarine environment. Thus $r \in Q_e$ for each link $e \in E$.

d. Ω {*1... n*}: Set of possible natural disasters characterized by their location and strength. The epicenter of a natural disaster is located at the center of the natural disaster $n \in \Omega$.

e. $P_e^{r,n} = \{1 \geq P_{e,i}^{r,n} \geq 0\}$: Probability such that, if natural disaster $n \in \Omega$ occurs, and route $r \in Q_e$ is selected in link $e \in E$ then cable i breaks. This probability depends on the distance of the cable from the natural disaster epicenter's and follows a certain given function, which decays as the distance of the cable from the epicenter increases [44] (e.g., following a Normal distribution).

f. $L_{e,n}^{a,r}$: Length damaged by natural disaster $n \in \Omega$, when route $r \in Q_e$ is selected in link $e \in E$. and r passes through n.

g. $L_{e,n}^{u,r}$: Cruising distance from offshore to the damaged part for each link $e \in E$, for each route $r \in Q_e$ and for each natural disaster $n \in \Omega$.

h. L_r: Length of router $r \in Q_e$ in km.

i. N_e: Bandwidth capacity of cables in link e.

j. T_e^r: Expectation of time to repair cable i in link $e \in E$.

k. C_d: Cost of cable deployment per km.

l. C_x: Cost of repair per km.

m. C_s: Shielding cost per km. In this context, shielding refers to burying cables underground, strengthening cables or providing additional protecting materials to resist physical attack from external aggressions.

n. C_t: Cruising cost per km.

o. C_p**:** Penalty per bandwidth, per unit time due to breach of service level agreement (SLA).

p. γ: Deployment and shielding budget.

q. δ: Acceptable minimum distance separating primary and backup cables further than 200 km from offshore. Note that, this distance marks the beginning of deep sea.

r. $X_e^{r,n}$: A pre-computed value such that its value is 1, if route $r \in Q_e$ selected for cable i of link $e \in E$, and the cable passes through natural disaster zone $n \in \Omega$.

s. $W_e^{r1,r2}$: Nearest distance in km, separating route of cable $i = 1$ *and* $i = 2$ in link $e \in E$.

t. E_k: Set of links in the same cut.

u. N_r: Set of natural disaster $N_r \in n$ that route $r \in Q_e$ passes through.

v. K: Set of network cuts.

Variable:

a. $R^{r}_{e,i}$: is a binary variable such that its value is 1 if route $r \in Q_e$ is selected for cable i in link $e \in E$ and it is 0, otherwise.

Objective Function:

The objective of this study is minimizing expected total expected cost which is a sum of expected repair cost, expected cruising cost and expected capacity loss cost of a network *G (V, E)* by considering occurrences of natural disasters.

a. Expected Repair Cost (ERC)

Natural disasters occurrence causes detrimental impact to submarine optical-fiber cables. This ranges from breaking cables to sweeping cables away. In this case, reparation activities involve cable re-deployment at the affected parts. Accordingly, we evaluate expected repair cost as the cost required to re-deploy the cable at the affected part. For each link $e \in E$ in a network. We compute this as the product of repair cost per unit length, distance damaged by natural disaster $n \in \Omega$, and the probability of cable failure.

$$\text{ERC} = \underbrace{\sum_{n \in \Omega} \left(\sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} C_x \times L^{r,a}_{e,n} \times R^{r}_{e,i} \right) \times P^{r,n}_{e}}_{\text{Expected repair cost}} \tag{3.1}$$

b. Expected Cruising Cost (ECC)

Reparation activities involve a round trip movement of a fleet from the nearest landing station to the affected part. This contributes huge cost to network operators and cable owners. Additional challenge in this context is legal and territorials' issues due to the fact that sometimes fleet operators have to seek permission before entering water body of another sovereignty. Occasionally, this takes long time, hence lead to delaying of reparation activities. Expected cruising cost in this context is evaluated as twice the product of cruising cost per unit length, cruising distance and the probability of cable failure.

$$\text{ECC} = \underbrace{\sum_{n \in \Omega} \left(\sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} 2 \times C_t \times R^{r}_{e,i} \times \left(L^{r,u}_{e,n} + L^{r,a}_{e,n} \right) \right) \times P^{r,n}_{e}}_{\textit{Expected cruising cost}} \tag{3.2}$$

c. Expected Capacity Loss Cost (ECL)

Network operators and their customers must come to an agreement before the commencement of service provision, this is commonly known as service level agreement (SLA). Normally service level agreement stipulates rights, responsibilities as well as penalty of either side. Failure of network infrastructures will definitely deny service to customers, consequently, network operators will be liable for penalty due to capacity loss. We evaluate expected capacity loss cost due to a natural disaster as the product of penalty cost, bandwidth capacity of a link, cable/link failure duration/time, and the probability that both cable $i = 1$ and $i = 2$ in link $e \in E$ fail/break due to occurrence of natural disaster $n \in \Omega$.

$$\text{ECL} = \underbrace{\sum_{n \Omega \in} \left(\sum_{e \in E} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} C_p \times N_e \times X^{r_1,n}_{e} \times X^{r_2,n}_{e} \times T^{r}_{e} \times R^{r_1}_{e,i} \times R^{r_2}_{e,i} \right) \times P^{r_1,n}_{e} \times P^{r_2,n}_{e}}_{\text{Expected loss penalty}} \tag{3.3}$$

Note that equation (3.3) is non-linear since we have two binary variables. We can linearize it, by introducing an auxiliary variable $S^{r1,r2}_{e}$ such that:

$$S^{r1,r2}_{e} = R^{r1}_{e,1} \times R^{r2}_{e,2} \qquad \forall e \in E,\ \forall r_1 \in Q_e, \forall r_2 \in Q_e,\ r_1 \neq r_2 \tag{3.4}$$

Subject to the following constraints:

$$S^{r1,r2}_{e} \leq R^{r1}_{e,1} \qquad \forall e \in E,\ \forall r_1 \in Q_e, \forall r_2 \in Q_e,\ r_1 \neq r_2 \tag{3.5}$$

$$S^{r1,r2}_{e} \leq R^{r2}_{e,2} \qquad \forall e \in E,\ \forall r_1 \in Q_e, \forall r_2 \in Q_e,\ r_1 \neq r_2 \tag{3.6}$$

$$S^{r1,r2}_{e} \geq R^{r1}_{e,1} + R^{r2}_{e,2} - 1 \qquad \forall e \in E,\ \forall r_1 \in Q_e, \forall r_2 \in Q_e,\ r_1 \neq r_2 \tag{3.7}$$

Thus expected capacity loss cost is given as:

$$\text{ECL} = \underbrace{\sum_{n\Omega\in}\left(\sum_{e\in E}\sum_{i\in\{1,2\}}\sum_{r\in Q_e} C_p \times N_e \times X_e^{r_1,n} \times X_e^{r_2,n} \times T_e^{r} \times S_e^{r_1,r_2}\right) \times P_e^{r_1,n} P_e^{r_2,n}}_{\text{Expected Capacity loss cost}} \qquad (3.8)$$

Accordingly, the objective function is the summation of expected cruising cost, expected reparation cost and expected capacity loss cost as follows:

$$\min \, (ERC + ECC + ECL) \qquad (3.9)$$

Constraints:

a. Deployment and Shielding Budget Constraint:

Deployment and shielding cost must not exceed budget setup (γ). Recall that our approach may select a route which passes through a candidate natural disaster zone given the fact it provides minimum expected total cost. In this case, this part will be vulnerable. Zhang *et al.* [16] investigates the minimum cost of shielding a network to guarantee connectivity subject to human activities or natural disasters such hurricanes, earthquakes, and tsunami, wherein they propose shielding vulnerable parts of the link or path. Since shielding the whole submarine optical-fiber cable system is not cost effective, our approach guarantees connectivity at a minimum cost by shielding parts of submarine optical-fiber cables that pass through candidate natural disaster zones ($L_{i,j}^{a,n}$). It follows that, deployment cost constraint is as follows.

$$\sum_{e\,\in E}\sum_{i\,\in\{1,2\}}\sum_{r\,\in Q_e}\left[\left(C_d \times N_e \times L_r \times R_{e,i}^{r}\right) + \sum_{n\,\in\,N_r}\left(C_s \times L_{e,n}^{r,a} \times R_{e,i}^{r}\right)\right] \leq \gamma \qquad (3.10)$$

Note that, whereas the first term provides deployment cost, the second term gives shielding cost of a given route.

b. Route Uniqueness Constraint:

If primary and backup cable take the same route, a simultaneous cable failure can occur in case that route passes through a natural disaster zone. In order to avoid simultaneous cable failures, we ensure that primary and backup cables take different routes.

$$\sum_{r \in Q_e} R^{r}_{e,i} = 1 \qquad \forall i;\ i \geq 1,\ \forall e \in E \tag{3.11}$$

c. Route Disjoint Constraint:

Simultaneous cable failures can occur if the routes of the primary and backup cable at any point and the point falls within the same natural disaster zone. In order to avoid routes intersection at any point, we provide the following constraint.

$$w_e^{r_1,r_2} \times S_e^{r_1,r_2} \geq \delta \qquad \forall e \in E,\ \forall r_1 \in Q_e,\ \forall r_2 \in Q_e,\ r_1 \neq r_2 \tag{3.12}$$

d. Network Connectivity Constraint:

Connectivity concept has been widely studied in virtual network design [49]. Ideally, the goal is to ensure that a physical link failure does not cause failures of virtual links in the same network cut as shown in Fig. 3.3.

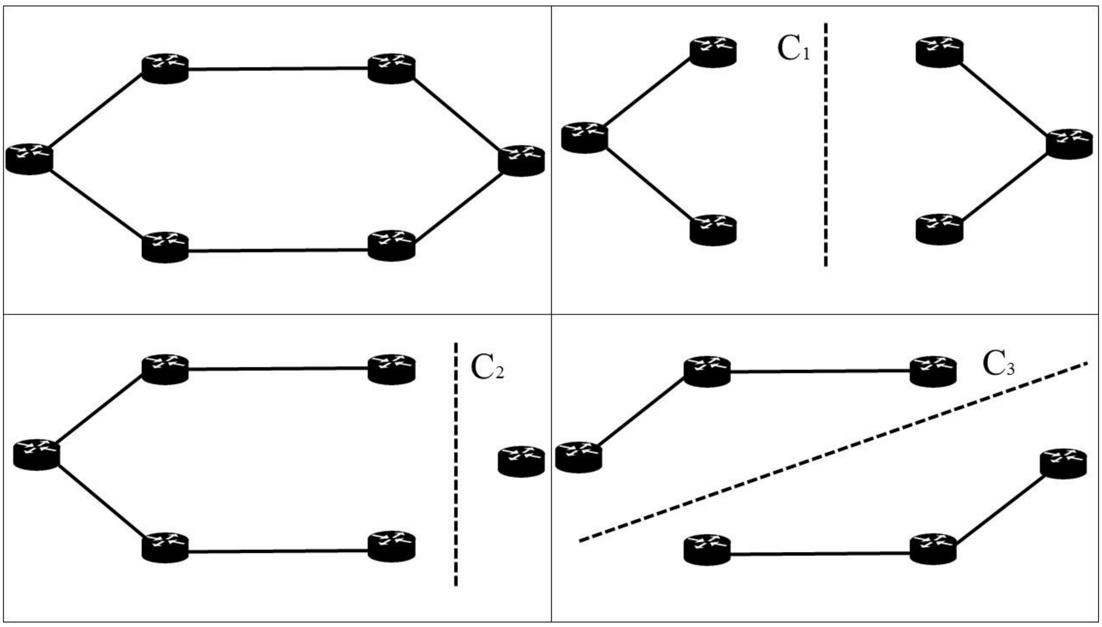

Figure 3.3 Possible network cuts.

In order to ensure network connectivity, we ensure that links that are in the same cut should not go through the same natural disaster zone. Otherwise, when a natural disaster occurs, it may break all the cables whose associated links are in the same cut and so the topology would be disconnected.

$$\sum_{e \in E_c} \sum_{i \in \{1,2\}} \sum_{r \in Q_e} X_{e,i}^{r;n} \times R_{e,i}^{r} < 2|E_k| \qquad \forall k \in K,\ \forall n \in \Omega \tag{3.13}$$

e. Constraints Due to Linearization:

Recall that in eqn. (3.3), multiplication of two binary variables make it non-linear. We linearize this equation by introducing auxiliary binary variable which requires the following constraints.

$$S_e^{r1,r2} \leq R_{e,1}^{r1} \qquad \forall e \in E,\ \forall r_1 \in Q_e, \forall r_2 \in Q_e,\ r_1 \neq r_2 \tag{3.14}$$

$$S_e^{r1,r2} \leq R_{e,2}^{r2} \qquad \forall e \in E,\ \forall r_1 \in Q_e, \forall r_2 \in Q_e,\ r_1 \neq r_2 \tag{3.15}$$

$$S_e^{r1,r2} \geq R_{e,1}^{r1} + R_{e,2}^{r2} - 1 \qquad \forall e \in E,\ \forall r_1 \in Q_e, \forall r_2 \in Q_e,\ r_1 \neq r_2 \tag{3.16}$$

The number of variables will be $|E| \times (I \times R + R^2)$ and the number of constraints will be $3|E|(I + R^2) + 1 + K \times |\Omega|$, where K is the number of cuts.

3.3. Illustrative Numerical Examples

We present numerical examples to evaluate our approach on mesh networks for different dimension of network clustering coefficient (0.05, 0.15, 0.25, 0.35,0.45, 0.55, 0.65, 0.75, 0.85, 0.95, and 1), irregular cable shapes, and different number of routes for each link (15, 25, 35, and 45). We generate random natural disasters of different radii (10 km, 20 km, 30 km, 40 km, 50 km, 60 km, 70 km, 80 km, 90 km, 100 km, 110 km, 120 km and 130 km). The probability of cable failure depends on the distance of the cable from the natural disaster epicenter's and follows a normal distribution which decays as the distance of the cable from the epicenter increases.

Likewise, all parameters used in our simulation are determined by information from public sources such as [45] and [46]. These parameters are normalized as follows:

deployment cost per km is normalized to 1, cruising cost per km is normalized to 0.4, and repair cost per km is normalized to 0.6. Mean time to repair is normalized to 1, penalty due to capacity loss is 100 per Tbps and each link assumes heterogeneous bandwidth capacity, whereby capacity of each link is uniformly distributed between 10 and 100 Tbps. Apart from that, we assume that the maximum distance of cable separation is 110 km, because this distance is sufficient to achieve a solution of higher precision, i. e., separating two cables more than 110 km would not benefit to avoid natural disasters.

The measure of clique of a network is termed as clustering coefficient [50]. In this study we investigate the results of our study by using ten scenarios with variable clustering coefficients. In each scenario we generate random natural disasters of variable radius size, candidate routes for each pair of landing stations, and a random topology of nodes with variable clustering coefficients. Moreover, we rerun our simulations 50 times on a computer with an Intel i3 2.4 GHZ CPU, 4 GB DDR3 RAM, and 64 bit Microsoft Window 8.1 operating system for each parameter set values and the results presented below are average of the results obtained with 95% confidence interval. Eventually, we compare our approach with a disaster-unaware using two key performance metrics of this study viz.: (i) reduction in expected cost (expected cost of repair, cost of cruising to the cable break location, and penalty due to bandwidth loss) and (ii) increase in deployment cost.

3.3.1. Clustering coefficient vs. costs

We evaluate the performance of our approach by considering different dimensions of clustering coefficient as shown in Fig. 3.4. Results in Fig 3.4 show that our approach reduces expected cost from 90% to 100% compared to disaster-unaware approach which reduces 0% to 10% of expected cost. Furthermore, there is an increase in deployment cost for both disaster-aware and disaster-unaware approaches as the clustering coefficient increases, because of an increase in number of links to be deployed.

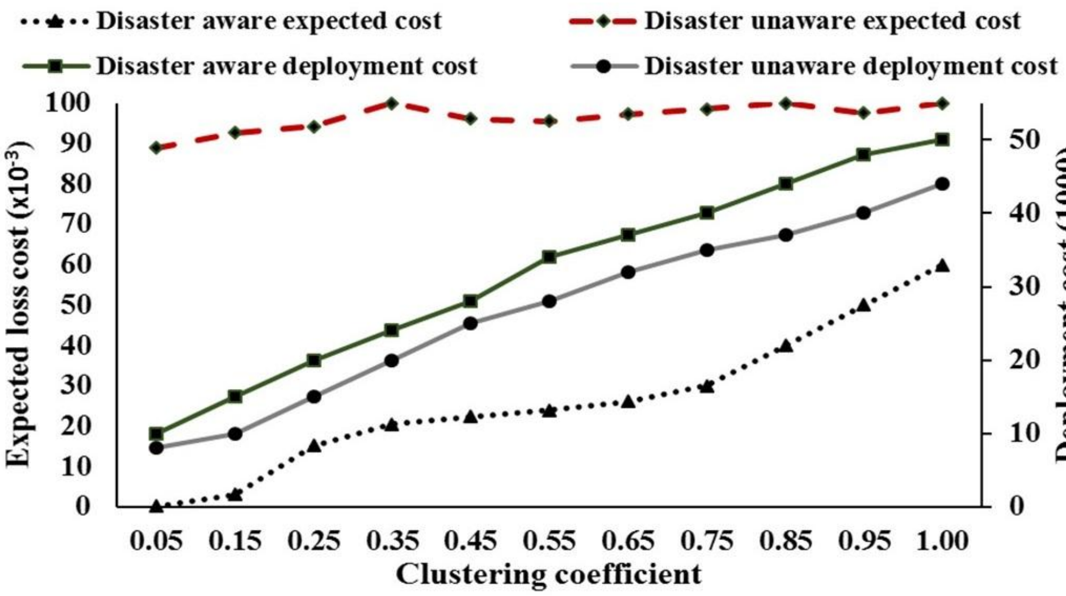

Figure 3.4 Clustering coefficient vs. Costs.

Figure 3.4 shows that expected cost for survivable and disaster-aware approach increases as clustering coefficient increases, because when there are more links in a network it is difficult to avoid all natural disaster zones. Apart from that, results in Fig. 3.4 show that, there is an increase of about 10% in deployment cost considering survivable and disaster-aware approach, which is attributed by long routes necessary to avoid deploying cables in natural disaster zones.

3.3.2. Radius size vs. costs

We evaluate our approach using varying dimension of radii of natural disaster zones as shown in Fig. 3.5. Results in Fig. 3.5 show that our approach reduces 90% to 100% of expected cost compared to disaster-unaware approach which reduces 0% to 10% of expected cost.

The increase in deployment cost for our approach is proportional to the increase in size of radii of natural disaster zones due to the fact that when a natural disaster zone is very large it is possible to avoid deploying a cable in natural disaster zone by using a long route which in-turn attracts increase in deployment cost.

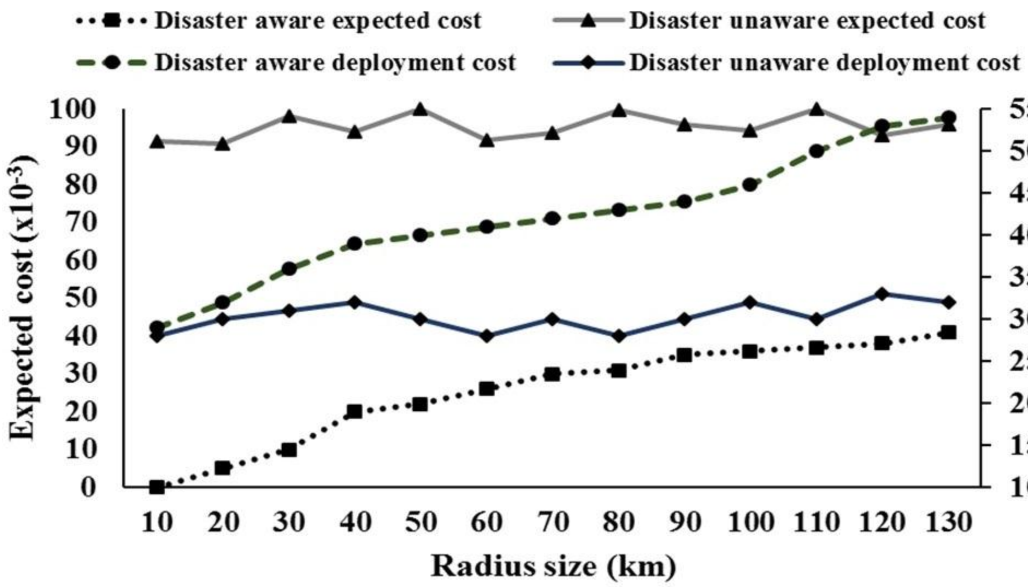

Figure 3.5 Radius size vs. Costs.

3.3.3. Clustering coefficient vs. execution time

We evaluate the execution time of our approach for varying dimensions of clustering coefficient as shown in Fig. 3.6. Results show that, execution time increases as clustering coefficient increases. For instance from 13 sec when clustering coefficient is 0.05 vs 995 sec when clustering coefficient is 1 on a computer with an Intel i3 2.4 GHZ CPU, 4 GB DDR3 RAM, and 64 bit Microsoft Window 8.1 operating system, mainly due to the increase in number of links in a network.

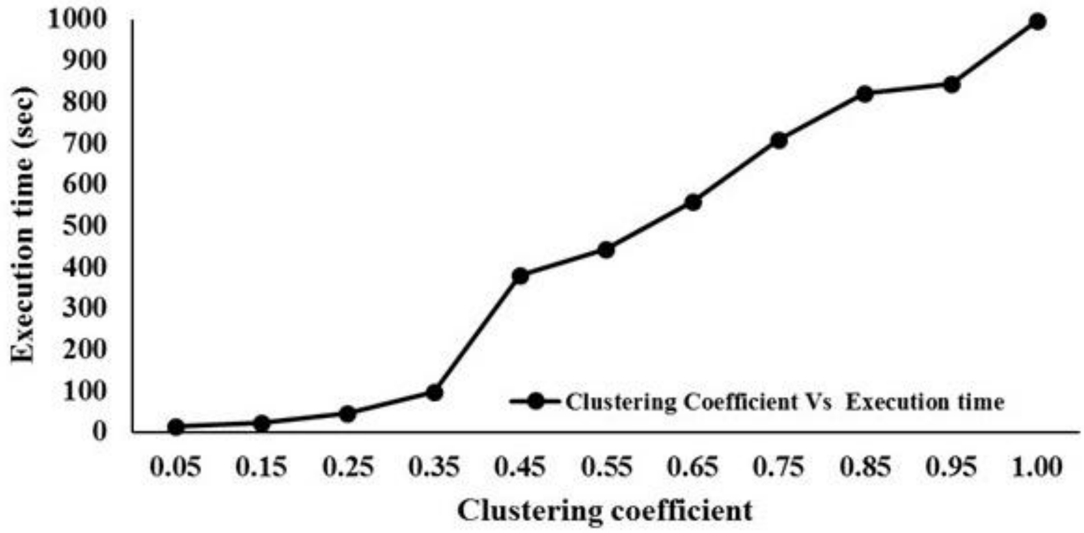

Figure 3.6 Clustering coefficient vs. Execution time.

3.3.4. Number of routes vs. costs

In this case we investigate the effects of number of candidate routes to the problem, by considering varying number of candidate routes as shown in Fig. 3.7. Similarly, survivable and disaster-aware approach reduces expected cost by 90% to 100% compared to disaster-unaware which reduces about 0% to 5% of expected cost. Figure 3.7 also shows that, deployment cost decreases as the number of candidate route increases because when the number of routes is very small we have limited number of candidate routes. Additionally, Fig. 3.7 shows that, as the number of routes increases the value of disaster-aware expected cost decreases due to the fact that there is more candidate routes to achieve a solution of higher precision.

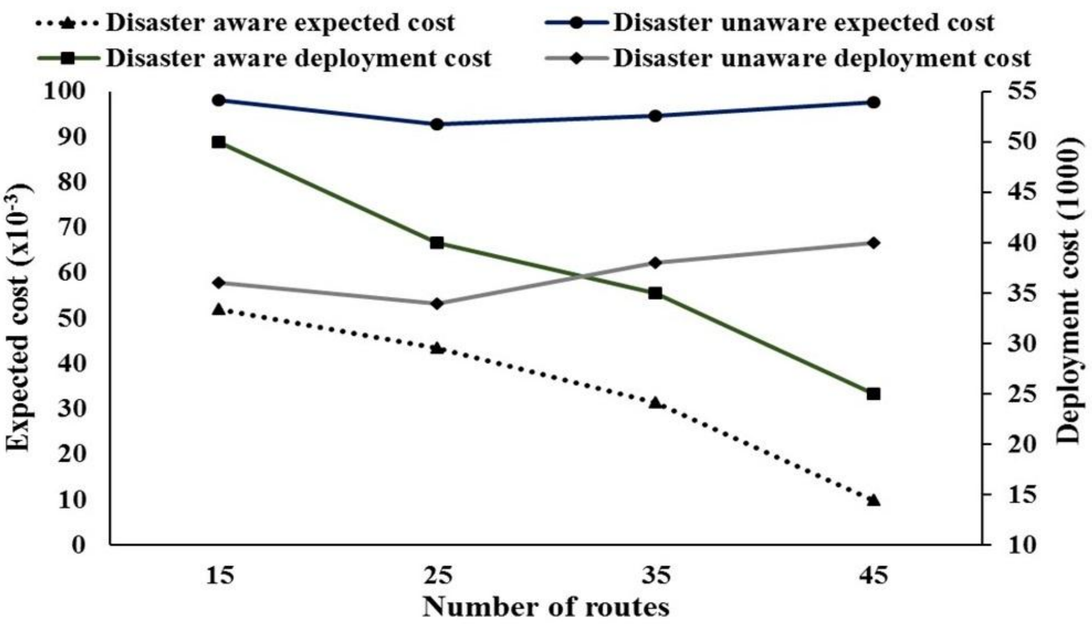

Figure 3.7 Number of routes vs. Costs.

Figure 3.8 shows selected routes for primary and backup cable deployment and it can be seen that our approach minimize expected cost by deploying cables in disaster free zones.

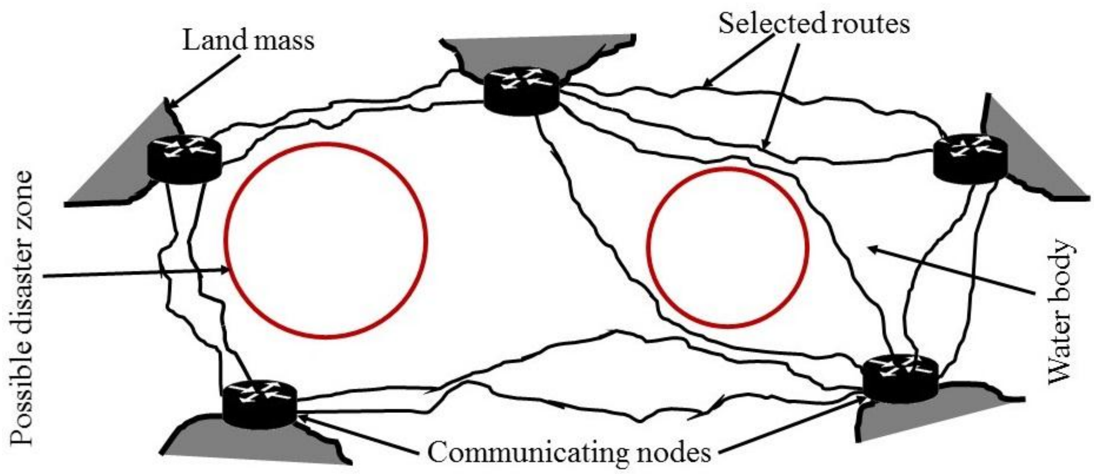

Figure 3.8 Actual path selected by our approach to connect mesh network.

3.4. A Case Study

We conduct a case study in order to evaluate practical applicability of our approach by considering MedNautilus submarine optical-fiber cable system [8] shown in Fig. 3.9. This system has the total length of 7000km and it connects seven landing stations viz: Athens (Greece), Catania (Italy), Chania (Greece), Haifa (Israel), Istanbul (Turkey), Pentaskhinos (Cyprus), and Tel Aviv (Israel).

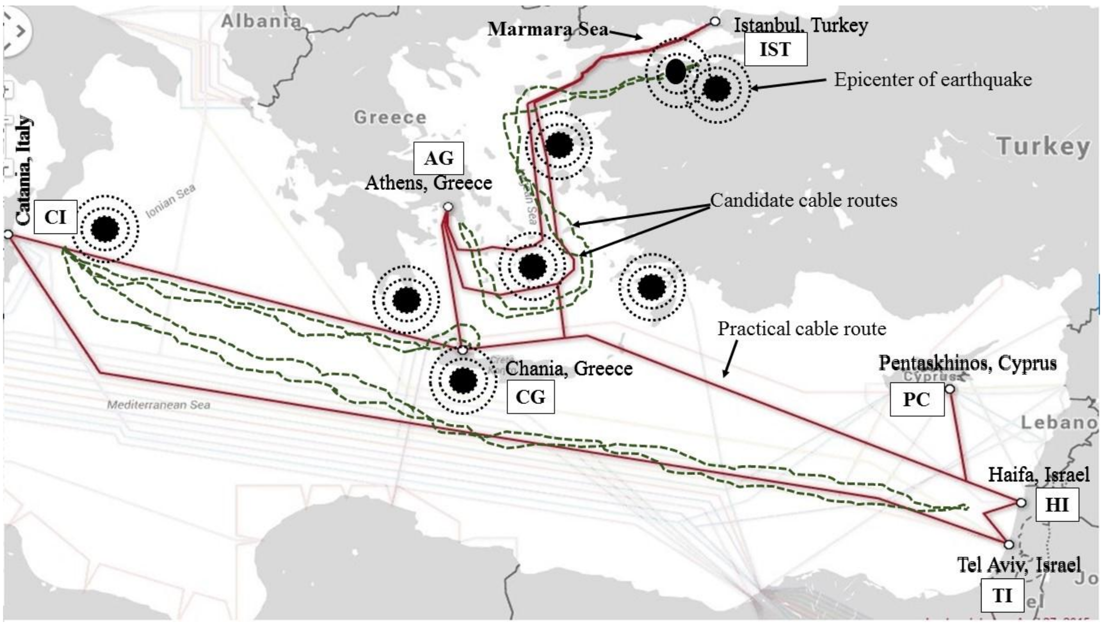

Figure 3.9 MedNautilus cable system found in Mediterranean basin.

Mediterranean Sea is susceptible to a number of natural disasters such as earthquakes and tsunamis that have caused huge damages to submarine optical-fiber infrastructure and killed thousands of people. Natural disaster zones shown in Fig. 3.9 by the dotted cycles are natural disasters occurred previously in this region according to seismic hazard map. Nevertheless, this region is vital for connecting Eastern Mediterranean countries, Western Europe, Northern Africa and Asia. According to the submarine cable interactive map [8], currently about 13 submarine optical-fiber cable systems pass through Mediterranean region.

In this framework, we evaluate our approach by using 25 routes for each link, then we report results for expected and deployment cost of each link as shown in Fig. 3.10. Results from Fig. 3.10 show that our approach reduces expected cost by 90% to 100% compared to disaster-unaware approach which reduces 0% to 10% at the expense of about 10% increase in deployment cost in our approach which is attributed by avoiding cable deployment in natural disaster zones.

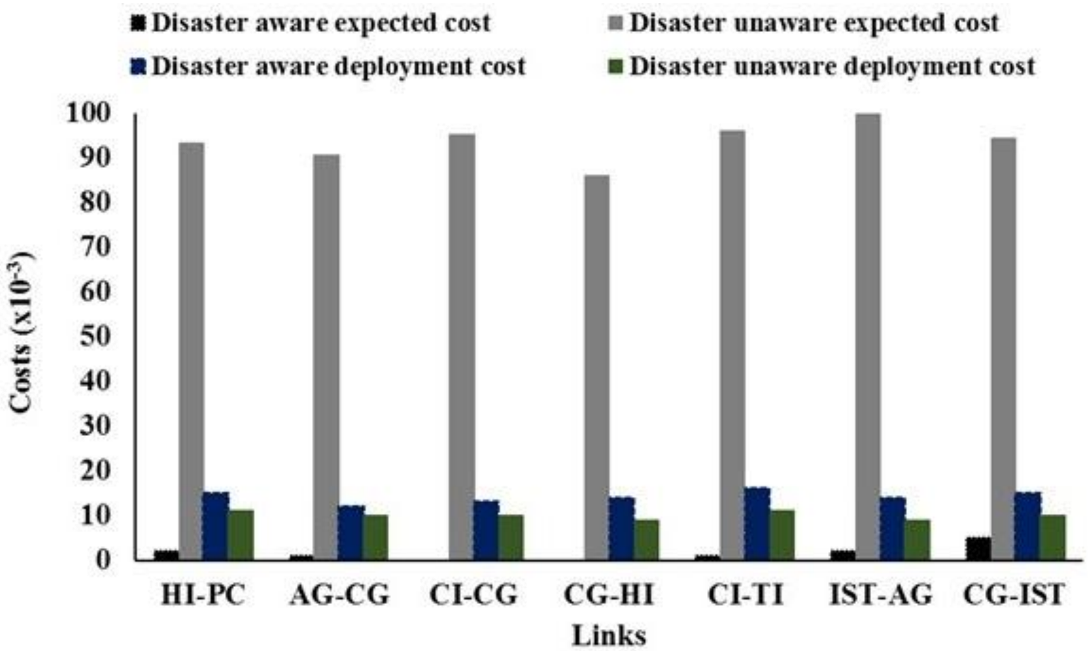

Figure 3.10 Disaster Aware vs. Disaster Unaware Expected Loss Costs of MedNautilus submarine optical-fiber cable system.

Figure 3.10 also shows that, link CI-TI, records higher value in terms of deployment cost because the distance separating the two landing stations is very long. Apart from that, Fig 3.10 shows that, link CG-HI has low expected cost because it is susceptible to less natural disasters compared to other links. There is fluctuation in expected cost as shown in Fig 3.10, which is attributed by the location of landing stations as well as the location of epicenters of natural disasters. For instance, link IST-AG, records about 99% of expected cost to the case of disaster-unaware approach due to the fact that this location is susceptible to a number of natural disasters and the width of Marmara Sea is very narrow to the extent that it is practically impossible to avoid deploying the cable in natural disaster zone. Nevertheless, our approach minimizes this effect by deploying the cable in zones with less effect, considering the fact that we model natural disasters by using probabilistic model.

We extend our case study by considering particular natural disasters that have occurred in deep sea and cause detrimental impact to submarine optical-fiber cables since the aim of this study is to address submarine optical-fiber cable failures resulted by natural disasters in deep sea. In this case we consider natural disasters which have occurred in deep sea of Mediterranean Sea. Figure 3.11 shows natural disasters that have occurred in deep sea of Mediterranean Sea.

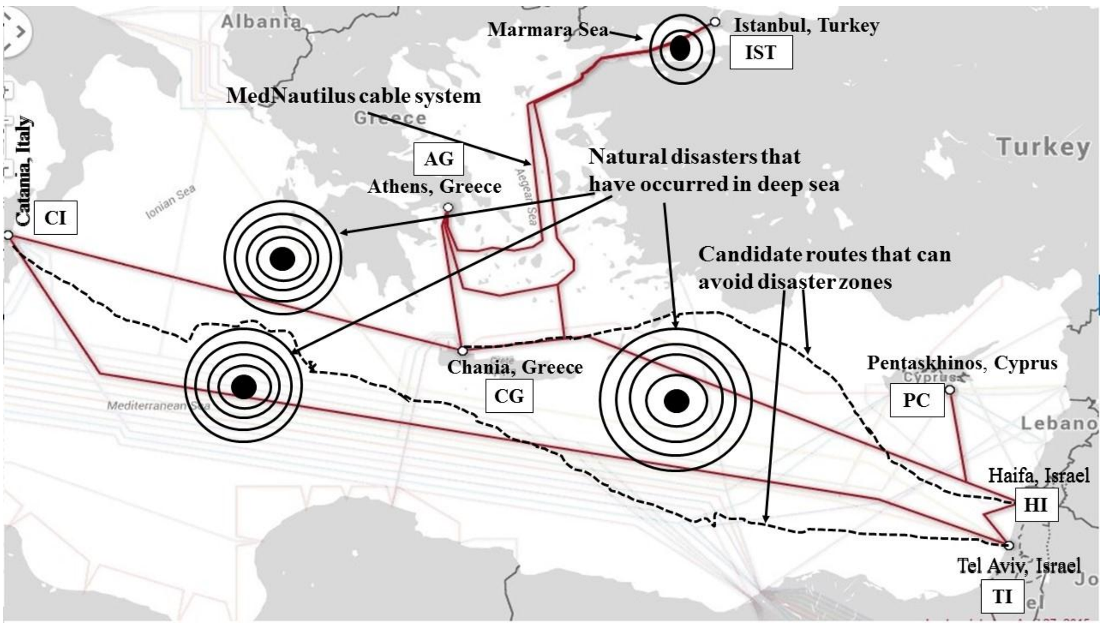

Figure 3.11 Natural disasters that have occurred in deep sea along Mediterranean Sea where MedNautilus submarine optical-fiber cable system pass through.

We apply our approach to these natural disasters and in particular we consider four links that goes through these natural disasters. Links of consideration in this framework are link CI-CG, CG-HI, CI-TI and IST-AG. Using our approach the expected cost of this system can be reduced significantly (i) by providing protection (backup cable) for each link and (ii) by avoiding deploying cable in natural disaster prone areas as shown in Fig. 3.11.

Figure 3.12 depicts the results for these links in terms of expected cost and deployment cost for each link. Results in Fig 3.12 show that our approach reduces expected cost significantly from 95% to 100% compared to disaster-unaware approach that reduces expected cost from 0% to 10%. Similarly, there is about 5% increase in deployment cost to the case of disaster-aware approach which is attributed by long routes taken in order to avoid deploying submarine optical-fiber cables in natural disaster zones.

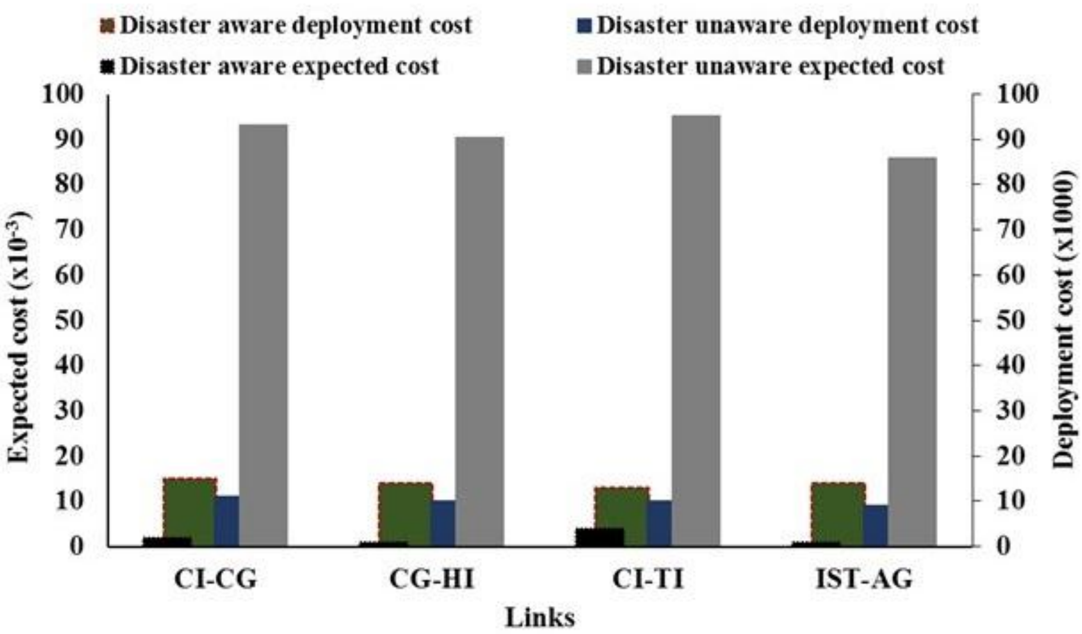

Figure 3.12 Disaster Aware vs. Disaster Unaware Expected Loss Costs of MedNautilus submarine optical-fiber cable system for natural disasters that have occurred in deep sea alongside Mediterranean Sea where MedNautilus submarine optical-fiber cable system pass through.

Apart from that, Fig. 3.12 shows that, link CI-TI records high value in terms of expected cost using disaster-unaware approach (about 99%) because this link is prone to two natural disasters that are located in deep sea, accordingly, this attributes to long reparation time as well as high reparation cost. Additionally, this link records high deployment cost because the distance separating the two landing station is very long as shown in Fig. 3.12.

3.5. Conclusion

In this chapter, we investigated the problem of minimizing expected cost incurred by submarine optical-fiber mesh network owners because of cable break/failure in deep sea. Expected cost is the summation of expected cruising cost, expected reparation cost, and expected capacity loss cost. We apply survivable and disaster-aware submarine optical-fiber cable deployment approach to achieve this objective.

We considered a mesh network with arbitrary number of nodes and links. In this context the nodes are separated by water body that is susceptible to natural disasters such as earthquake, tsunami, hurricane etc. Moreover, we modelled natural disasters as disc with a given radius wherein the epicenter of a natural disaster is at the center of the natural disaster. The challenge here to avoid deploying the cables in natural disaster zones by using optimal deployment budget.

We provided an Integer Linear Programming formulation to address this problem supported by illustrative numerical examples. Accordingly, we learn from the results that our approach reduces expected cost significantly at the expense of a slight increase in deployment cost. We extended our study by conducting a case study, wherein we apply our approach to a practical submarine optical-fiber cable system which is susceptible to a number of natural disasters in deep sea. Once again numerical results in this case reveal that our approach perform better for any clustering coefficient. In a nutshell, our approach shows promising results compared to disaster-unaware approach.

CHAPTER 4. CONCLUSION AND FUTURE WORKS

In this thesis, we investigated the problem of survivable and disaster-aware submarine optical-fiber cable deployment. We investigated the problem of minimizing expected cost incurred by submarine optical-fiber owners because of failures resulted by natural disasters. The expected cost in this context is the summation of expected cruising cost to visit and repair affected part of the cable, expected reparation cost to repair affected part of the cable, and expected capacity cost due to breach of service level agreement (SLA).

The challenge here is minimizing expected cost by avoiding deploying cables in natural disaster zones using optimal deployment budget. Apart from deployment budget constraint, other constraints include: route uniqueness, regular protection, route disjoint, and connectivity constraints. In order to address this problem, we provided a survivable and disaster-aware submarine optical-fiber cable deployment approach. The novelty of our work is to determine the expected cost to be incurred by submarine optical-fiber cable owner for each route used for cable deployment in case a natural disaster occurs. We bifurcate this problem into a simplified problem where we consider connecting a pair of two nodes and the enhanced problem wherein we consider connecting a mesh network as described below.

4.1. Survivable and Disaster-Aware Submarine Optical-Fiber Cable Deployment for Point to Point Communication

In the first case, we considered the simplified problem of connecting a single pair of source and destination nodes and elliptical cable shape. The two nodes are separated by water body that is susceptible to natural disasters such as earthquake, tsunami, hurricane etc. We modelled natural disasters as disc with a given radius wherein the epicenter of a natural disaster is at the center of a natural disaster. Eventually, we developed a solution for this problem supported by illustrative numerical results which show the potential merits of our approach.

4.2. Survivable and Disaster-Aware Submarine Optical-Fiber Cable Deployment for Mesh Networks

We extended our study by considering practical assumptions to address the enhanced problem of connecting submarine optical-fiber cable for mesh networks. Practical experience reveals that (i) geographical constraints such as roughness of seabed, undersea valleys, and sea depth, are main determinants of shapes of the cables in a three-dimensional space, (ii) submarine optical-fiber cable systems consist of more than two nodes forming line, ring or mesh topology networks. Accordingly, in this case, we investigated the problem of minimizing expected cost incurred by submarine optical-fiber mesh network owners because of cable break/failure in deep sea resulted by natural disasters. In this case we apply survivable and disaster-aware submarine optical-fiber cable deployment for mesh network approach in order to achieve this objective. We considered a mesh network with arbitrary number of nodes and links, whereby, communicating nodes are separated by water body that is susceptible to natural disasters such as earthquake, tsunami, and hurricane. Moreover, we modelled natural disasters as disc with a given radius, and the epicenter of a natural disaster is assumed to be at the center of a natural disaster. Moreover, we provided a solution for this problem supported by illustrative numerical examples. Finally, we conducted a case study, wherein we applied our approach to a practical submarine optical-fiber cable system found in Mediterranean Sea in order to evaluate the practical advantage of our approach. In a nutshell, numerical results from this case study show the potential merits of our study.

In this study we provided a solution to the problem of minimizing expected cost incurred by submarine optical-fiber network operators. Practical experience shows that submarine optical-fiber cable failures cause a significant economic loss to network operators, service providers and subscribers whose services are interrupted. Mitigating this cost simultaneously would require consideration of the global economic loss of the related parties, which in turn will increase the complexity of the problem because of the increase in number of parameters. Considering the fact that, consumers of this research are cable deployment companies and network operators we provide a solution that consider loss of network operators. Nevertheless, this study provides a benchmark for other studies that may consider a global economic loss of all the related parties. The followimg is the publication which is the building block of this thesis: D. L. Msongaleli, F. Dikbiyik, M. Zukerman and B. Mukherjee, "Disaster-Aware Submarine Fiber-Optic Cable Deployment", *IEEE International Conference on Optical Network Design and Modeling (ONDM)*, May 2015, Pisa, Italy.

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RESUME

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