Cornerstone of global communication: Vulnerabilities of submarine telecommunication cable from networks

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Declaration

I, Zhiheng Jiang, hereby declare that this dissertation is all my own original work and that all sources have been acknowledged. It is 10968 words in length.

Accompanying GitHub repository: https://github.com/Hypergear/UCL_Dissertation

Contents

Abstract

With the rise of global internet connectivity and the increasing availability of inexpensive computer devices. The submarine telecommunication cables (STC) play as the backbone infrastructure to provide the data traffic in the case of international information transmission. However, STC is extremely vulnerable to damages such as natural disasters and human-led attacks. If the damage is taken, the bandwidth deterioration or lagging of the internet services will occur on end-users' computers. At the core of this paper is a modelling analysis of the global STC under a topological network structure to determine the subregional high risk area. As the result, 88 STC vulnerable countries and an uneven distribution of network dependency can be located. For a regional STC network system, we proposed a method to improve and analyze its topological robustness. These findings may provide some inspiration to the industry and politicians by revisiting the reliability and vulnerabilities of the STC system under the current protection measurements.

Keywords: Internet, Telecommunication, Marine infrastructure, Network science.

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This work has also gained vast support from the a various opensource communities, regardless of open datasets from TeleGeography or python packages such as NetworkX. Also the useful studies from the research community. Their humble work makes this research possible.

I am also grateful for the support from my parents and my corgi - Julie, who have continuously motivated me throughout this study.

Acronyms

There are some frequent used acronyms for certain items/technologies.

STC – Submarine telecommunication cable
TTC – Terrestrial telecommunication cable
CLS – Cable landing station
CDN – Content delivery network
CIP – Critical infrastructure protection
ISP – Internet services provider

Jargon

If you are new to telecommunication industry, learning these jargons before proceeding is highly recommended

Bandwidth – The maximum amount of data transmitted over an internet connection in a given amount of time

Routing – A process of path selection while transferring data across multiple network systems.

Capacity – Default referring to potential capacity, the total amount of design capacity that installed all available equipment at the ends of the cable.

Lit capacity – The amount of capacity that is actually running over a cable.

List of Figures

List of Tables

Chapter 1

Introduction

Motivated by the progress of information technology on mobile devices combined with the rise of the 5G technology and cloud computing services, the demand for higher stand internet services can be foreseen. The world needs a medium to transmit a large amount of data inexpensively more than ever. As the *highway* of data communication, the optic fibre is the most common tool for wired long-distance data communication.(Kangovi 2017) There are two types of state level fiber optic cables: fibre optic terrestrial telecommunication cable(TTC) and fibre optic submarine telecommunication cable(STC). In terms of useability, the latter gains a bigger market share. (G. Marra et al. 2018) Nowadays, STC is responsible for more than 98% of global internet transmission, reaching approximately more than 1 200 000 km globally.(Winseck 2017; Q. Wang et al. 2019) In some terms, any internet service depends on STC's functional working, in fields such as academia, education, entertainment, finance, health care, and the military.

STC is already a irreplaceable resources in all aspects of people's daily life, the failure could cause a significant negative impact on the social and economic disruptions in a community or society. The failure of an STC might not disrupt access to the worldwide internet, as the nature of the internet routing topology, (Calvert, Doar, and E.W. Zegura 1997) suggested that the connection can still be obtained by a longer and less stable connection. (Turner et al. 2010). However, this is not true for all countries. In 2008 a dragging ship anchor damaged one or more STCs in the Mediterranean which subsequently caused 50% to 100% of internet service interruptions across the middle-east area. (Zetter 2008) More recently, in 2022 the volcano eruption in Tonga caused the failure of Tonga's only STC, which subsequently led to an internet blackout with the rest of the world for nearly five weeks. (Bateman 2022) Due to the commercial interest and limited internet usage, usually less developed countries and remote islands such as Chile or the Marshall island do not have an alternative STC for redundancy. (Dominey-Howes 2022) Obviously, these countries are more dependent and suffer more losses if the STC breaks down.

Even though STC is a world spread infrastructure, there are still four billion people who do not have access to the internet. Satellite internet, on the other hand, can be used to replace the STC by using a group of non-synchronous orbit satellites. (Graydon and Parks 2019) These satellites rotate around the earth obit, providing wireless internet connection to the customer near the earth's surface. If the satellite is located in geostationary earth orbit, the user will suffer from high latency and limited bandwidth. Again, they acquires hundreds of thousands of satellites to provide worldwide coverage which gives higher standards on the internet services provider(ISP). (Deutschmann et al. 2021) Regardless, satellite internet services always have higher requirements on the user budget than STC, as the professional technical devices and expensive data packages need to be pre-purchased before usage. (starlink 2022)

The rest of paper is organized as follows. Firstly, in Section 2, the vulnerability, legal protections and consequences of STC breakdown are introduced in details. Then, the related datasets and data pre-process are provided in Section 3. After that, the analysis procedures including a local STC optimization approach are given in Section 4 and 5. Finally, Section 6 and 7 give the discussion and conclusions.

Chapter 2

Literature Review

The United Nations Office defines the term Critical infrastructure for Disaster Risk Reduction (USDRR) as *"The physical structures, facilities, networks and other assets which provide services that are essential to the social and economic functioning of a community or society."* (USDRR 2022) To the importance of the STC, in 1998, US presidential directive PDD-63, also known as Critical infrastructure protection(CIP) aims to protect *"..the assets, systems, and networks, whether physical or virtual, so vital to the United States that their incapacitation or destruction would have a debilitating effect on security, national economic security, national public health or safety, or any combination thereof."* (McCue 2015) As the backbone of network communication, STC is ineluctably one of the items within.

In contrast to the importance of the STC in the real world, the research attention on STC vulnerabilities remains limited. This work will discuss three fields of literature: distance from relative infrastructure, factors that lead to the STC failure, regulations and international law applied to STC, and the digital divide under STC framework.

2.1 Existing studies of infrastructure resilience

Robustness analysis of essential infrastructure (eg. gas, electricity, communication) networks has been widely explored in the literature, but the impact of STC failure has been addressed by only few authors. (Cotilla-Sanchez et al. 2012; Sang et al. 2022; Ouyang and Z. Wang 2015) A robust system is characterized by its ability to resist, tolerate, absorb, and recover services under various unfavorable occurrences. (Holling 1973) The infrastructure resilience analysis approaches in the previous literature include fault tolerant assessment (Santos, Lung, and Montez 2005), network science analysis (Ulusan and Ergun 2018), simulation method (Satumtira and Dueñas-Osorio 2010), surrogate measure (Shin et al. 2018) and others. Each classification is a well-established research angle to quantify the resilience of the infrastructure. But no applications on a global scale. For the STC vulnerabilities, these analyses are carried out at the level of a country or a region, rather than a global system. STC is a special case because of the scale of its challenges in maintenance. Next I will discuss some of these in terms of their relevance to other infrastructure systems.

Using the complex networks theory, (Hu et al. 2020) examined the structural distribution of the US electricity grid by modeling the electricity market across the 50 states. Utilizing an undirected graph as the scaffolding, Jun and his colleagues investigated the network features from 4 data properties and successfully identified an uneven distribution of the US power market in power generation and the sale side. Take another example from the liquefied natural gas network, (Clegg and Mancarella 2019) topologically measures the liquefied natural gas infrastructure resilience in UK under the network science framework. The paper quantifies the liquefied natural gas network to assess the energy security of the UK, during climate emergency events during the winter. Adopting more hybrid heating technologies, allowing a more flexible switch between gas and electric heating will result in lower gas price spikes and overall gas network resilience while facing the short-term supply shock in a real-world emergency.

2.2 Factors that lead to STC failure

The current real-world challenges STC remains on two perspectives: The first major damage source can be caused by natural hazard or animal incursion; the second category will focus on human-lead destructions, whether accidental or intentional. Protecting the fragile fibre twist pair within the STC is the top priority, STC is divided into five different protection classes to overcome the different working conditions and budget balance. (Al-Lawati 2015; Libert and Waterworth 2016; ZTT 2019)

2.2.1 Natural

Considering the cost of assembly and the importance of the network connectivity, the STC is designed to achieve high reliability of 25 years of service life without any maintenance. (Worthington 1984) STCs are laid on the seabed where the depth could reach up to 8000m under the condition of high water pressure, rough rocks combined with marine corrosion to the STC's protective layer. (Beaufils 2000; Laque 1975) Burying into the seabed is the most common way to mitigate the chance of cable failure from external aggressions.

2.2.1.1 Natural hazard

During the cable installations, the deployment crew will try to avoid seamounts, the exposed cable could be damaged by chafing against the seabed or steep terrain. In addition to that exposed cables are more likely to suffer from undersea turbulence by overstretching the cable or applying impact force while colliding with the adjacent rocks. (Carter 2014) Just like any other terrestrial infrastructure network, earthquakes, volcanic eruptions, and landslides are also believed to be potent natural hazards for STC. (Pope, Talling, and Carter 2017) Earthquakes can cause significant movement of the sediments, which might subsequently break off the cable from the landslides on the seabed. (Hughes et al. 2015) Volcanic eruptions produce hot lava flow and steam with the spread of rock fragments which can cause damage to both exposed/unexposed STC in any term. (McDonald et al. 2017) But some believe that volcano eruptions are not the primary cause of the cable breaking, in both Indonesia's Anak Krakatau volcano in 2018 and Tonga's submarine volcano eruption in 2022, there was a time difference(around an hour) between internet traffic dropping and entirely going offline (Duckett 2022; S. T. Grilli et al. 2019) This could potentially mean the volcano eruption still remains partially functional after the largest eruption, revealing the origin of the cable failure comes from other geotectonic movements such as submarine landslide; submarine earthquake or even tsunami. (Latter 1981)

If the cable failure was the result of landslides, the actual repairing crew might suffer from a range of issues, from overturning ocean circulation to locating the ends of damaged cables, which would result in delays in repairing progress. In the case of Tonga 2022, the repair vessel *CS Reliance* did not prepare enough cables aboard because the broken cables were moved more than 80 km due to the landslide or shockwaves. (Needham 2022)

2.2.1.2 Animal

The engineers in the cable design crew tend to use the cable with stronger armor protection when the STC reaches a very shallowed water zone(less than 50m depth) or regions where the cable is not suitable to be buried under the seabed, such as rocky outcrops, animal habitats or fishing harbours where intensive external aggression could apply to the STC. Moreover, more than 90% of marine life and erosion of sharp broken rocks by turbulent flow further evaluated the threat to the cables. The majority of marine animals show no harm to the STC, but many historical records show sharks(especially the Carcharhinid shark family) are particularly interested in attacking STCs. This action is also known as sharkbite (L. Marra 1989) some research suggests that the electromagnetic fields or acoustic vibrations generated by the cable combined with the aggressive, curious personality attract the shark's attention from "fish biting". (Eichengreen, Lafarguette, and Mehl 2016; West and Zoo 2014)

2.2.2 Human

The world submarine network did not experience global disruptions thanks to the network rerouting, increasing supply of cable ships(A specialized ship to install and repair the STC) and fast-growing cable breakdown detection technology in recent decades. (Inc 2020) This section will discuss the STC disfunction due to human activities.

2.2.2.1 Accidental

There are about 150-200 STC failure cases annually, the marine activities such as fishing dredges and anchoring are the two primary reasons causing the damage to the STC, around 72% of failures are directly caused by these. (Kordahi, Stix, and Rapp 2016) Furthermore, the failures caused by fishing and anchoring are more likely to happen in the shallow water, the chance decreases as the water gets deeper (Mamatsopoulos et al. 2020) The fishing dredge is towed along the seabed to harvest the species at the bottom of the ocean. This action can directly cause damage to unburied STC (Carter 2010) When anchoring the ship, there are two types of damage that can occur: dragging damage and impact damage. Fig 2.1

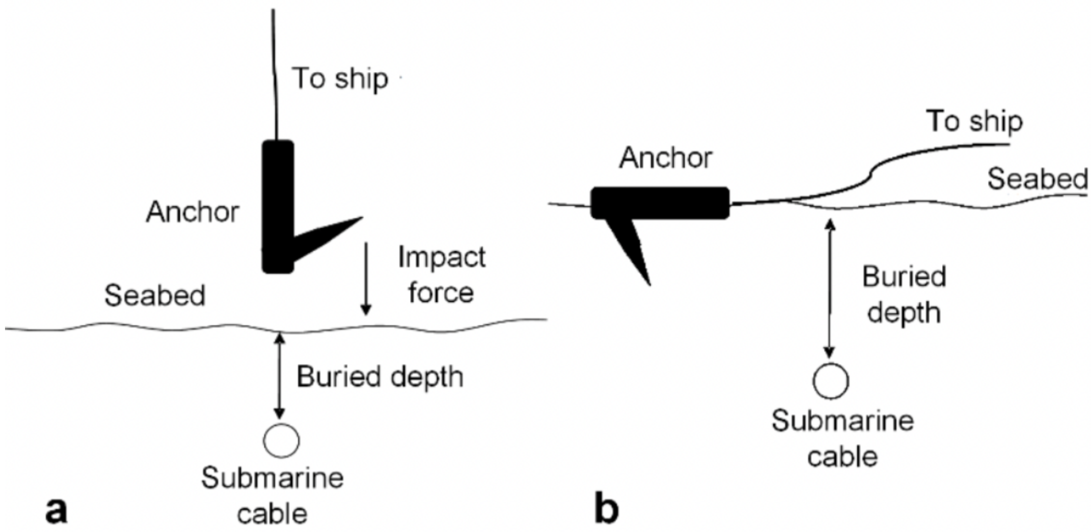

Figure 2.1: Impact and drag damage on STC by anchoring (Zheng et al. 2022)

2.2.2.2 Intentional

Considering the role of intelligence in strategic and tactical judgments during armed conflicts, disrupting the source of intelligence is linked to the outcome of the military operation. (Gentry 2019) The first offensive cable cutting can be traced back to WWI, one of the very first orders after the war declaration between Britain and Germany was to destroy Germany's STC in the English channel. The remaining cables were also under the surveillance of the code breaker team "Room 40" in London. (Bruton 2017) Resulting of the counterattack of *SMS Emden*(a german navy cruiser) destroyed a British cable landing station at Tabuaeran. (Kennedy 1971)

STC attacks include, but are not limited to, total breakdown, temporary disablement, interference, and disruptions. These faults could cause delays or loss of data packages on a particular cable, even if the global capacity is overloaded. (Gentry 2019) Modern intentional attacks apply to physical failures in the system infrastructure and failures of the network to carry traffic as a result of cyberattacks.

2.2.2.2.1 Physical

Any approach threatening STC caused by kinetic impact is included in this area. The target facilities could either be the STC itself or the landing station on land.

- At the sea:
  Similar to any marine law on the high sea, the lack of information sharing and the ability of monitorization on thousands of miles long STC dramatically lower the difficulty when malicious people are trying to attack cables. (Lindsay 2015) In addition to that, some specialized equipment(e.g. submarines and diving suits) provides more options to cause damage. In 2013, the Egyptian Navy caught three hackers on a fishing boat near the city of Alexandria who were attempting to cut the SEA-ME-WE 4 cable by utilizing a diving suit. This cable connects from France to Singapore via 16 landing stations, which is capable of carrying 2.3 Tbit data per second. (Bump 2013)

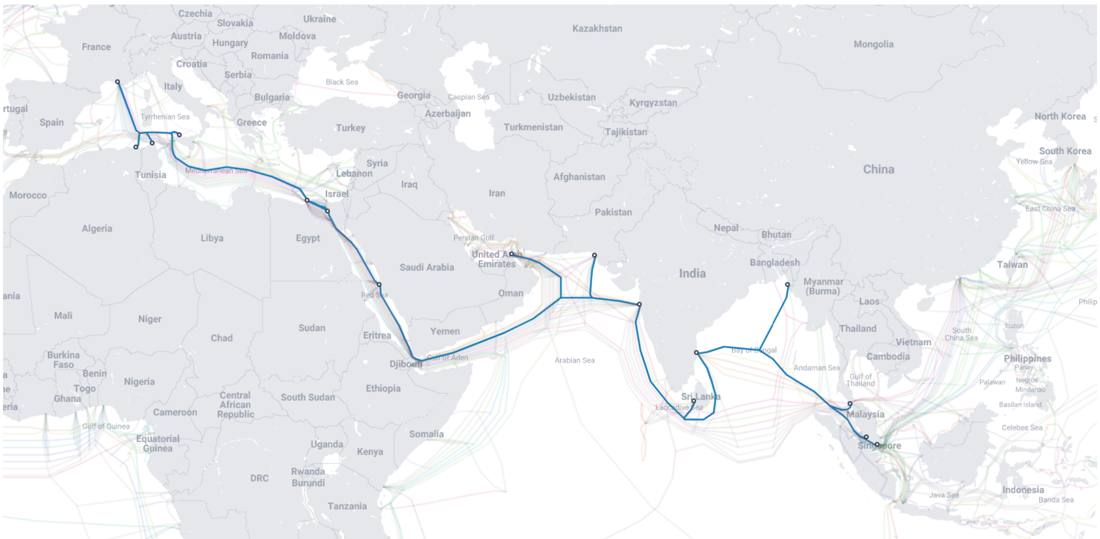

Figure 2.2: Physical path of Seamewe4(TeleGeography 2022)

Indeed, cutting STC in the high sea is a low-risk, low-investment with enormous achievement for economic sabotage or geopolitical purposes, which drew the Russian attention to the cables in the transatlantic ocean, especially in North Atlantic. (Hicks et al. 2016) As one of the world's most cable crowded water, the STC in the north Atlantic is responsible for more than 90% of internet bandwidth between Europe and North America. (Inc 2020) Recent evidence shows an increasing Russian naval activity was even greater than the Cold War level. (BBC 2022; Shalal 2017) Kremlin has two main weapons threats to the STCs: submarines and surface spy vessels that can deploy remotely operated vehicles or crewed submersibles. (Sutton 2021a) For example, Losharik is a specialized nuclear submarine that can be carried by a larger 'mother' submarine over a long distance. Before its fire accident in 2019, the Losharik could perform topographical research and threaten STC within 1000m below the sea. (Roth 2019) As for the surface vessel, Yantar is the most famous one, a 'special purpose intelligence collection' employed by the Russian Navy, this title is also seen as a euphemism for a spy ship. Considering, Yantar's deployment and field surveying often near the STCs and occasionally turned off the AIS noted off the attention from NATO countries. (Sutton 2021b)

- Landing station:
  In contrast with the invisibility of the STC under the water, the on-shore cable landing station is a more obvious target. As the terminal of the STCs and the switching site between TTC and STC, CLS are often located in a town away from major cities. (CSRIC 2016) For budgetary reasons, many countries share one landing site for multiple cables, and the landing site is often less benefited by military forces. For example, the CLS in Bude (a town in England) connects eight STC, but the closest tourist trail is only 200m away from the main office. (map 2022) This clustering could lead to a greater risk to national security when facing unlawful violence(e.g. terrorists). (Sechrist 2012)

- Espionage:
  Instead of breaking down the network, extracting the data without being no-

tified is more in the interest of the attacker. Espionage can be accomplished in three ways: inserting a backdoor into the cables or other hardware components, targeting the CLS, and intercepting the cables at sea. (Morcos and Wall 2021) Each one is easier than the one before it, and the last one is believed to be the most challenging in engineering. (Chirgwin 2014) Suggests that placing secret devices by removing protected armour without damaging the high sensitive optic fibre from the high water pressure shock is less likely to happen under the current technology. On the one hand, if the target cable is located 1 000 m below sea level, the diver will be unable to withstand the water pressure, and the manipulator arms on the submersibles will be unable to polish and splice the fiber in a dust-free environment. Practically, it is much easier(and legally) to tap the data on the landing stations. A document released by the Washington Post revealed a secret system called "Upstream" from NSA was designed to access communication on fibre cables without damaging the existing connection. (Timberg 2013) As a result, because the UK is the entry point from the Atlantic and 80% of fiber data flows through the US, the CLS in Britain is the ideal location to deploy such a system. (Khazan 2013)

2.2.2.2.2 Digital cyber attack

(Suganami, Carr, and Humphreys 2017) Illustrates a concept of viewing data as critical infrastructure in part of the complex global internet supply chain, in the way that identifying the STC in the IoT environment rather than the cable itself. Hackers may remotely control the STC network management system to gain administrative rights. From that point, they could identify physical or software vulnerabilities, disrupt the data traffic or create backdoors for further usage. (Morcos and Wall 2021) It is really likely to occur according to (Sechrist 2012), most of the firewalls and the secure protection software in most network management systems are not up to date.

At the point of writing, there has been no significant global internet failure directly or indirectly caused by STC in the past decades. Even if we ignore the fact that the cable failure was caused by natural disasters, global STC connectivity remains fragile from a legal or military standpoint, and even terrorist organizations from the standpoint of ransoming for EU-US financial market stability. (Clark 2016)

2.3 Regulations and international law applied to STC

Ban Ki-moon, the former Secretary-General of the United Nations sums up the wisdom in the Oceans and Law of the Sea Report (UN 2016) *"Submarine cables are a fundamental component of the critical global infrastructure and play a direct role in sustainable industrialization; indirectly they contribute to all other areas recognized as important for sustainable development."* Just like any diplomatic business, as a transnational communication system, STC connects multiple countries, even different continents, this dramatically complicates the jurisdiction. The attention of international law protection has been extended to the STC, Tallinn Manual - an academic, non-binding study on cyber law written by a group of NATO experts state that *"(STC) generally are treated in the same fashion as cyber infrastructure located on the land territory"* (Schmitt 2017). The proper legal position of STC, however, is based solely on two international agreements: the 1884 Convention for the Protection of Submarine Telegraph Cables (Cable Convention) (Convention 1884) and the 1982 United Nations Convention on the Law of the Sea (UNCLOS) (UN 1982). Cable Convention was the result of 20 years of industrial experience of the submarine telegraph cables at that time, which was not the only product of diplomacy but also combined the reflections of the fishery, ocean transportation industry, navy and electrical engineers from 27 countries. The author summarized some key articles from the Cable Convention as they are still the foundations of the STC regulations.

i) The convention applies to the cable even it is outside of territorial water.

ii) Any intention or culpable negligence break or injury on an STC will be subject to criminal penalties. But it is not applying to the case where captain damaged the cable to save the ship or his passengers.

iii) If a cable was broken or injured during the laying or repairing of another cable, the owner of the laying cable shall bear the cost of repairing.

iv) The vessel working on the laying or repairing submarine cable shall confirm the signal with the few preventing collisions at sea. Other vessels shall withdraw and keep the distance of one nautical mile, so not to interfere with cable laying or repairing operation.

v) If a vessel can prove they have sacrificed an anchor, a net, or other fishing gear in order to avoid injury of a submarine cable. The owner of that submarine cable shall pay over these losses.

vi) This convention does not apply when a country is in a war.

If Cable Convention only gives some basic guidelines for vessel operation and STC damage compensation, the more recent UNCLOS provides a standard framework of responsibilities, supervision and regulations across the nations. (Carter 2010) The UNCLOS divides the marine area into five zones. (NOAA 2015) Four primary zones can be identified in terms of STC jurisdiction. (Davenport 2012)

i) First zone includes internal water and territorial waters, which marks any water inside of "baseline" (Westington and Slagel 2002) or the sea within 12 nautical miles from the baseline. In this zone, the country has full sovereignty of the STC, laying or repairing cable needs to be applied via diplomatic communication channels beforehand. In many countries, the criminalization of espionage in this area is also written in the local law. (Kraska 2015)

ii) Next is Contiguous zone, a buffer band within 12-24 nautical miles from the baseline, which aims to prevent the legal issues regarding *"customs, fiscal, immigration or sanitary laws and regulations"* (Pyc 2017). However, its functionality is done by the server site where the STC lands or the government cyber security intelligence agency.

iii) Following that is the Exclusive Economic Zone(EEZ), which extends up to 200 nautical miles from its baseline. The nation is entitled to develop or harvest any natural resources and establish artificial islands here. (Louisiana 2005) However, in article 79, UNCLOS recognizes the right of everyone to laying cables within the EEZ zone (UN 1982). Therefore, the ownership and the cable destruction responsibility are still quite vague at this stage.

iv) Lastly, any water beyond the EEZ and continental shelf is the High Seas, where domestic law no longer applies. Anyone may lay or repair STC in the high sea, but the damage or injury to other STC still needs to face judgement from the international court of justice. (Davenport 2012)

To improve the existing legal status of STC, (Rishi 2017) proposed an assumption by assigning a lead agency to create protection zones in the shallow water where activities are likely to damage the STC should be strictly prohibited there. Under such a framework, broader maritime planning and better spatial management need to be considered, with the circumstances of an increasing gap between the importance of the STC and the amount of legal protection it receives.

2.4 Barriers to connectivity

Even though STC is a world spread infrastructure, there are still 2.9 billion people who do not have access to the internet, especially in developing countries where the people are not covered by 2G or 3G signals. (ITU 2021a)

The barriers to effective use of internet data also apply to the ability to digitally connection rather than the physical/software failures in the STC system. The challenges facing global broadband connectivity are discussed in more detail below.

2.4.1 Lack of infrastructure

Accessibility to the internet has closed roll-out with infrastructure, Most ISPs do not deploy infrastructures in areas with less commercial prosperity. Although constructing new infrastructure is usually associated with coverage, barriers such as the lack of electricity, lack of road(harbour) access, and underdevelopment of domestic backbone networks. These observations are particularly prevalent in the rural areas and low-income regions, the challenge in terrain; higher deployment costs and government corruption give a longer cost recovery period. (Chen and Wellman 2004)

The stable supply of electricity is the essential prerequisite for any internet connectivity, to sustain the functional working of both landing stations and sub-base stations. Fig 2.3 shows a map indicating the lack of electrical infrastructure around the world. The lack of electricity is particularly serious is Africa. The region is also known for its poverty (WorldBank 2011) and more than half of the population does not have access to electricity. (WorldBank 2018)

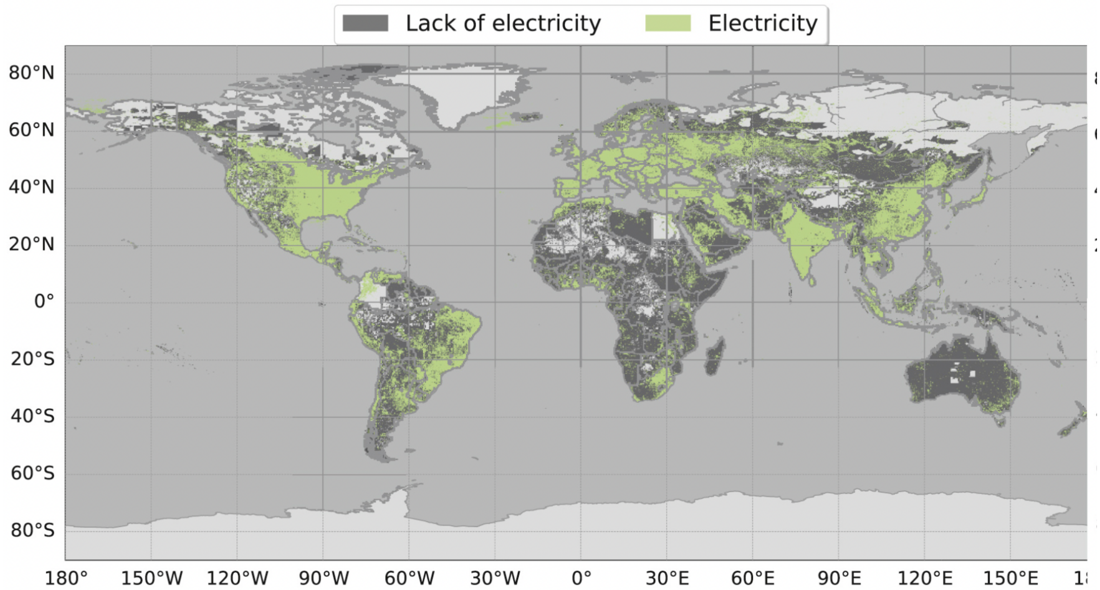

Figure 2.3: Electricity infrastructure distribution(del Portillo, Eiskowitz, et al. 2021)

2.4.2 Affordability

Internet affordability can still be a barrier even if the electricity infrastructure is in place. By estimate, there are still around 10% of individuals who do not have access to the internet globally. (Johnson 2022) At the regional level, users in Africa are paying 3 times the global median price for the broadband service fee for a similar level of service. (ITU 2022b)

People's disposable income and internet data package subscription fees are the two major barriers to utilising broadband services. Broadly speaking, the device cost has always been the most significant issue for low-income groups, but recently intense price competition amount terminal device brands and a well-established hardware reuse chain has dramatically reduced the price barrier. The monthly data package services have become a luxury, especially in the COVID-19 era, the fixed broadband services play a bigger segment in people's gross national income(GNI) which climbed from 2.9% in 2020 to 3.5% in 2021. (ibid.) The ITU is aiming for more affordable broadband services to everyone with less than 2% of GNI by 2025. (ITU 2021b)

2.4.3 Extend connectivity

However, as an alternative technology to replace STC, the application of satellite internet has re-gained popularity recently. (Ashford 2004) Despite the limited market share that satellites internet holds in the global telecommunication market, the quality of the services is sufficient for its users, (del Portillo, Cameron, and Crawley 2019) statistical estimates of the total system throughput for different technologies.

Utilizing non-synchronous orbit satellites rotate around the earth's orbit, providing wireless internet connection to the customer near the earth's surface. If the satellite is located in geostationary earth orbit, the user will suffer from higher latency and more limited bandwidth than STC. Low Earth orbit (LEO) satellites can significantly mitigate these issues. Still, LEO acquires hundreds of thousands of satellites to provide worldwide coverage, which gives higher standards to the internet service provider(ISP). (Deutschmann et al. 2021) Regardless, LEO has always been the most commercially successful satellite internet service and also gains extra technical standpoint during the manufacturing processes, which resulting a higher standard on user budget than STC, as more professional technical devices and expensive data packages need to be pre-purchased before usage. (GSMA 2016) On the other hand, if the service area is retained in 100-10 000km^2 on a small number of base stations is required to achieve suboptimal working conditions with minimal maintenance. (Djuknic, Freidenfelds, and Okunev 1997) This makes the LEOs particularly useful for facilitating the telecommunication infrastructure damage recovery (Alnajjar et al. 2014) to permanent communication infrastructure in rural areas. (Bleicher 2018)

Chapter 3

Data

This section demonstrates and discusses the data was identified to characterize the essential requirements and to estimate the STC network system performance, before the highlighting any analysis. The STC data process can be categorized into 4 sections: dataset gathering, dataset pre-process, data storage, data category classification.

3.1 Dataset gathering

There are three comprehensive open datasets of the global STC were utilized in this research. All three datasets provide some information on cable name, cable length, ready to service date and cable owner. They differ in extra information(eg number of fiber pairs) and number of cables documented

- Submarine cable dataset
  DS1: The *Submarine Cable Map(SCM)* is an online web map service powered by TeleGeography, which gives the world STC GPS location and its landing points. TeleGeography has 15 years of experience in telecommunications market research and consulting. Its research results sponse to companies such as Amazon AWS, Cisco, and Google cloud.

  DS2: For detailed STC properties, the *Submarine Cable Almanac(SCA)* offers information including planned budget cost, number of fiber twisted pairs. This report updates quarterly with the most recent data and technical breakthroughs in the submarine telecommunication industry.

  DS3: The *Infrastructure Map* provides detailed STC designed capacity and annual lit capacity of the global STC network. The data in Infrastructure Map is directly collected from the official website for each STC and peer reviewed by a group of experts from TeleGeography and the community.

- Global bandwidth throughput dataset
  DS4: Recall that more than 98% of global internet transmission is handled by the STCs(Winseck 2017), the annual survey from ITU documents the "total international bandwidth usage per second" and "individual bandwidth usage for each internet user per second" across 237 countries from 2007 to 2020. ITU collected and harmonized the information from the state telecommunication/ICT ministries or national statistical offices.

3.2 Data pre-processing

For various reasons, the cable property data on few cables are not publicly released. In very rare cases, the property data on an STC shows a conflict of information between datasets or significantly outlies the rest of the values under that data property. To overcome this, the author uses Interactive Transmission Network Maps (BDT 2022) as the additional validation dataset and adopting the majority rule strategy from the voting system (Kuncheva et al. 2003) to decide the most reliable information within. It is worth mentioning that the data from SCA holds two votes as the data properties are reviewed more frequently(4 times every year) than other datasets. All the datasets mentioned above remain in the public domain for any non-commercial usage.

3.3 Dataset Storage

All the raw data and processed clean data are stored in an SQLite database which is kept in secure cloud storage to ensure the data confidentiality, availability and durability.

3.4 Data category classification

Since the research scope focuses on submarine telecommunication cables, the following types of fibre optic cables are not included in this research. Firstly, the fibre cables lay after the STC landing point which is also known as the terrestrial telecommunication cable(TTC), these cables play as the highway to provide the domestic internet connection or speed up the data traffic between STC landing stations from one country to another. TTCs are usually constructed and controlled by the local ISPs, they are much longer and harder to trace the locations. For example, the Zayo group built at least 170222km of TTC in the contiguous US where most of the connections between the east coast and west coast are relayed on this. (Infrapedia 2022) Secondly, the cables used for military or national security purposes are excluded because their existence is extremely confidential and they are using private networking, which is not open to civilian broadband. (Ruffin 2000) The third exclusion consists of private cables and dark fibres, these cables are either used to transmit private information between servers with high standards on performance and security or the constructed cable but currently not on services. Because of their special usage, the network topologies are usually point-to-point, star or ring which do not contribute to the majority of the people. (Sima et al. 2007) Lastly, the STCs which are only designed to serve particular sea operation stations are also excluded. A typical example is oil drilling platforms where the single channel communication is directly connected to the TTC and transmission is used purely for commercial reasons. For example, *Abu Dhabi* is the cable with a length of 420km which connects the UAE and Abu Dhabi National Oil Company's offshore production facilities. (Nielsen 2017; Jandenul 2021)

- High level data description
  The High level data description aggregates the data based on the countries'

belonging which gives an abstract view of the STC connection.

- Low level data description
  Low level data helps to explain the STC connection in more concrete terms, such as STC landing cities and service status. A coastal country may consist of one or many landing cities, this will dramatically increase the number of nodes and edges to be considered. This level also gives the most detailed entries of their construction in the network of connections, as each edge is labeled with a unique color to identify their route path under the sea.

Chapter 4

Methods

To approach the goal of identifying the vulnerability in the STC network, the author first introduces the key concepts and terminologies in this study. Secondly, we assess the future risk of bandwidth shortages due to the increasing demand for internet throughput. Subsequently, a framework of STC data flow and various centrality analysis were proposed to identify the potential influential path/landing station. Finally, an STC improvement scenario in the southern Pacific Ocean is described.

4.1 Graph theory and Network science

Network science and graph theory are two highly overlapped fields to model and mathematically describe the relational connection between multiple objects, even though the two research fields can be used interchangeably to illustrate a similar idea: the objects (nodes, vertices) are associated by a logical connection (links, edges). (Barabási 2016) But the nuanced differences between the two statements still exist, which means they can not be interpreted with one.

- Graph theory is a branch of discrete mathematics that provides the fundamental theorem and essential algorithms for the given graph. (neo4j 2022) The entity of node and edge object could be seen as a set of objects with different types of items.

- In contrast, network science focuses on the observation of real-world representations of the connection to understand the structure and quantify the dynamics of the complex system between the objects. (Friedrich 2019) For example, society is the linkage between individuals under the association of families, friendships, classmates and coworkers etc.

4.1.0.1 Internet routing in graph theory

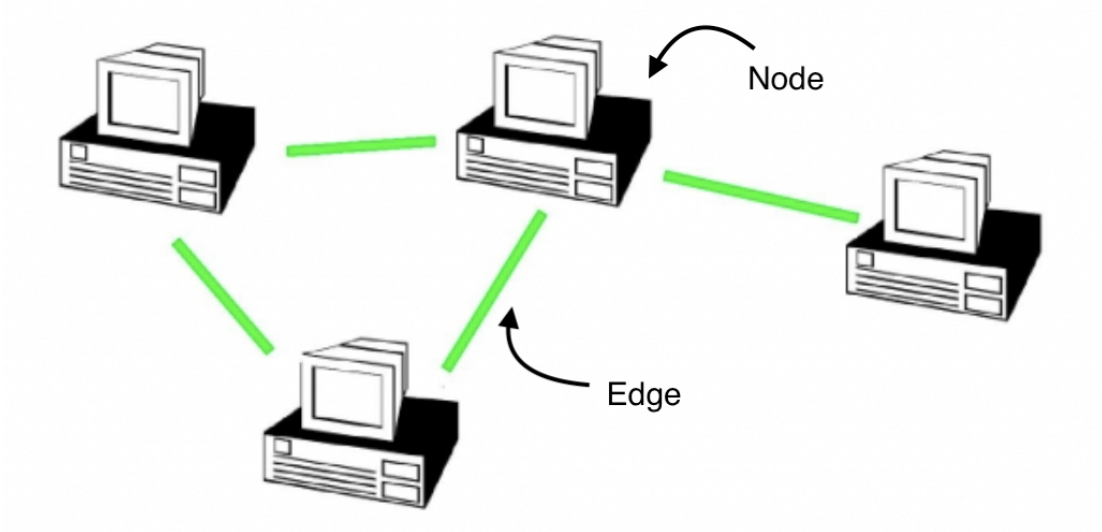

Figure 4.1: Computer routing in graph theory (Barabási 2016)

The construction of the internet routing network system is valid for an undirected graph as the internet cables provide synchronous communication, allowing data upload/download to happen simultaneously from both ends. (Gkantsidis, Mihail, and E. Zegura 2003) The system components in such a graph are often called nodes and each direct interaction between two nodes is also known as edge.

In a network system, we label a node with V_i, where i is the index of the components in such network system, which is labeled as $i = 1,2,3...n$.

E is a set of edges between the nodes where each edge association is denoted as $E_{xy} \to ((x, y \subseteq V_i) \cap (x \neq y))$

We denote K_i as the number of edges directly connected to the node V_i in the network. This number is also known as the degree. In an undirected network system, the total number of edge L can be calculated by the following equation. $L = \frac{1}{2} \sum_{i=1}^{N} K_i$

4.1.0.2 Attributes in the STC graph

To review the global STCs from multiple aspects of dynamic correlations and bring quantitative constructions needed for the analysis. The network science and graph theory provide methods to take into consideration of the quantitative relationship by inserting the numerical values into the nodes and edges within the STC network. The network's nodes and edges attribute definition is presented in Table 4.1

Category	**Attributes**	**Relevance**
Node	Label	The name of landing city and country
Node	Position	Lon/Lat of of the given node
Node	Adjacent	A list of nodes that directly connect by an edge
Edge	Label	The name of cable
Edge	Connection	Two nodes that construct this relationship
Edge	Capacity	The designed maximum data transmission can be carried of the STC per second
Edge	Length	The length of the STC between two landing points
Edge	Cost	The budget cost when the cable was designed
Other	Other	Undirected graph, each node has the infinite capacity to route data between two cables

Table 4.1: Network's attribute

4.1.0.3 Keywords/philosophy in the network science

A variety of network analytical toolboxes are available under such a quantitative network, enabling the analysis approach to measure the topology and attributes of the network from a collection of multi-dimensional information in Table 4.2

(Barabási 2016)(Diestel 2017)(Hoffman 2021)(Muscoloni and Cannistraci 2016)(Najera 2021)(Newman 2017)(Saqr et al. 2020)(Xavier and Iyengar 1998)

Concept	Explanation	Application
Degree	Number of edges connecting to a node	To gain observation of the distribution of connection in a network
Path	A set of edges that connects from V_i to V_j	A allocate the spatial movement from the origin to destination for a given condition
Neighbors	The node(V_i) is neighbor to a node(V_j) such that the edge E_{V_i,V_j} exists.	The diversity of the choice when routing from one node to another
Connectivity	The measure of the connection between the nodes, there are two or more isolated subgraphs if no path exists between any given two nodes	If the global internet can be accessed between two countries, either they are connected by STC or the combination of STCs and TTCs
Flow	The non-negative capacity associated with each edge	The capability of the data movement that no edge can exceed this limitation
Centrality	A measure to the importance of the node in a network	To classify the STC landing points based on their cohesiveness. This allows centrality to be considered as a coefficient to describe node importance
Betweenness	Betweenness centrality measures the number of times a node lies on the shortest path between other nodes.	Provides another view of network elasticity by considering the most influential routing nodes in a network. For example, the transit stop in a connecting flight has higher betweenness in the flight network
Rich club coefficient	A measure to identify the presence of the connection between well-connected(a large number of degree) nodes	The rich club coefficient assesses the group robustness and the ability to remain functional when the key group member quit from the collaboration

Table 4.2: Network philosophy and key concepts

4.2 Bandwidth shortage

Prior to performing any suitable analysis, there is a problem that needs to be resolved. The raw dataset contains certain bandwidth data that is not accessible to the general public. To overcome the problem of missing data on bandwidth, the author decided to employ Butter's law of bandwidth to estimate the potential bandwidth capacity that can be carried by STC. In the context of STC, optical fiber is the most fundamental and essential material in photonic data communication. Similar to Moore's law, Butter's law is based on the historical observation that the amount of information that can be transmitted through the optical fiber has been doubling every 9 months thanks to the development of new technologies such as wavelength-division multiplexing.(Hadaway et al. 2016)(Buttle, Meyer, and Kudrle 2014)

$$n_i = n_0 \times 2^{(y_i - y_0)/T} \tag{4.1}$$

Where n_0 is the initial bandwidth throughput in the year y_0, T is a constant reference to the number of years required to double the bandwidth throughput. The value of n_i is the resultant bandwidth in the year y_i, thus its logarithmic value shows a linear dependency on n_0.

4.3 Policy-Based Routing

The path between the origin and destination in a network could either be statically predefined or adaptively changed based on the algorithm. In many real world router setups, the routing decision changes dynamically based on the instantaneous status within the network, the factors leading to the new route could be: current network topology, traffic load and latency. (Medhi and Ramasamy 2017) The first priority for all the routing algorithms is to prevent deadlock with the secondary objective of achieving maximum efficiency by minimizing the routing cost. (Duato, Yalamanchili, and Ni 2003) Considering an undirected graph(G) with N nodes and M edges, where each edge is assigned a weight to represent a physical property of 'distance'. The target is to find a route between two nodes along a set of edges. Therefore, the theoretical minimum routing cost is the sum of weights under all the edge choices. The routing algorithm that mathematically discovers the best route is called the shortest-path algorithm. There are four types of weight properties applied to the edges in their investigations, they are Simple, Spatial length, Budget cost, Bandwidth capacity. The detailed summary description can be found in Table 4.3

Property	Symbol	Explain	Application
Simple	C^S	Each edge weight is assigned to value of 1	The path where data flows through with the minimum number of edges along the way.
Spatial length	C^L	The edge weight is the actual length of STC between the landing stations	When the data transmission speed is constant, time is directly proportional to distance. The route with the shortest length in STC gives the minimum time taken for data to travel between landing stations.
Budget cost	C^C	The edge weight is the average cost of deployment based on the length	STC owner recovers the cost of deployment by charging the money from the local ISP. An STC may be preferred by ISPs due to its low charging price.
Bandwidth capacity	C^B	The edge weight is the maximum data throughput capacity that can be carried in that cable	Each STC is labeled to a design bandwidth capacity, it is the theoretical limit of data carriage ability. It is useful when users are sending large size files via STC.

Table 4.3: Edge properties

4.3.1 Network Analysis

To analyze such complex network with a large number of nodes and edges, the research boundary is not only the physical connection of STC but also an abstract quantitative network to deal with the communication between the nodes and edges.

As the weakness may either occur on the underwater STC or the cable landing stations, the locations in the global STC network with the high value of centrality gain more interest than others. The node with high centrality referred to the importance of an actor in a topological network structure. (Hoffman 2021) There are two centrality measurements employed in this investigation: degree centrality, betweenness centrality - The detailed strength and weaknesses can be found in Table 4.4

Concept	Definition	Explain	Application
Degree centrality	The count number for edge directly connect to the node (Sharma and Surolia 2013)	A node with a higher degree of edge acts the more central role of a network	Degree centrality shows how many nodes can be directly reached by such node, even though this node might be far off on the boundary of this network
Betweenness centrality	$s(E) = E(x, y)$ (Hansen, Shneiderman, and Smith 2019)	The node plays a hot spot role in many shortest paths	If all the information must pass through a node before reaching the destination, this node is the most important as the efficiency of the communication is dependent on it. But betweenness centrality compute intensive in large scale network

Table 4.4: Network analysis compare

4.3.2 Network optimization

To overcome the problem of STC incidents, rerouting the data flow to an alternative or secondary infrastructure would in worst performance but functional internet services. If the country/region only consists one STC connection, it is considered a high-risk country for STC failure due to its low redundancy. South Pacific Ocean has been known for its isolation from the majority of the world, and the deployment of STC is not as well-developed as the rest of the world. This makes the country(such as Tonga) extremely vulnerable and dependent on its only STC to communicate with the rest of the world, but this risk could be mitigated by laying additional STC cables to increase its network redundancy. (Laporte 2015) Inspect a similar issue from Chinese postman problem(CPP) and provides an idea from another perspective.

Algorithm 4.1: CCP algorithm in pseudocode (TUM 2015)

```
input: Grouph G_i   output: Grouph G_o
Begin
    odd_list = []
    if G == EulerianCircuit
        return G
    while x in G.node
        if x.degree \% 2 == 1
            odd_list.add(x)
    while odd_list != empty
        distance = MAX
        node = i, j
        for x in odd_list
            for y in odd_list
                if 0 < path(x,y) < distance
                    i = x
                    j = y
        connect_nodes(G, i, j)
        remove_node(odd_list, i, j)
    if G != EulerianCircuit
        start again
    else
        return G
End
```

CPP indicates additional edge(s) needed to form an Euler circuit graph, a walk can visit every edge exactly once by starting from any given node. (Tan, Cui, and Y. Zhang 2005) Thus, each node will have a positive number of pairs of edges to provide the route for the incoming and outgoing paths. This provides a baseline of one redundant STC for each landing station.

Over-redundancy, on the other hand, is a by-product of the CPP, which creates extra edges in order to satisfy the CPP algorithm. Although redundant edges result in a more reliable network design, they also come with higher building costs. Here, the author introduces the rich-club coefficient which describes the connectivity between nodes with a high degree centrality, under the presumption that nodes with higher degrees centrality are obtaining more geographic advantages in the network. (Ma and Mondragón 2015)

$$\phi(k) = \frac{2E_k}{N_k(N_k - 1)}$$

Chapter 5

Results

In this section, author presents the results of the STC network vulnerability analysis at two levels where their topologies are not pre-specified.

The analysis starts off with a generalized country level STC network connection, focusing on the shortage of the STC due to the natural growth in the international internet bandwidth and the country's internet robustness when multiple STC failure happens simultaneously. To better understand internet accessibility, the author acquires a comprehensive route level network for the STC paths. The analysis is based on 4 edge property measurements with 3 assessment approaches.

5.1 Study scope

As a marine based infrastructure, STC is not suitable and applicable to be deployed in all countries. Since the first STC was laid in 1989, the global broadband network interconnects almost all the countries in the world with 183 countries owning at least one STC cable. Countries left out were either territorially landlocked(eg. Mongolia and Ethiopia) or geopolitically less interested into it(eg. North Korea).

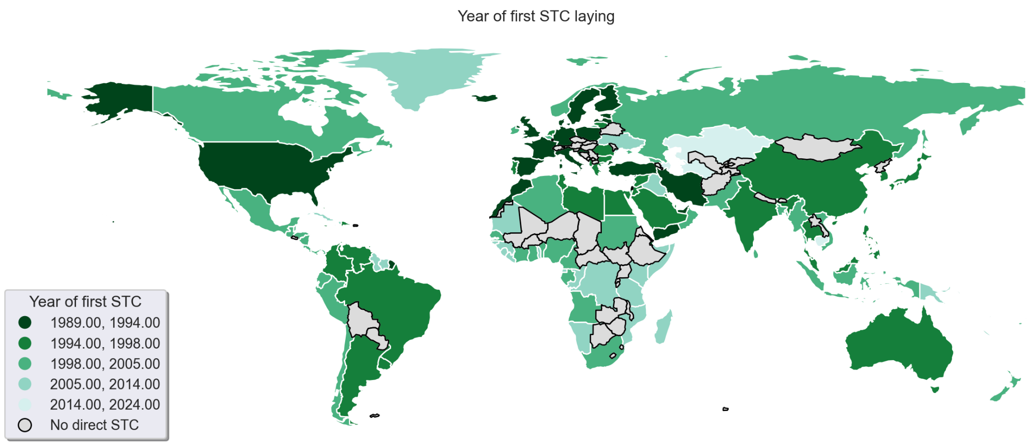

Figure 5.1: Map of first STC cable laying year

5.2 High(country) level STC

5.2.1 Distribution of STC between countries

The high level data aggregates the territorial information at the country level, which includes the mainland, dependent areas and overseas territories. (Nationsonline 2022) This makes some small overseas islands part of its administrative territories. For instance, Guam is an unincorporated territory of the US in the western pacific Ocean (DOI 2016) which is responsible for 7 out of 20 STCs connections between East Asia and West America. (TeleGeography 2022) This leaves 396 edge connections spread over 183 countries.

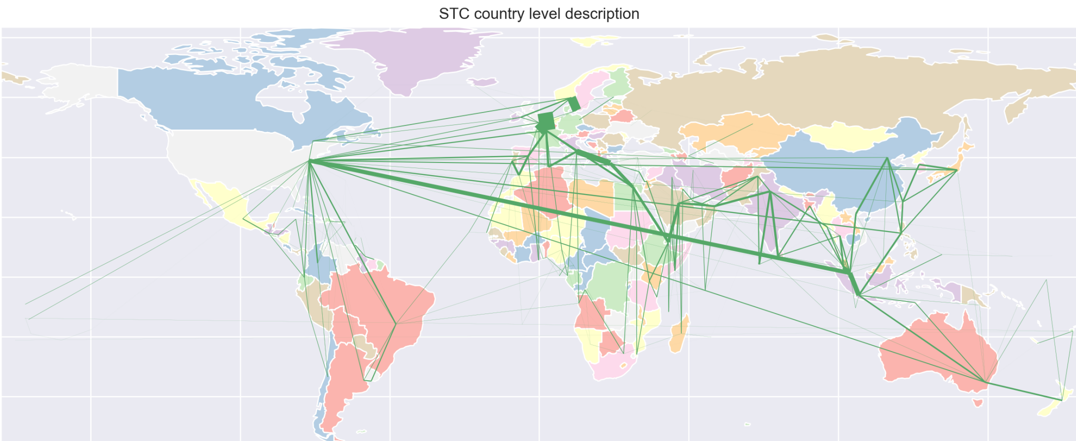

Figure 5.2: Country level connection

Figure 5.2 presents the visualization of the country level STC connection, where each node is the representation of one country and at least one edge is directly connected to it. The edge width is proportional to the count of STCs in charge of the end-to-end connection between two nodes.

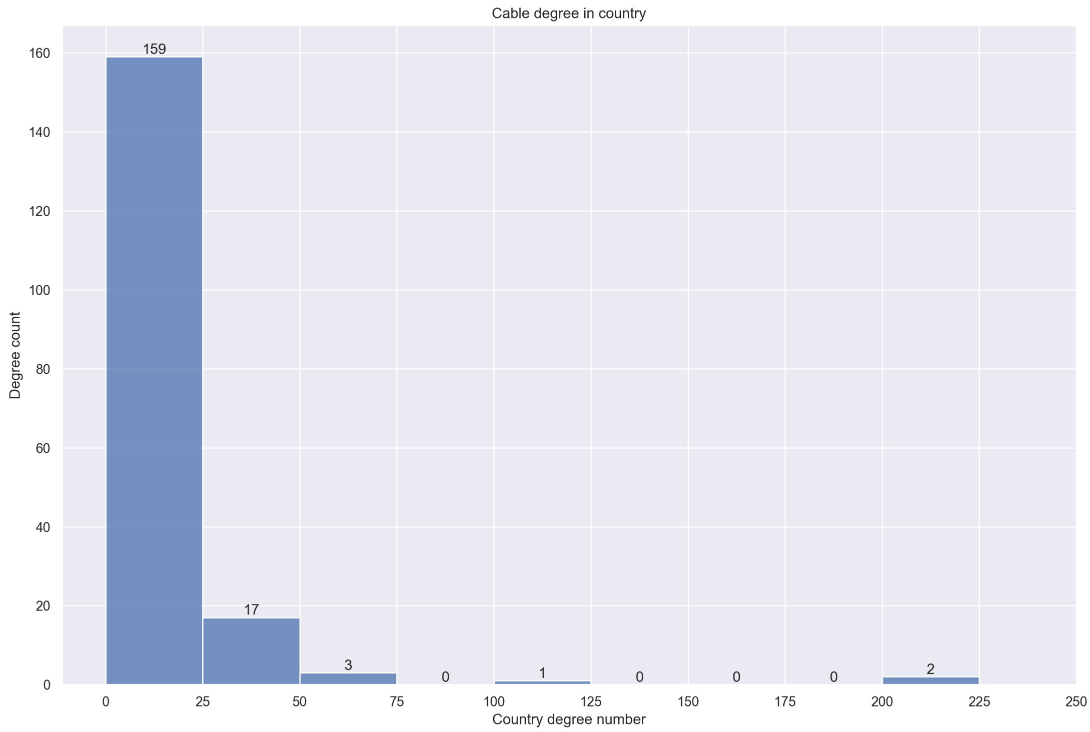

Figure 5.3: Country degree in histogram

Combined with Figure 5.3, a high clustering of the domestic connections in Southeast Asia and Europe can be expected. As the majority of countries have fewer than 25 direct STC connections to other states, in this case the design of STC tends to build a loosen and distributed network in a small area. Countries such as $K_{Indonesia} = 224$, $K_{UnitedStates} = 216$, $K_{UnitedKingdom} = 118$ are way outnumbered by the rest of 180 countries, accounting for 26% of global landing station count. These nations typically have far more redundant cables than the rest of the world as a result. With an density of $\frac{1}{17}$, this network has a nonnegligible gap between its actual edges and its maximum number of edges.

5.2.2 Bandwidth shortage due to the nature growth

Despite the development of the local caching services(eg. CDN) over the last two decades, increased investments in STC by the tech giants and continued construction of data centers around the globe, the demand for international bandwidth usage seems to increase in the next few years according to the estimation and statistics from ITU. (ITU 2022a)

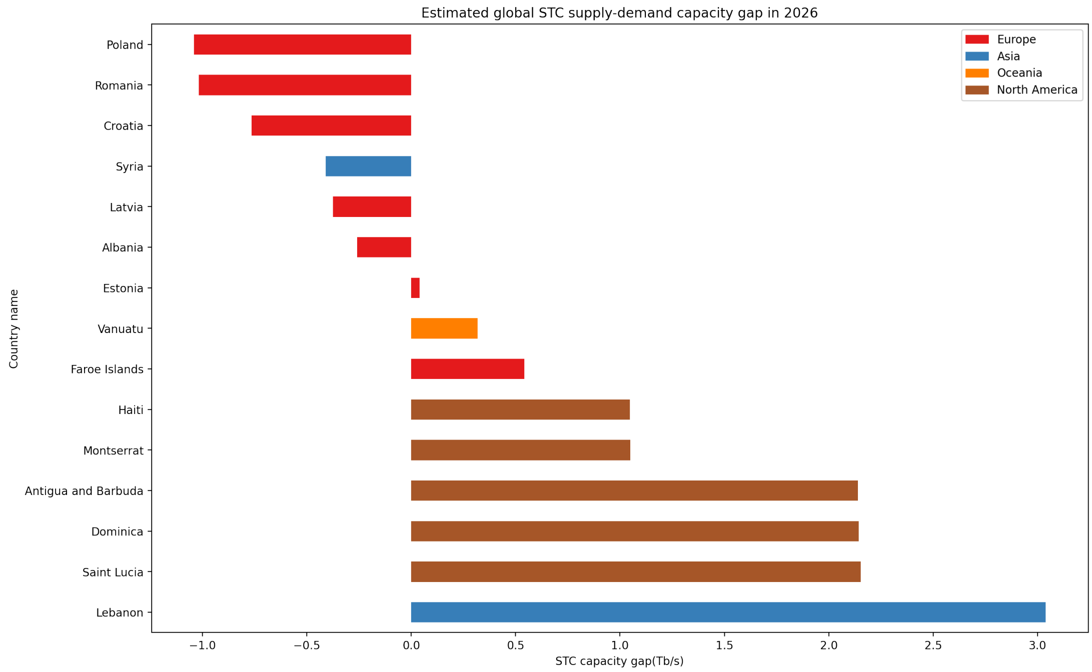

Figure 5.4: Country most vulnerable to international bandwidth shortage

Figure 5.4 shows the top 10 countries that have the risk to overcome the gap between international bandwidth served by the STC and increasing internet services demand from its people. Even though Poland, Romania, and Croatia are the countries most at risk from this scenario, as members of the Europe Union, the actual deficit is less than the paper result since the bandwidth shortage can be made up by TTC from adjacent countries. In contrast, countries with less political stability(eg. Syria) and those that are geographically located in an island(eg. Vanuatu) will suffer be more affected by this, especially during the internet rush hours.

5.2.3 STC redundancy analysis

With over 100 yearly accidents from human unintentional incidents (eg. fishing dredge and anchoring) to natural hazards as well as the potential hostile attack for military purposes. (Mauldin 2017) It is not hard to imagine the scenario where a country's internet services is disrupted by multiple cable losses at the same time. The strength of the internet is evaluated by determining the residual bandwidth after removing the cables with the highest bandwidth in order to simulate the effects of such a disruption in the worst case scenario.

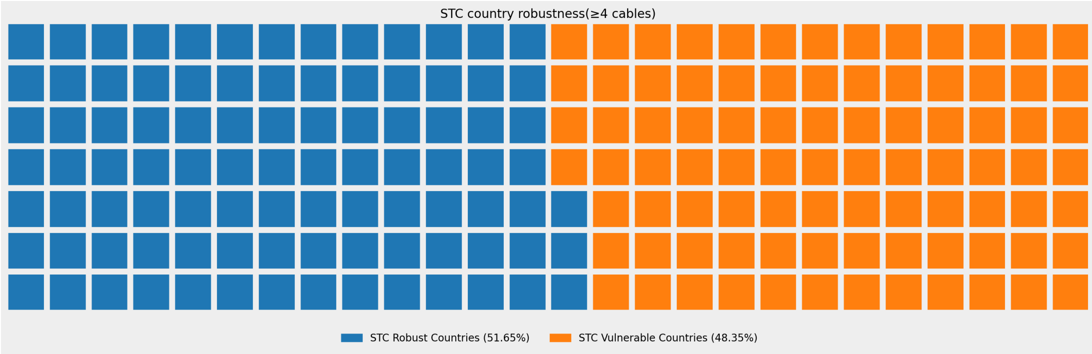

Figure 5.5: STC country bandwidth robustness compare

First, nations with less than three redundant cables are regarded as being more susceptible to internet connection problems. Since simultaneous STC failure on three cables has historically been extremely unlikely, it would also be advantageous if the nation could continue to maintain essential communications with the outside world. Figure 5.5 lists the share of countries falling under this use case. The STC vulnerable countries($K_i < 4$) can not obtain the STC connectivity, which could be crucial for some island countries or territories since the absence of the TTC means a potential loss of 100% of the international bandwidth. STC robust countries($K_i >= 4$) are less likely to suffer from this however.

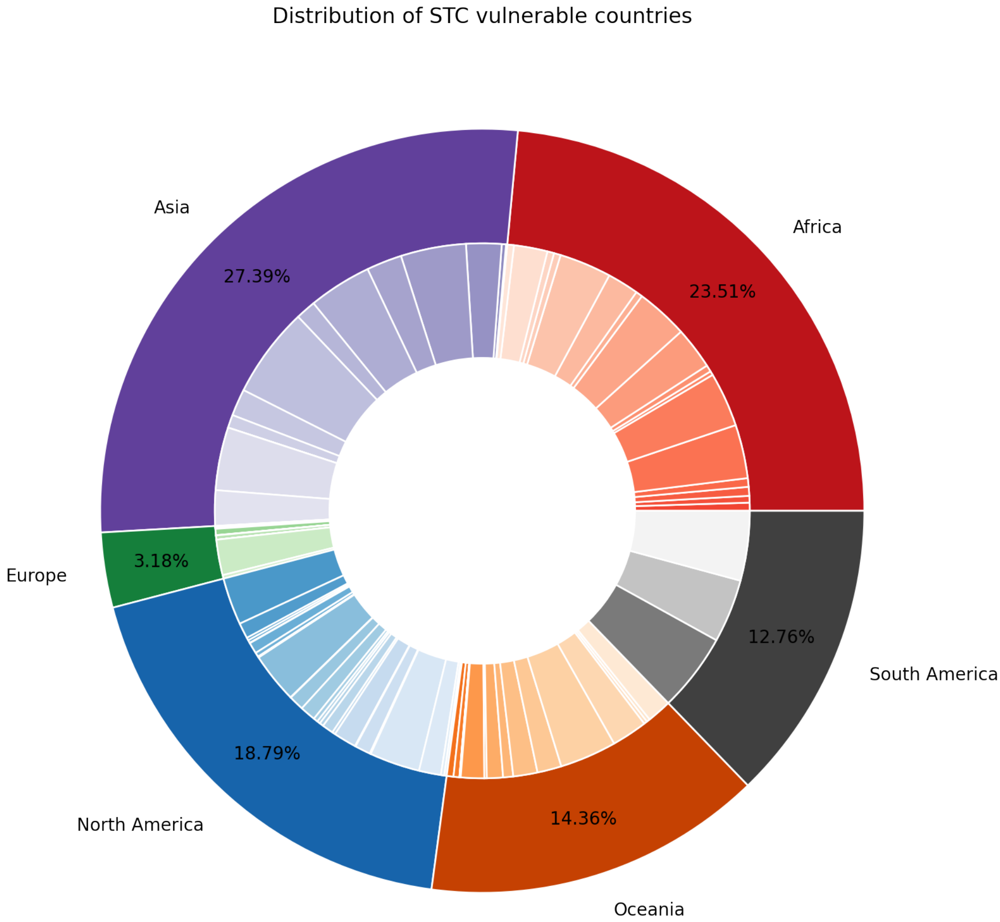

Figure 5.6: Spatial distribution of STC vulnerable countries

To further investigate the STC robustness, Figure 5.6 shows the spatial distribution of the STC vulnerable countries. The inner ring provides the chunk for each county while the outer ring represents the overall bandwidth from each continent. Asia > Africa > North America > Oceania > South America > Europe are the continents with the highest percentage. According to the data, Asia is the region that is most at risk because it contributes the biggest number, yet the segment is made up of a handful of countries with high bandwidth. In contrast North America and Africa, a smaller sector from each country with a high number country count. As a case concerns South America, which only consists of 3 vulnerable countries: French Guiana, Guyana and Suriname with an evenly distributed bandwidth allocation. The countries only deliver a summed capacity and cable count of 209.65Tb/s and 2.67cables/country.

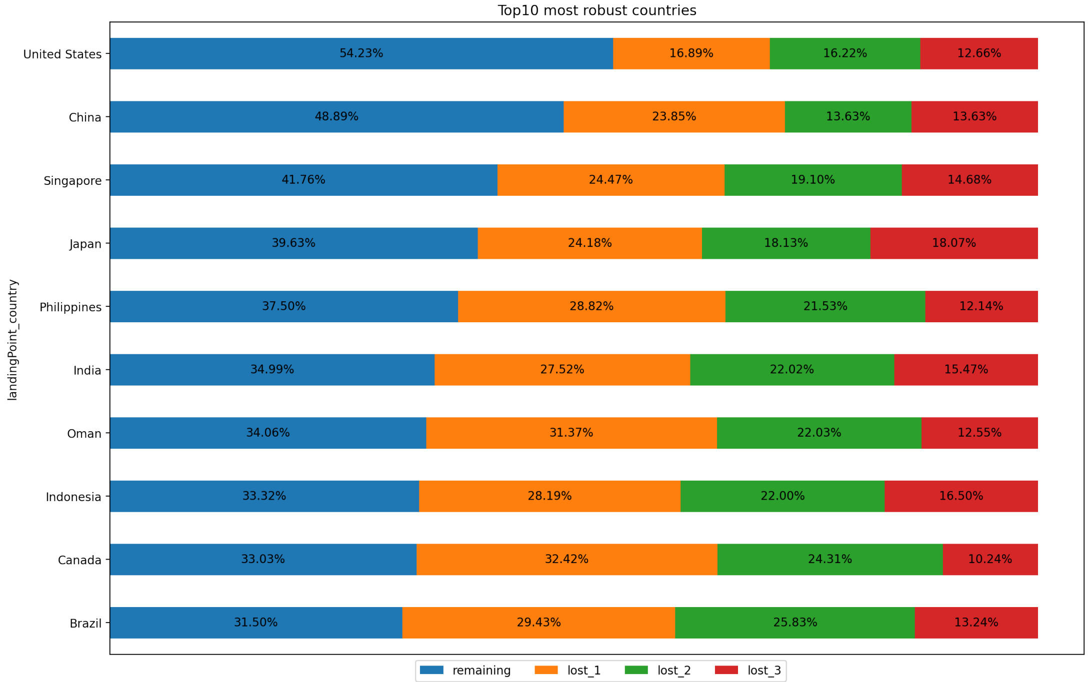

Figure 5.7: Scenarios of STC failures with most robust countries

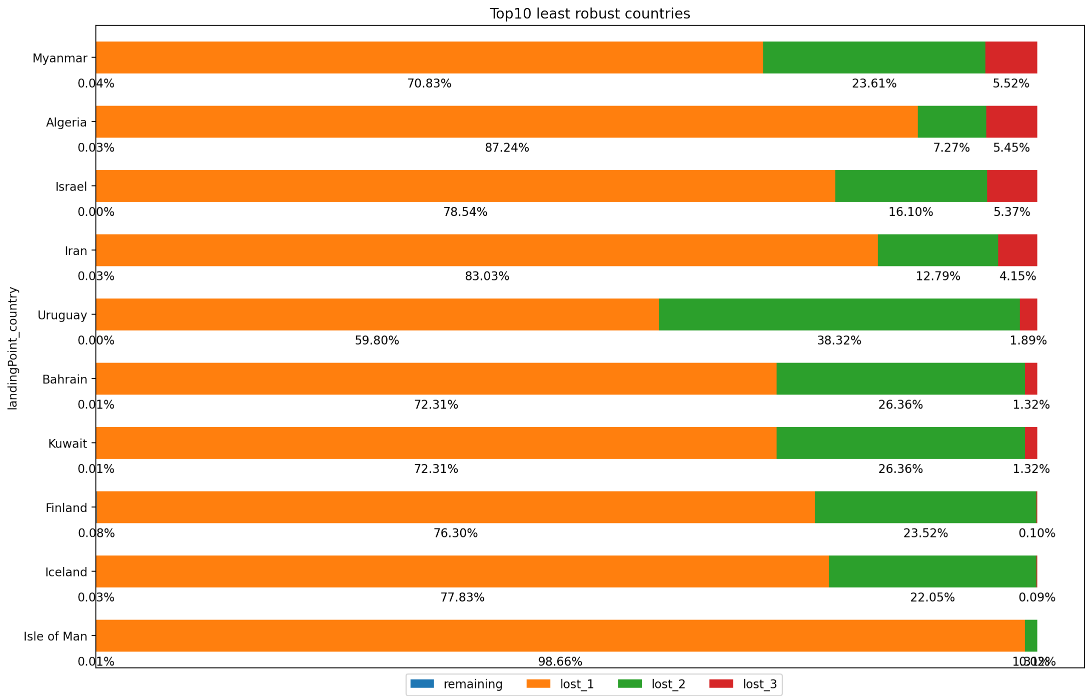

Figure 5.8: Scenarios of STC failures with lest robust countries

There are 94 countries assigned to the STC robust group, as each of which is capable of withstanding three or more STC losses. The nation might experience a decrease in its capacity for international bandwidth as a result of a cable breakdown. However, losing one or two cables is more likely to occur in the real world. Figure 5.7 and 5.8 shows the resultant remaining bandwidth in percentage to retain internet connectivity if the top three widest cables fail.

Due to its great loosen cable distribution and accessibility of redundant cables, the USA is the top player in terms of bandwidth that is still available despite multiple cable failures, with cable edge $K_{usa} = 29$ and estimated potential bandwidth of 1479.76Tb/s. The overall US bandwidth can be predicted to decrease by 250Tb/s (16.89%) as a result of the connection loss of its widest cable *Dunant*. Even in the worst case scenario in this study where top3 cables are failing at the same time, USA would still obtain the remaining international bandwidth capacity of 642.43Tb/s which outnumbered the actual demand(41.16Tb/s in 2022). (ITU 2022a) Besides that, the continental USA is geographically adjacent to Canada and Mexico which may provide additional TTC bandwidth capacity if needed.

With an estimated 98.66% bandwidth loss due to disconnect in its biggest cable, Havhingsten/Celtix Connect-2, and the remaining 1.42Tb/s capacity from the other three cables, the Isle of Man is a poor example of the cable distribution design.

5.3 Low(landing station) level STC

To better understand how STC is distributed across the world, the author also concerns a detailed low-level route for the STC paths. Figure 5.9 below outlines the landing stations and the geographical path of the global STC connections.

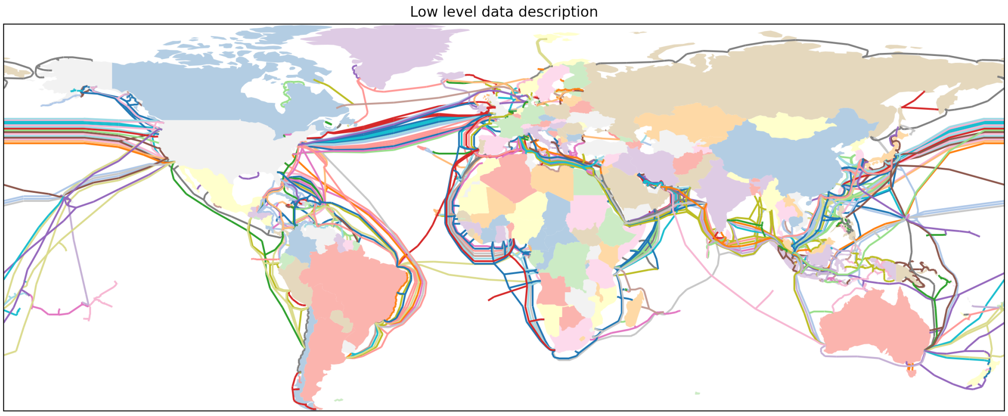

Figure 5.9: STC network in landing station level

From Table 5.1 we can also observe a highly skewed STC cable data distribution as the mean values are closed to 75% with a rapid increase in cable capacity, cable length, cable cost after that.

	Country	Landing station	Cable capacity(Tb/s)	Cable length(KM)	Cable cost(million USD)
count	183.00	1335.00	501.00	501.00	501.00
mean			50.42	3406.04	119.61
std			231.24	5986.72	182.44
min			0.00	5.00	0.25
25%			0.25	225.00	15.00
50%			5.91	775.00	40.10
75%			44.38	3472.00	122.00
max			4000.00	45000.00	1007.78

Table 5.1: Summary for low level STC data

5.3.1 Policy-Based Routing

Considering the nature of routing in a complex network, the path between source and destination node can be selected from vast options. Figure 5.10 shows a case of data communication between Yemen-India via STC. There are numerous alternate paths that can be found, many of which cover greater distances or evade more landing sites, even though there are only six routes shown on the map.

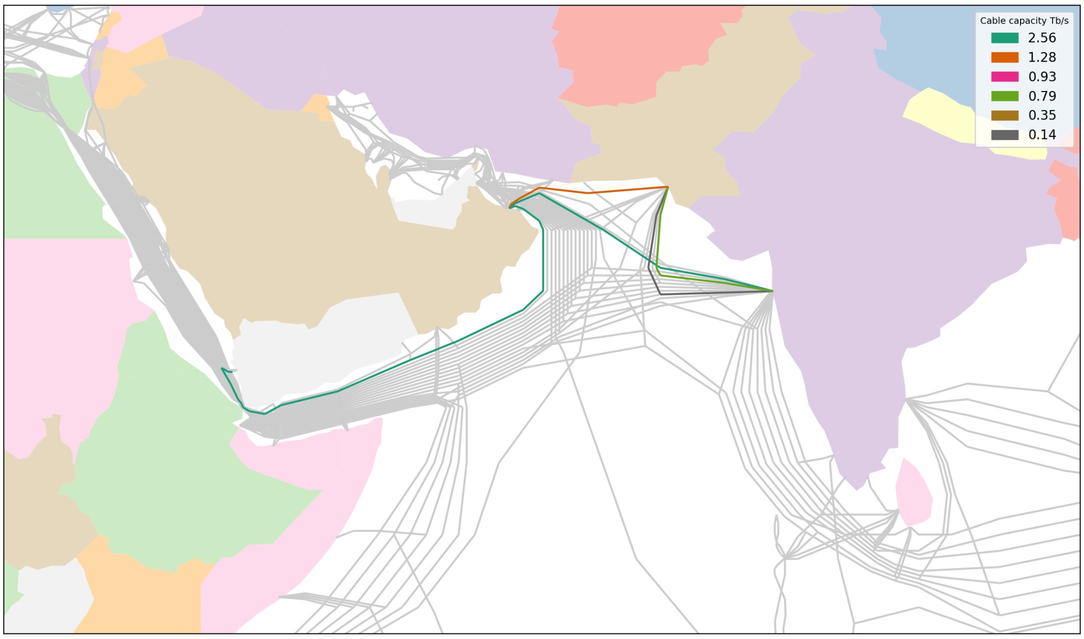

Figure 5.10: STC route options from Yemen-India

A variety of information must also be taken into account while approaching network routing and choosing the best path. (Baumann et al. 2007) In this case, the author compare the routes from Bude(UK) to Shanghai(China) to identify the optimal path under different use case for data transmission.

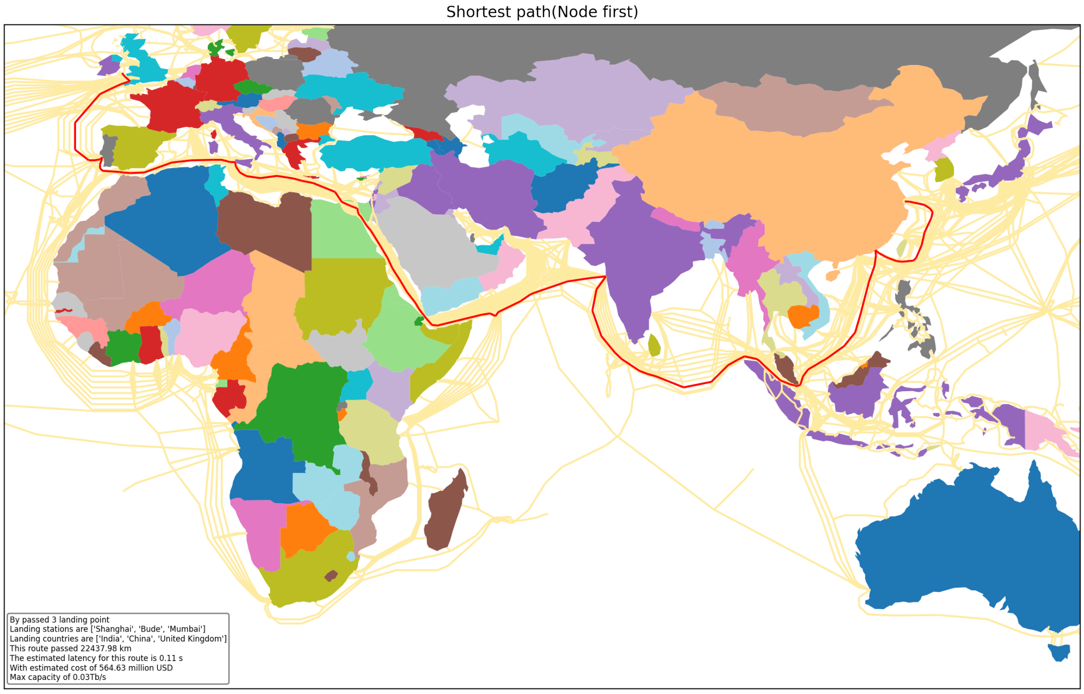

Figure 5.11: Low-level shortest-path route (C^S)

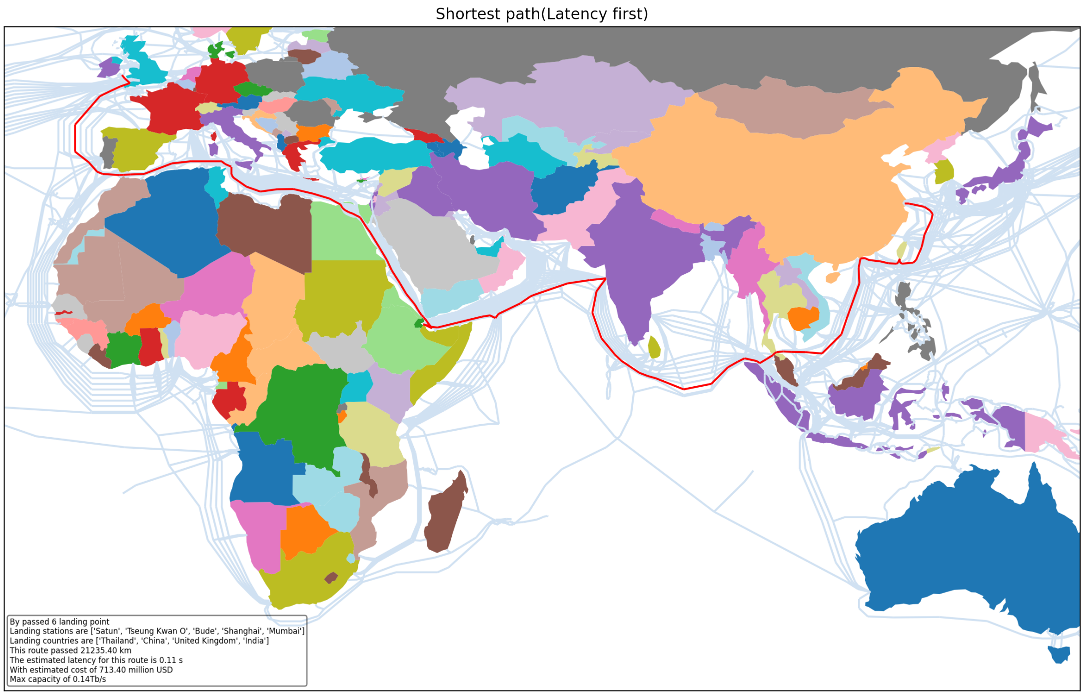

Figure 5.12: Low-level shortest-path route (C^L)

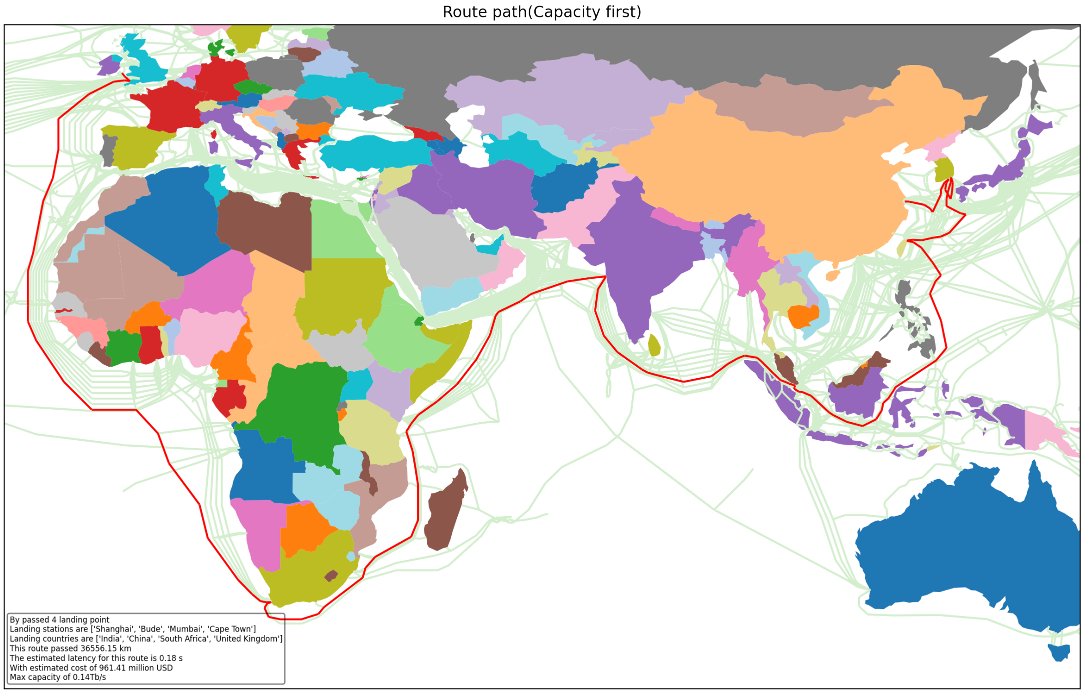

Figure 5.13: Low-level shortest-path route (C^B)

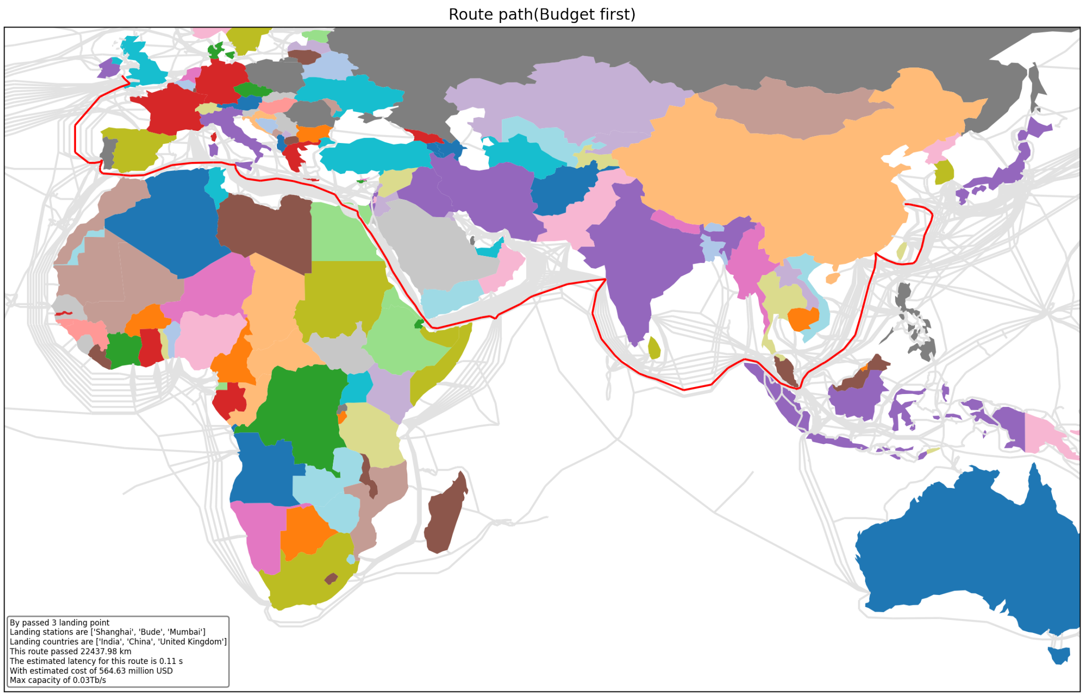

Figure 5.14: Low-level shortest-path route (C^C)

As Figure 5.11 to 5.14 shown, the paths are chosen by the data packages based on their routing policies. In such an instance, C^B chooses a geographically longer route in exchange for a wider bandwidth capacity in comparison to other routes. Using Mumbai(India) as the routing transit station is the common practice in this study case. The importance of Mumbai in global STC connection will be presented in Section 5.3.2. It is also interesting to see a high overlap between the STC routes and some of the most important shipping trade routes, take C^S as an example, the route passes through the English Channel, Strait of Gibraltar, Suez Canal, Bab al-Mandab Strait, Malacca Strait before reaching its destination. It is risky for the cables from anchor damage, as a large number of ships are right above the STC cables in the shipping route area. In addition to that, cable density in these regions are usually higher than normal due to the narrow width alone the bank(205m for Suez canal), damage from natural hazard or explosions may cause failure on multiple STCs.

5.3.2 Degree centrality

The degree centrality offers a quantifiable measure to categorize the nodes based on their cohesiveness, allowing us to evaluate the significance of each landing station individually. Accordingly, the count of adjacent edges for each landing station will be assessed, Figure 5.15 captures the results of the degree centrality based on the landing stations. Mumbai(India) is the headmost with $K_{Mumbai} = 160$ and 0.43 degree centrality, followed by Shima(Japan) and Jeddah(Saudi Arabia), their high values can be explained by the geographic importance as the transit countries. Japan is the gateway to connect Asia and Pacific ocean, similarly Saudi Arabia is located near the Suez Canal the shortest sea connection between Asia and Europe. Another side of the coin, the landing stations with the lowest degree centrality can be found in the island countries or regions with only one cable connect to it eg. Aeng Batu Batu(Indonesia), Balluta Bay(Malta)

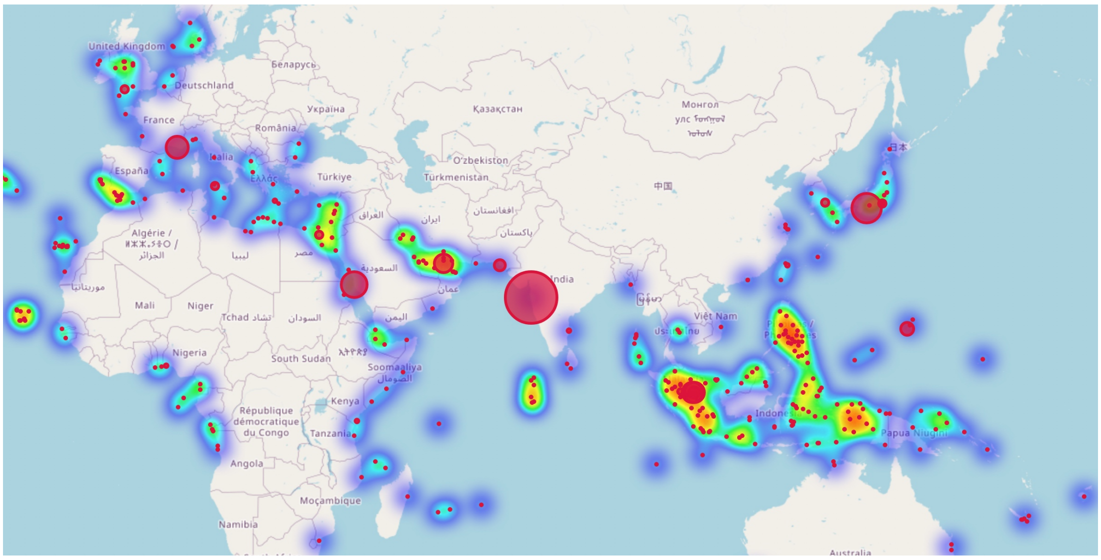

Figure 5.15: Low-level degree centrality map

The landing stations with a high degree centrality are playing a more significant role in the STC network, arguably such design is not ideal in terms of risk assessment. The high degree centrality nodes consist the feature of intensive connection, the failure in the node itself cause by unexpected accidents (eg. power blackout, riots, terrorist attack) would consequently in more serious damage to the communication globally as the data routing can not proceed to the succeeding landing station. Besides the landing stations mentioned above, Singapore is also extremely valuable to the STC network but can not directly be observed from the map. Because Singapore is a small island, the two landing stations(Changi North and Tuas) are only 35km apart, the accident in one landing station is likely to implicate another.

5.3.3 Betweenness centrality

To account for the topological cable breakage at the sea, one important issue that needs to be considered is the geographical distribution of the cable usage while transmitting the data package. The betweenness centrality returns the ratio in which the node is sitting alone on the shortest path between any two nodes, it can be seen as a comprehensive measure of the routing path selection in terms of the possibilities. With a different focus on the data routing policies, Figure 5.16 visualize the distribution of the betweenness centrality individually while Table 5.2 statistically summarizes the value.

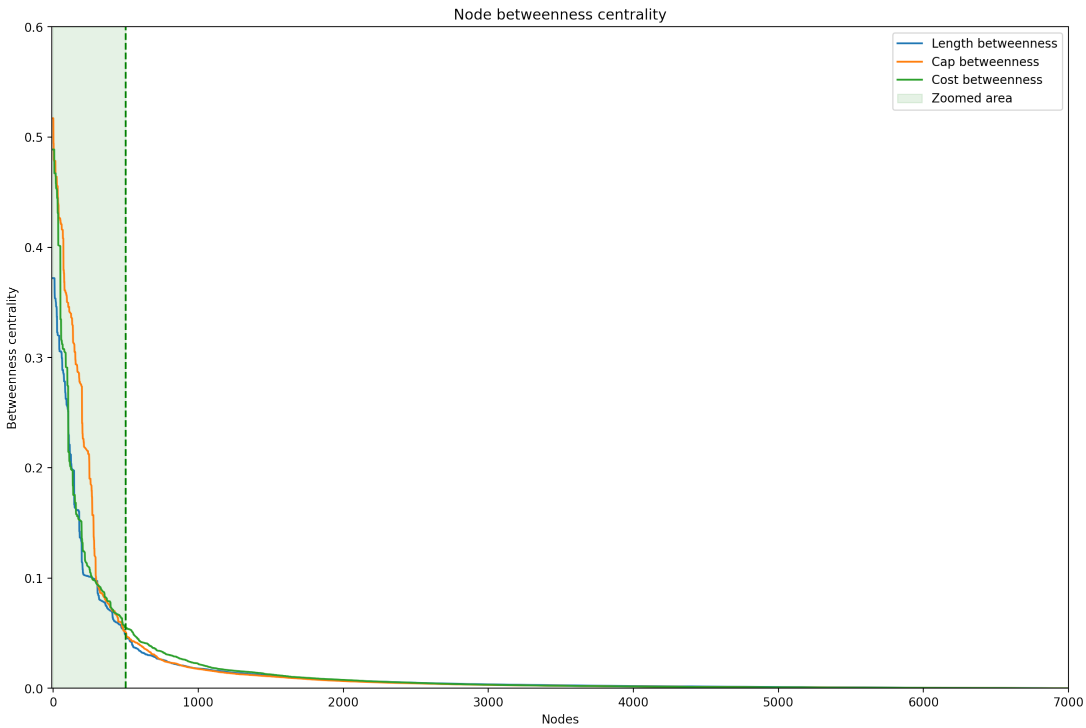

Figure 5.16: Betweenness centrality Overview

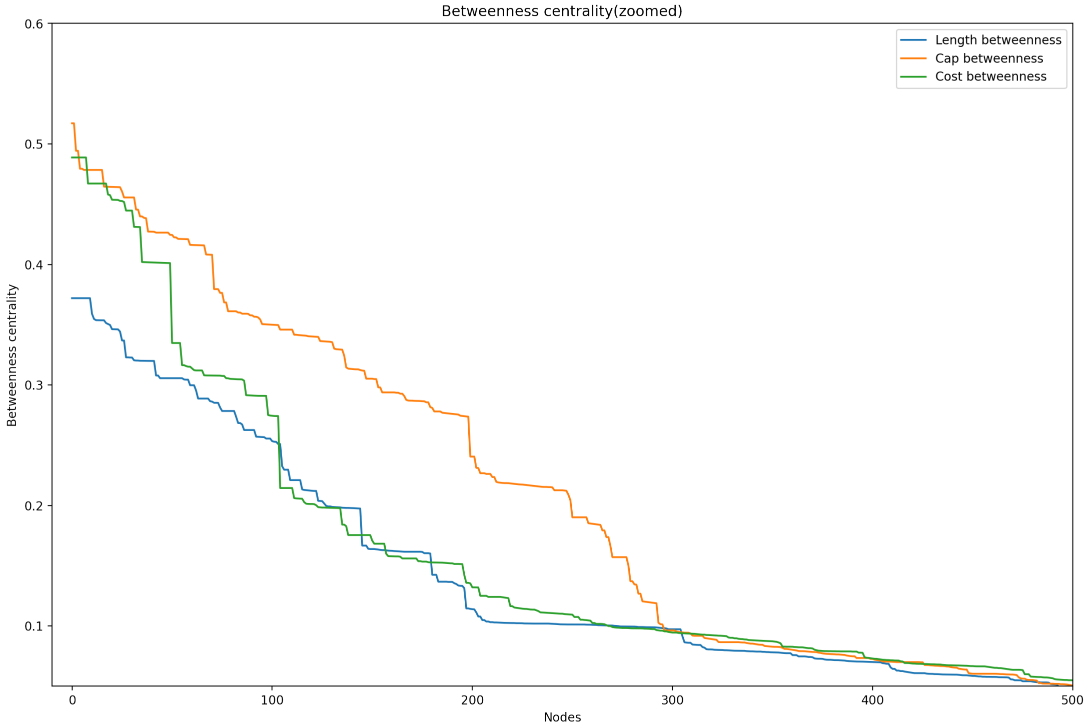

Figure 5.17: Betweenness centrality Zoomed

	Latency	Cost	Capacity
count	7229	7229	7229
mean	0.015085355	0.016789418	0.019458784
std	0.043984581	0.051353499	0.064554104
min	0	0	0
25%	0.000892193	0.000609267	0.000675097
50%	0.002603469	0.002106302	0.002119711
75%	0.008613072	0.009043768	0.007870817
max	0.371998844	0.48875602	0.517119399

Table 5.2: Summary of low-level betweenness centrality

Figure 5.16 displays a power-law distribution pattern based on the betweenness centrality for each routing policy, and Table 5.2 presents the relevant summary statistics. In network science, this is a poor design since the performance of the route choice is mostly dependent on a small number of nodes. If the failure happens on the high betweenness centrality node, this design would result in a dramatically deteriorate of the efficiency of the data flow when the network is switched to the sub-optimal route(eg. takes more time to the destination, narrowed bandwidth, higher usage cost).Figure 5.17 provides a zoomed view of the first 500 nodes from Figure 5.16, showing a more in-depth data pattern across various routing strategies. It is evident that Bandwidth > Cost > Latency in the first 300 nodes, which mostly explains why there is such a large gap between the mean value with the contrast of little variation in 75% values from Table 5.2.

Therefore, if any highlighted node or cable in Figure "Betweenness Latency" to Figure "Betweenness Cost" fails, a greater loss in global STC bandwidth can be expected when compared with the latency. Furthermore, compared to other routing strategies, the distribution of latency betweenness shows a shallow curve with a lower standard deviation, which suggests a looser network with higher resilience. In other words, transmission delay would be less affected by the disconnect on a key node than bandwidth capacity.

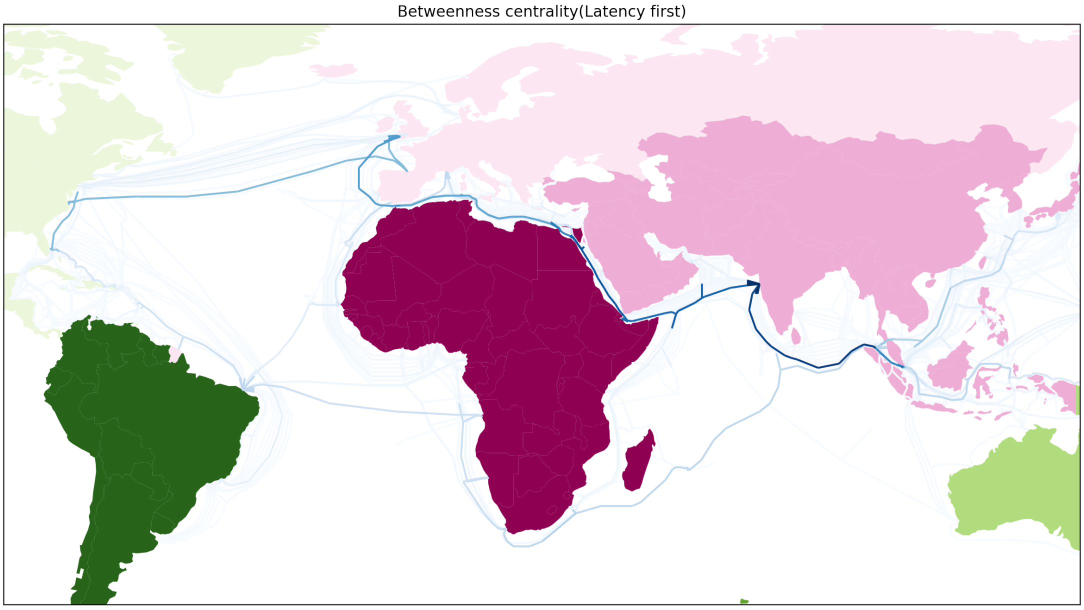

Figure 5.18: Betweenness centrality map(C^L)

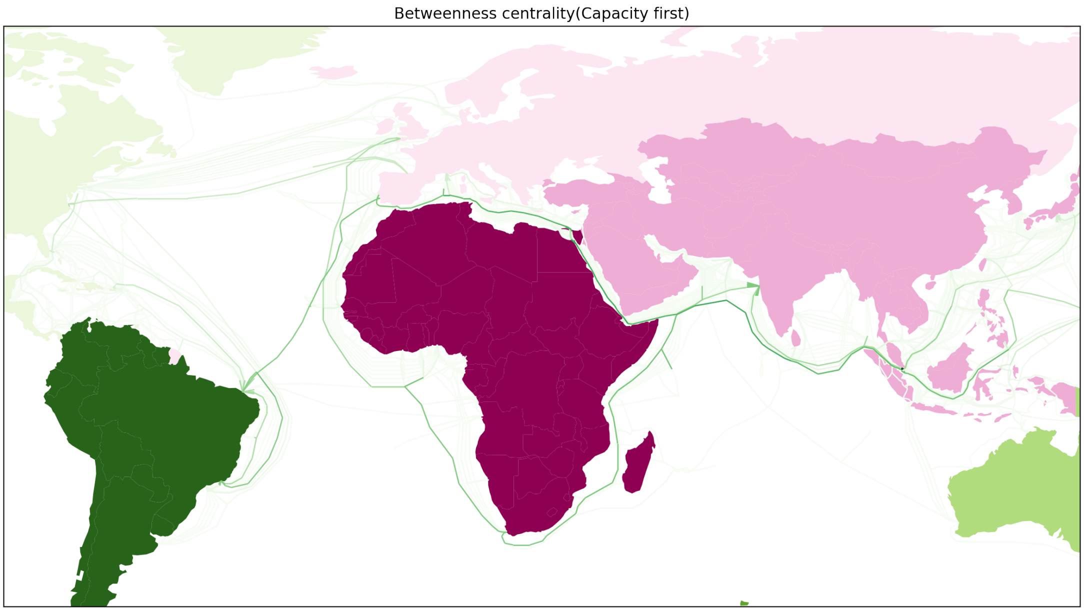

Figure 5.19: Betweenness centrality map(C^B)

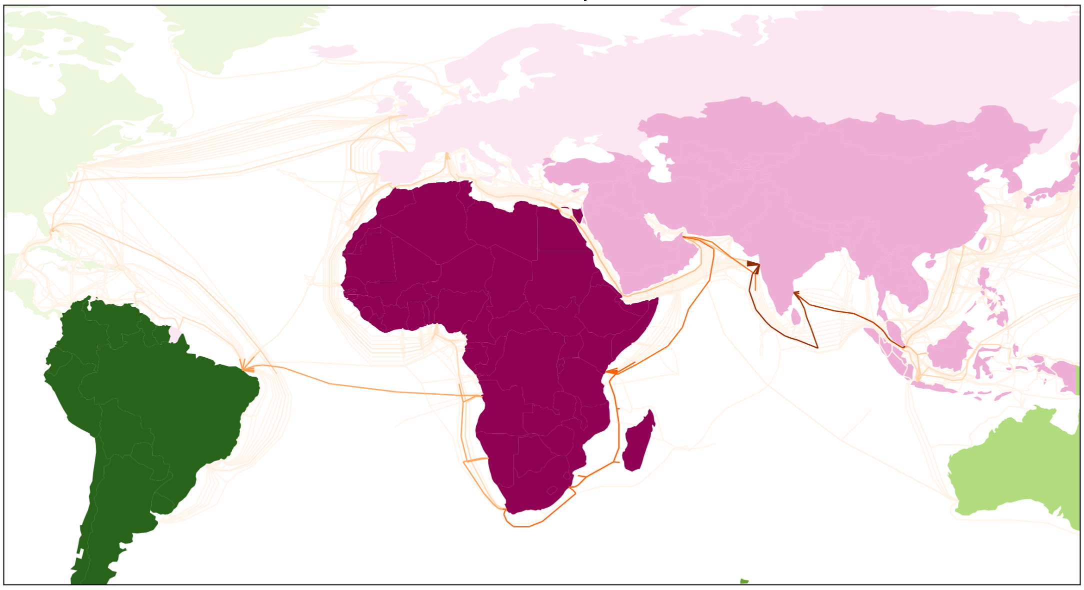

Figure 5.20: Betweenness centrality map(C^C)

Figure 5.21 aggregates the betweenness results above to provide a summary of the node distribution to the adjacent cables. Of the three classes of routing policies, each group is showing a different focus on patterns. It is crucial to use various distance metrics over the entire STC network to demonstrate the function of betweenness centralities.

Out of 3 routing policies, the spatial pattern reveals some informative clues. Firstly the latency betweenness measure of C^L appears to maintain one highlighted connection between two geographic adjacent continents, especially in the route connecting from Singapore(Asia) to New York (North America) via UK(Europe). This outcome may have been influenced by the demand in the finance sector(eg Stock exchange), as the data synchronization between financial data centers usually consists of the feature of high requirements for real-time transmission. Secondary, the bandwidth betweenness shows a widespread distribution, this offers many benefits from reliability to data accessibility. This distributed architecture might not propose a critical bandwidth shortage problem to the remaining servers even if the malfunction occurs on the most important node(eg India). As some of the web-services services can be hosted on the existing cloud or CDN deployments, the widespread wide bandwidth cables are most clearly benefiting from the cloud-hosted resources(eg. trending YouTube videos) on the nearby CDN service stations. Finally, the cost betweenness highlights the necessary nodes required to achieve the minimum cost, showcase route from Singapore to Brazil via India, UAE and South Africa is highlighted, while this route avoids the most cable congested water lane in the Mediterranean Sea instead of an open connection in South Africa. It is interesting to find out the overlap between C^B and C^C in East Africa where the cables(eg 2Africa) are more advanced in budget control and bandwidth capacity.

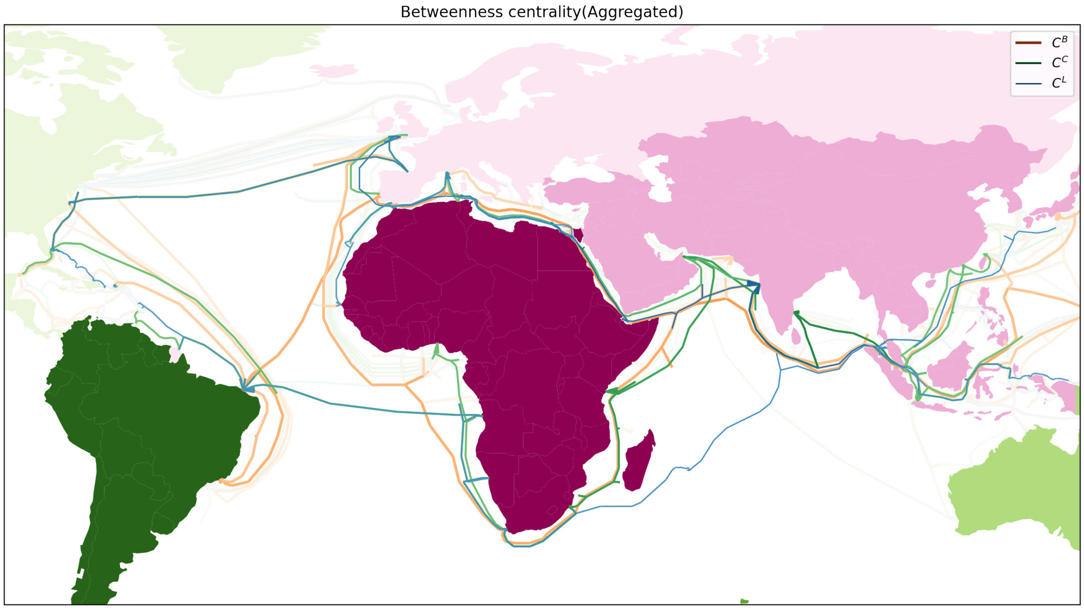

Figure 5.21: Aggregated betweenness centrality map

Figure 5.21 aggregates the previous betweenness analysis into one visualization to provide a snapshot of the top 5% most important routes around the world. With a high clustering in Southeast Asia, MENA(Middle East and North Africa) and Celtic Sea, this finding could be utilized to simulate the consequence of the cable accident in those regions by estimating the impact on overall network functionality reduction.

5.4 Network optimization with CPP

The Tonga volcano eruption on 20 Dec 2021 was reportedly the greatest volcanic explosion to have occurred since 1883 on record, which subsequently caused the destruction of Tonga only STC on 15th Jan. (CNN 2022)

After 38 days of lack of full access to broadband, repair ship Reliance replaced 92km of STC between Tonga to Fiji. (Tomé 2022) Satellite telecommunication was used to support communication with the outside world during that period, however the traffic shrank by around 99%.

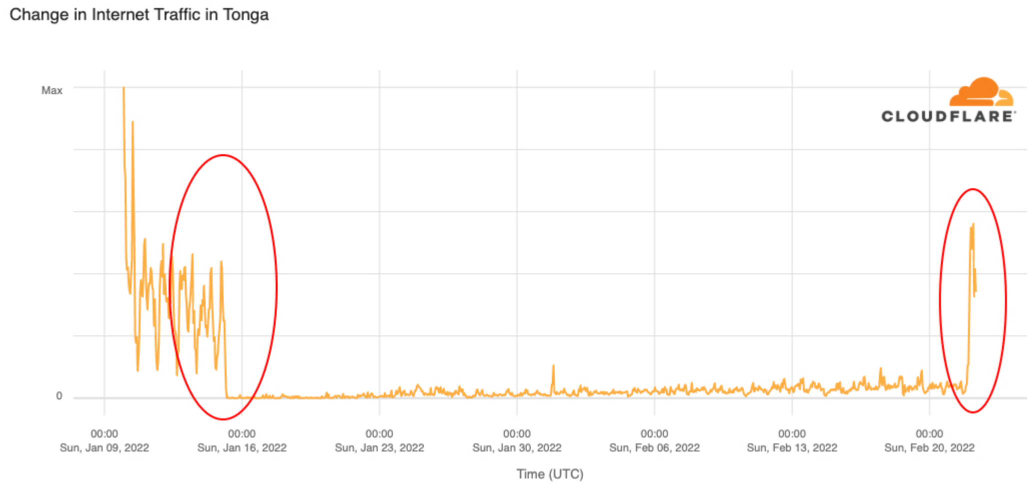

Figure 5.22: Tonga internet traffic during the STC failure(Cloudflare 2022)

5.4.1 Redundancy analysis

Building multiple cables as backup internet services will help Tonga overcome the fault scenario and mitigate the consequences of connectivity loss on the primary cable. This acquires at least two cables, whether they are STC or TTC, connecting to the same landing station. On this basis, the author uses the Chinese Postman Problem (CPP) for network improvement. According to the CPP's theory, edges can be classified as either in-degree or out-degree, and each node contains at least one pair of each type of edge. Out of many solutions, we found an optimal solution by minimizing the total length of the additional route planned to be built.

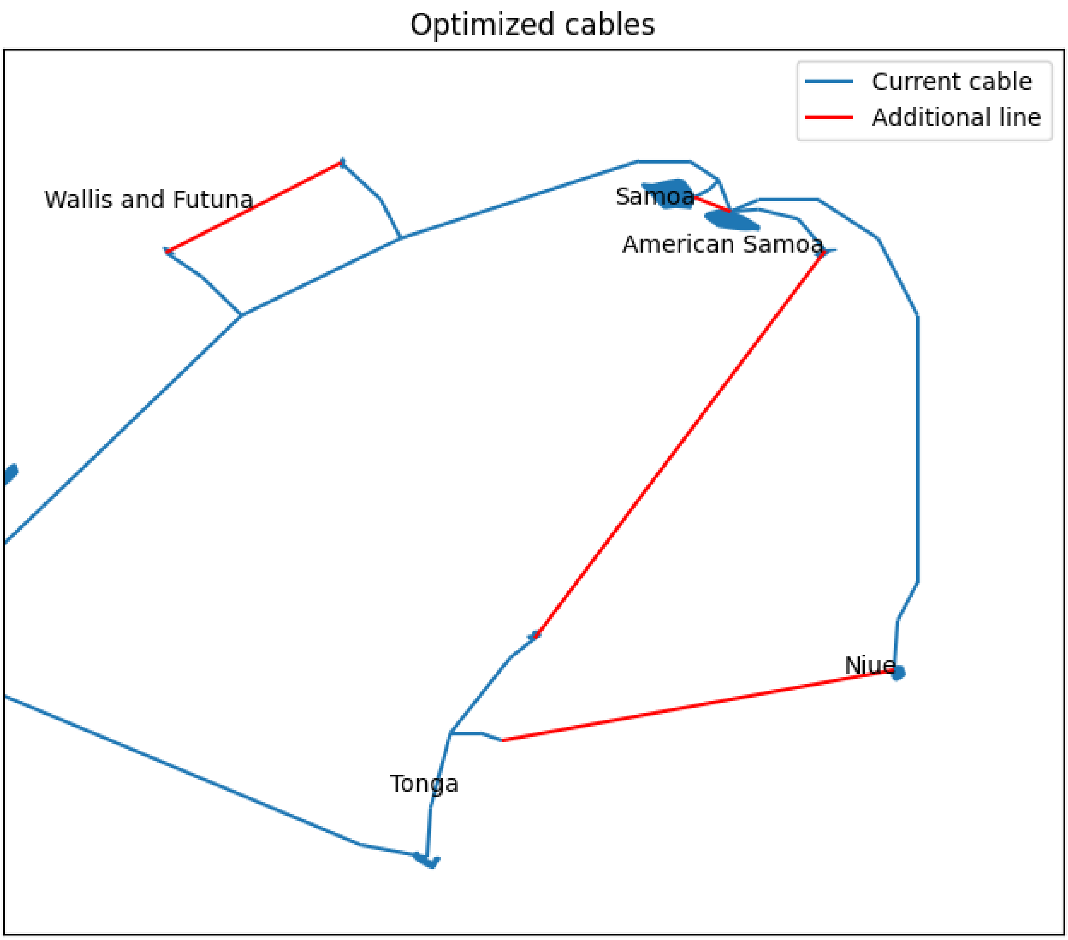

Figure 5.23: Planned STC optimization for Tonga

This modification to the STCs would make the network more efficient by allowing more nodes to participate in the information transformation, the average degree centrality was increased from 0.0588 to 0.0660 locally in these regions. On another positive note, network becomes more distributed by reducing the dependency on essential communication between the high degree nodes. According to the analysis in Figure 5.24, the average rich-club coefficient is now 0.2660 compared to 0.2741 before to the improvement, indicating a weaker rich-club effect in the optimized design as the degree different is smaller.

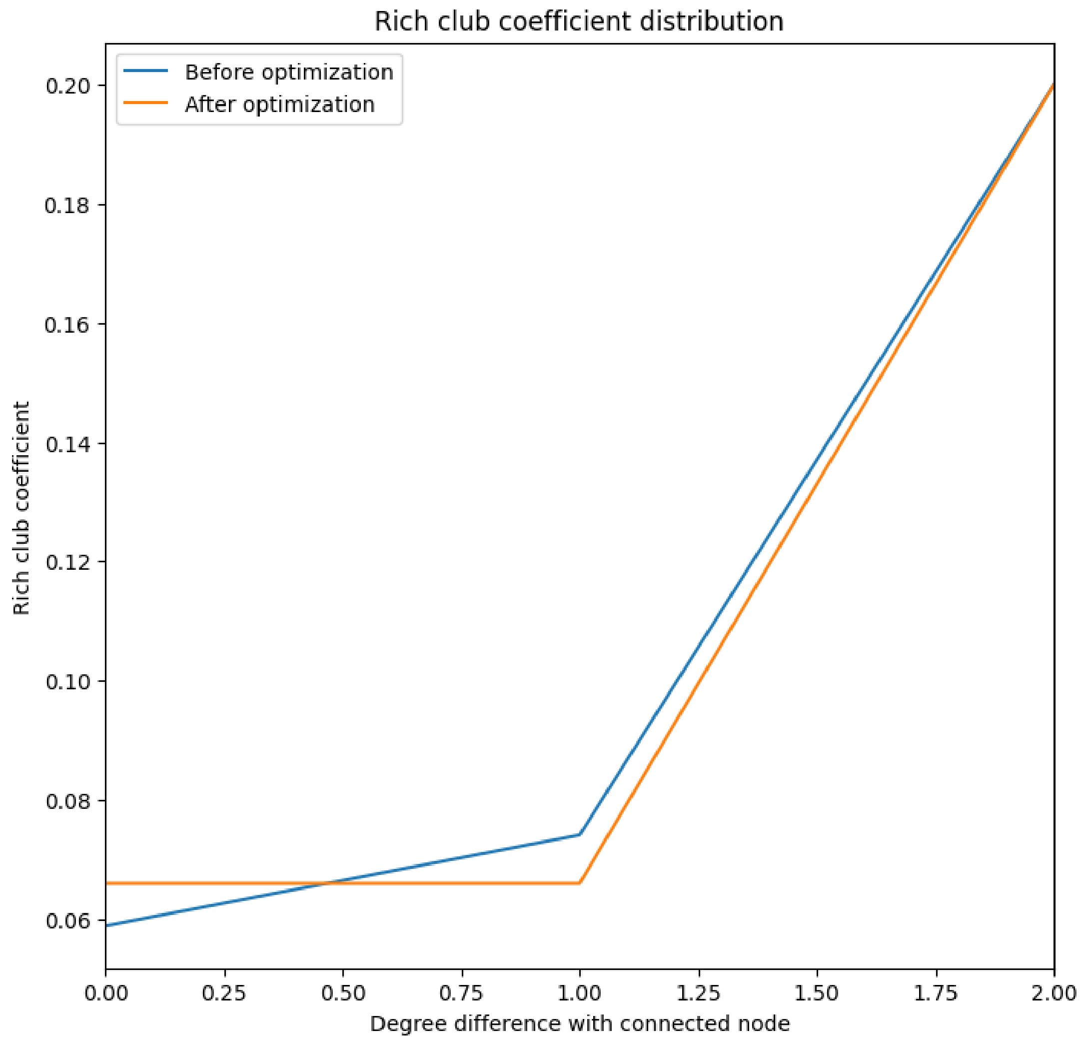

Figure 5.24: Rich-club analysis in Tonga

5.4.2 Financial cost

Any modification to the existing system could bring extra cost, especially when laying the additional cables for extra redundancy. The cost of deploying extra STC and the implementation of start link as an alternative technology in the Tonga region will be compared and contrasted in this section.

While analyzing the cost of the existing cables in the near water against with cable attributes by regression analysis, an adjusted R-squared of 0.963 suggests a good fit to the budget estimation of the planned cables. The expected lengths of the two cables from Tonga to Niue and American Samoa are 618.18KM and 517.63KM with the cost of $13.29 and $10.54 Million USD separately. These cables will directly benefit people in Tonga, Niue, and American Samoa. They also offer a sub-optimal route for nearby countries such as French Polynesia and Cook Islands.

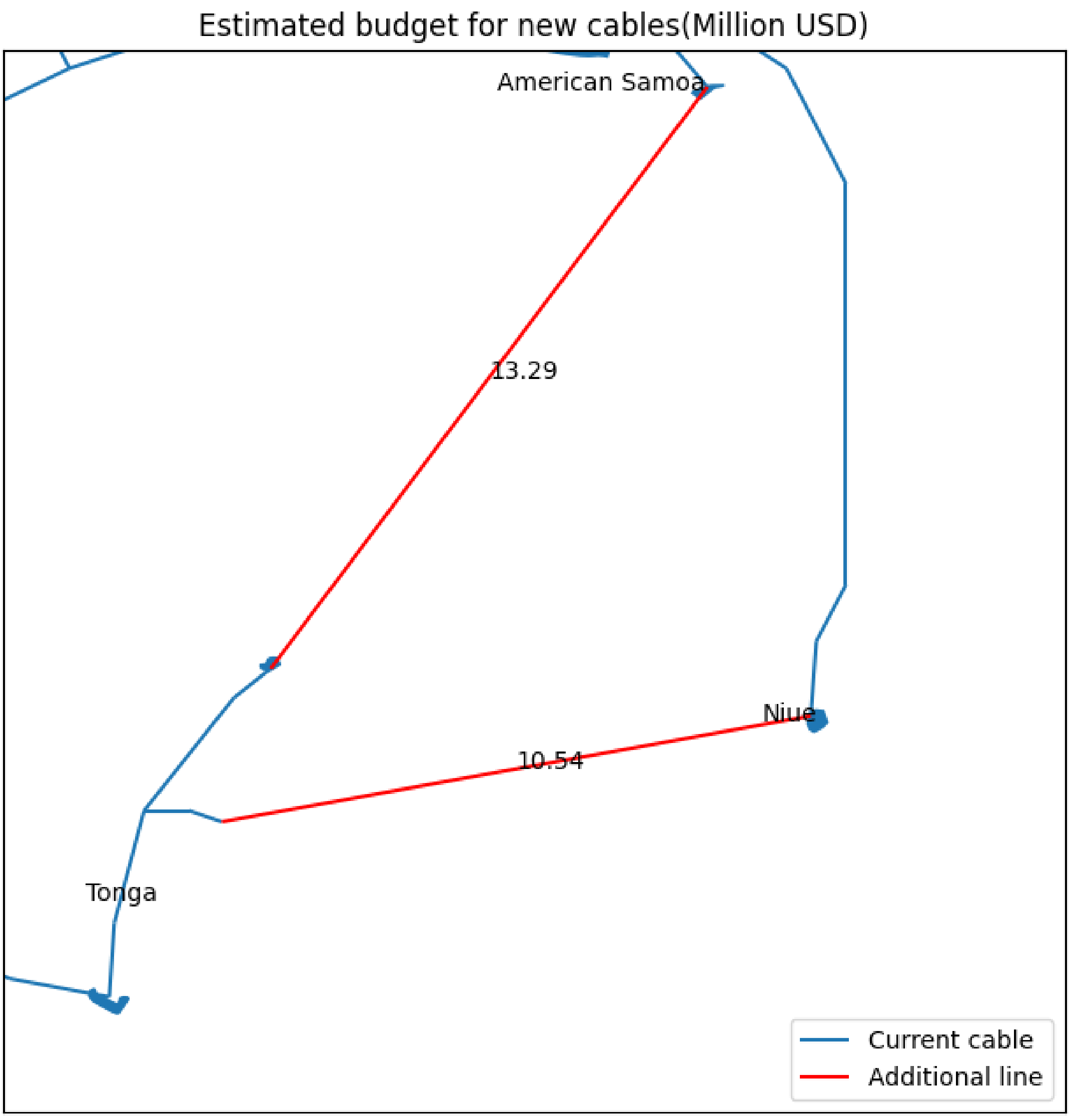

Figure 5.25: Estimate cost to deploy redundant cables

With 25 years of industrial average service life, the infrastructure life expectancy will be based on that. Star link is the most common consumer level satellite internet services, as an alternative technology to the STC. Hardware ($599) and services ($110/Month), which together make up the price to use the Start Link (starlink 2022), can be estimated to reach $112 per capita during the following 25 years. Meanwhile, the STC is sharing the same infrastructure cost regardless of the number of internet users, the capita cost is inversely proportional to the number of subscribed users to the network. As Figure 5.26 shows, by the estimate from ITU in 2016 there are 55612 internet users in Tonga, Niue and American Samoa, it would be more cost-effective to invest in STC if more than 1862 units (individuals or companies) are willing to pay for the most standard data package in the next 25 years.

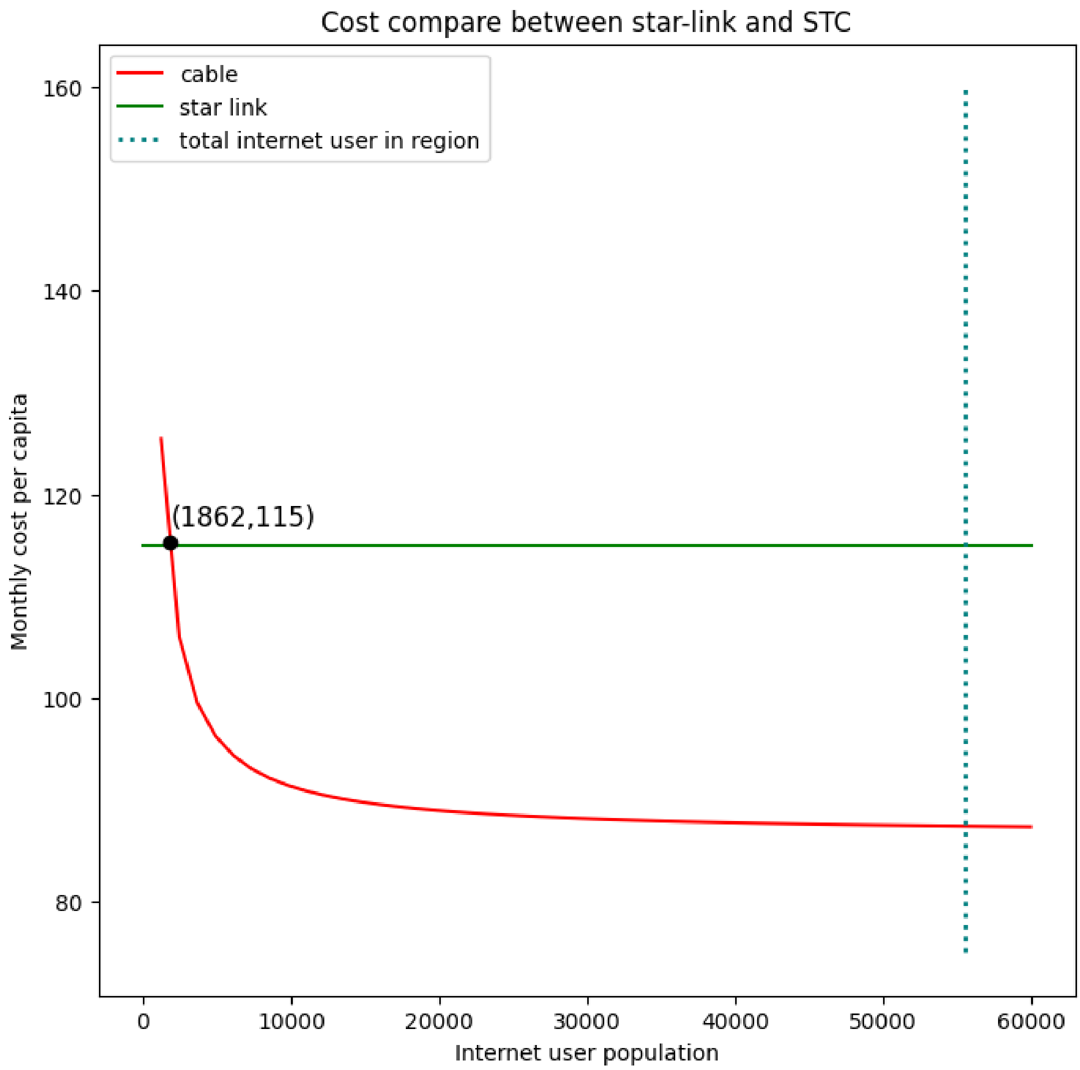

Figure 5.26: Cost of new STC compared with alternative technology

Chapter 6

Discussion

This paper studies the topological structure of the STC network and analyzes its vulnerability at both country level and route level. This section aims to comment on the findings and reflect on the limitations due to their real-world implications.

Firstly, the country level network consists of a wider range of areas by averaging the geographical differences and accessibility to the cable repair resources. For instance, different water conditions measurements, waterway and no-shipping zone, rich and poor countries. A more explicit analysis would help to clarify the damage results. Secondary, landlocked states are not included in this study, this was partly because of the lack of construction data in TTC. Consequently, the international bandwidth purely flowing through the TTC network is ignored. Thirdly, the property status for some STCs are not publicly available. The estimation was based on the cable length, year of construction, budget cost and the status of existing cables in the nearby water. The actual capacity in usage is less than estimation since the most cited metrics are potential capacity(max possible bandwidth) rather than lit capacity(actual running bandwidth).

As the STC network's topological structure is the main focus. Testing results of the shortest-path analysis from UK to China and global betweenness centrality analysis using different distance measurements to simulate the assortment of focus on the routing strategies. The shortest path finding merely discloses some theoretical paths, the routers in the real-world also need to consider factors such as instantaneous availability of the cables, communication jamming and pre-defined rules in the routing table etc. The overlap of a handful of landing stations with the high value of betweenness centrality also suggests the potential risk of workload overwhelming on the popular landing stations when they are chosen by multiple routing policies simultaneously.

However, STC failure could also be dependent on a variety of regional circumstances. Future research will examine the role of CDN, high volumes of fishing, cargo shipping, water saltiness, and earth tectonic hazard frequency. This study was motivated by the analysis of the route pattern in the real-world distribution when the weakness of STC can be targeted, the identification of adjustments for the quality infrastructure setup through avoidance of the missing connections. Yet, these arguments do not go far enough.

To overcome the vulnerability, redundancy is not the only available option to fill the missing capacity gap due to the absence of a primary cable. Instead, redundant cables are especially weak against human-led destruction. States can influence the cable deploying companies with a more frequent cable status patrol or by adding prevent cautions such as setting up cable protection zones to prevent the damage from fishing dredge or anchoring. Yet these precautions do not exclude the risk of natural hazards. Avoiding the seismic, volcanic, and landslide zone on the cable path is meaningful to prevent destruction from the geologic activities before laying the cables. Thus the open communication and negotiation between ISPs and cable operators before the proper deployment helps to reduce the uncertainty of the network stability.

Another aspect that also helps to better understand the vulnerability is the countermeasures in the internet backbone landing stations while facing major events such as unexpected hostile attacks on infrastructure or internet blackouts due to a natural hazard. Moreover, the dependency on energy infrastructure and cascading effects on the bandwidth deteriorates in the nearby states, along with the negative side effects on other internet-dependent businesses such as government administration, banking services and other digital services. Leading to a higher requirement for cable and relative infrastructure protection.

Additionally, developing emergency planning and keeping open communication with the damage control crew and in-hand repair tools(materials, vessels) are the keys to maintaining broadband connectivity. Moreover, the satellite internet communication devices also help to enhance the robustness against STC failure. In view of this, installing the redundant cables and utilizing satellite internet services as the backup technology by driving the diversification of the broadband access entrance can be considered a bright side to the global internet connectivity resilience.

Chapter 7

Conclusion and Recommendations

The submarine telecommunication cable network is an essential infrastructure that urgently needs to be protected, but academia and international legislation should not dismiss the negative social and economical tensions caused by STC failure, especially when the intentional attack(eg military and terrorism) can be achieved very easily.

This paper modeled the global STC network and analyzed the topological vulnerabilities from 2 arguments(cable, landing station) in 2 visibility levels(country, local) as the means of assessing the robustness of alternative cables when the primary fails.

The study firstly analysis all the states(n=183) with STC connections, the broadband threshold of internet shortage in the next few years remains low, but around 48% of the countries are formed in the most vulnerable class. The most vulnerable states must improve their telecommunication infrastructure quality to minimize the probability of internet blackout at the state level. Also, a further territorial investigation shows the high dependency of a handful of key landing stations on international internet connectivity. In addition, we also compared the impact of emerging internet services infrastructure(star-link), their usage as an emergency substitute, which might back up the additional connectivity. From the standpoint of cable shortages in internet vulnerable countries and the increasing participation of international tech giants recently, future research will also take into consideration larger international geopolitical contestation.

However, these findings need to be seen in context of certain limitations. There are deviations from real observations for nations with domestically abundant internet content resources, like the US; or that have adopted the same language as sizable proportion of internet users, such as China. Consequently, the estimation in the model could result in excessive or inadequate network flows. On the other hand, modeling the local accessibility of internet connectivity goes beyond the network's topological structure and may also take local/international legislation and marine sciences into account.

Due to the short duration of the project lifecycle, the model will be expanded to include GraphEmbedding and representation learning in future research. Exploring the role that CDN can play in mitigating the consequences while facing the major STC disruptions or internet peak hours.

As data communication plays a crucial role more than ever, the importance and vulnerability of the STC should seriously be recognized by relative experts from oceanography to geopolitics.

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Chapter 8

Appendix

8.1 Country level network visualization

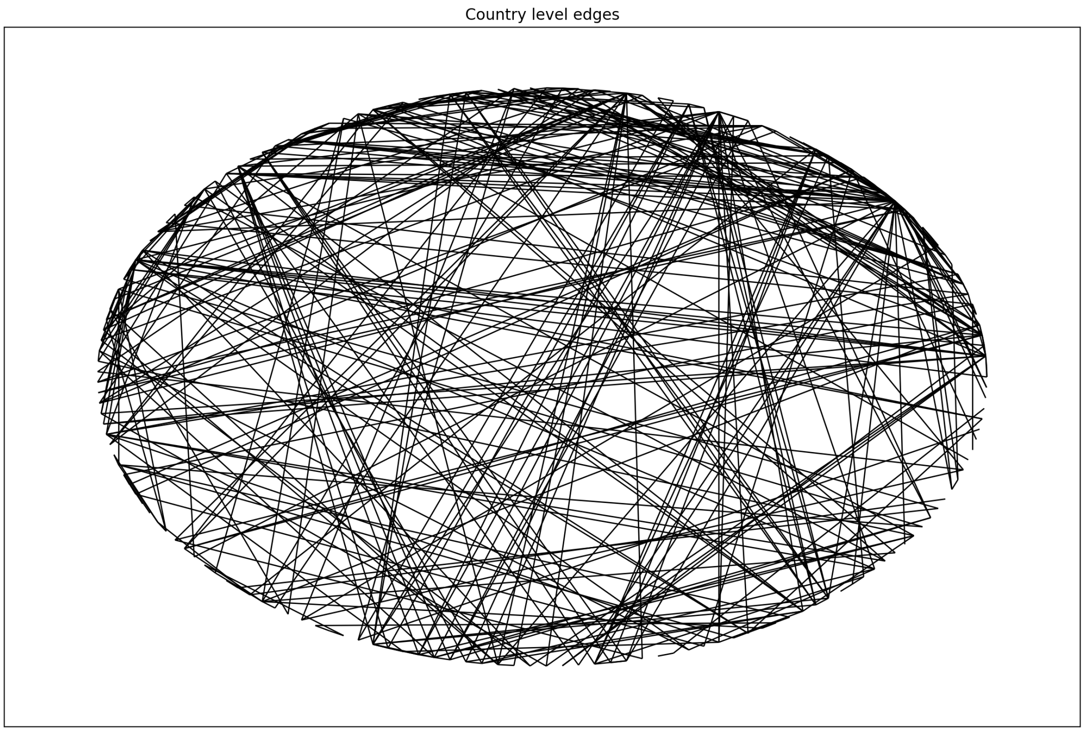

Figure 8.1: Country level network visualization

8.2 Landing station level network visualization

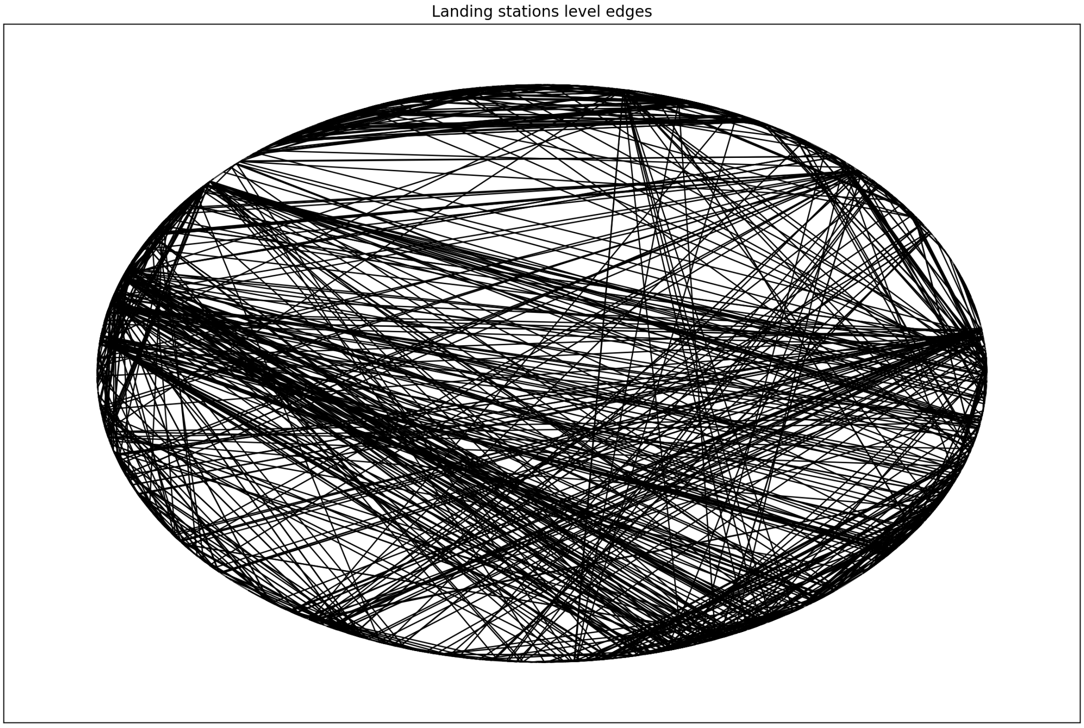

Figure 8.2: Landing station level network visualization

8.3 Country's first STC

Table 8.1: Country's first STC

Country	First cable year
Denmark	1989
Sweden	1989
United Kingdom	1989
Isle of Man	1990
Spain	1990
Poland	1991
Estonia	1992
Finland	1992
France	1992
Iran	1992
United Arab Emirates	1992
United States	1992
Cyprus	1993
Turkey	1993
Croatia	1994

Continued on next page

Table 8.1 – continued from previous page

Country	First cable year
Djibouti	1994
Faroe Islands	1994
Germany	1994
Guernsey	1994
Iceland	1994
Italy	1994
Jersey	1994
Latvia	1994
Morocco	1994
Yemen	1994
Anguilla	1995
Antigua & Barbuda	1995
Argentina	1995
Australia	1995
Barbados	1995
Dominica	1995
Greece	1995
Grenada	1995
Guadeloupe	1995
Lebanon	1995
Lithuania	1995
Malta	1995
Martinique	1995
Monaco	1995
Saint Kitts & Nevis	1995
Saint Lucia	1995
Saint Vincent & Grenadines	1995
Sint Maarten	1995
Syria	1995
Trinidad & Tobago	1995
Tunisia	1995
Uruguay	1995
Virgin Islands (U.K.)	1995
Albania	1996
Brazil	1996
Portugal	1996
Bahamas	1997
Bulgaria	1997
Cape Verde	1997
Cayman Islands	1997
Main land, China	1997
Colombia	1997
Dominican Republic	1997
Egypt	1997
India	1997

Continued on next page

Table 8.1 – continued from previous page

Country	First cable year
Jamaica	1997
Japan	1997
Jordan	1997
Malaysia	1997
Netherlands	1997
Northern Mariana Islands	1997
Philippines	1997
Romania	1997
Saudi Arabia	1997
South Korea	1997
Thailand	1997
Virgin Islands (U.S.)	1997
Bahrain	1998
Kuwait	1998
Libya	1998
Qatar	1998
Venezuela	1998
Aruba	1999
Belgium	1999
Brunei	1999
Curacao	1999
Indonesia	1999
Ireland	1999
Israel	1999
Myanmar	1999
Norway	1999
Oman	1999
Pakistan	1999
Singapore	1999
Sri Lanka	1999
Taiwan, China	1999
Vietnam	1999
Bermuda	2000
Chile	2000
Costa Rica	2000
Fiji	2000
French Guiana	2000
Georgia	2000
Honduras	2000
Mexico	2000
New Zealand	2000
Panama	2000
Peru	2000
Russia	2000
Belize	2001

Continued on next page

Table 8.1 – continued from previous page

Country	First cable year
Canada	2001
Ecuador	2001
Guatemala	2001
Nicaragua	2001
Turks and Caicos Islands	2001
Algeria	2002
Angola	2002
Benin	2002
Cameroon	2002
Cote D'Ivoire	2002
Gabon	2002
Ghana	2002
Mauritius	2002
Nigeria	2002
Reunion	2002
Senegal	2002
South Africa	2002
Sudan	2003
Saint Martin	2004
Bangladesh	2005
Haiti	2006
Iraq	2006
Maldives	2006
Montserrat	2006
Saint Barthelemy	2006
Bonaire, Sint Eustatius and Saba	2007
New Caledonia	2008
American Samoa	2009
Greenland	2009
Kenya	2009
Madagascar	2009
Mozambique	2009
Papua New Guinea	2009
Samoa	2009
Tanzania	2009
Comoros	2010
French Polynesia	2010
Guyana	2010
Marshall Islands	2010
Micronesia	2010
Somalia	2010
Suriname	2010
Equatorial Guinea	2011
Gibraltar	2011
Congo, Dem. Rep.	2012

Continued on next page

Table 8.1 – continued from previous page

Country	First cable year
Congo, Rep.	2012
Cuba	2012
Gambia	2012
Guinea	2012
Guinea-Bissau	2012
Liberia	2012
Mauritania	2012
Mayotte	2012
Namibia	2012
Sao Tome & Principe	2012
Seychelles	2012
Sierra Leone	2012
Togo	2012
Tonga	2013
Ukraine	2014
Vanuatu	2014
Cambodia	2017
Palau	2017
Christmas Island	2018
Saint Pierre and Miquelon	2018
Wallis and Futuna	2018
Cook Islands	2020
Niue	2020
Solomon Islands	2020
Azerbaijan	2022
Cocos (Keeling) Islands	2022
Kazakhstan	2022
Kiribati	2022
Saint Helena	2022
Tokelau	2022
Turkmenistan	2022
Timor-Leste	2024

8.4 Country's cable connection

Table 8.2: Country's cable connection

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
Albania	Croatia	1	0.0006
Albania	Italy	1	0.0025
Algeria	France	4	510.8073
Algeria	Spain	2	40.16
American Samoa	Samoa	1	2.4915
Angola	Brazil	1	40

Continued on next page

Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
Angola	Cameroon	2	15.3
Angola	Italy	1	140.4585
Anguilla	Virgin Islands (U.K.)	1	1.1
Antigua & Barbuda	Montserrat	1	1.0501
Antigua & Barbuda	Saint Kitts & Nevis	1	1.1
Argentina	Dominican Republic	1	19.2
Argentina	United States	1	140.4585
Argentina	Venezuela	1	4.84
Aruba	Colombia	1	45
Australia	Cocos (Keeling) Islands	1	39
Australia	Indonesia	3	336
Australia	Japan	2	25.7399
Australia	Papua New Guinea	2	28.4
Australia	Timor-Leste	1	187.338
Australia	United States	5	198.28
Bahamas	Panama	1	8.4
Bahrain	Kuwait	4	194.2385
Bahrain	Saudi Arabia	1	1.28
Bangladesh	Sri Lanka	3	269.3584
Barbados	Saint Lucia	2	2.1501
Belgium	France	1	0.1399
Belgium	United Kingdom	4	105.6925
Belize	Guatemala	1	8.4
Benin	France	1	20
Benin	Ghana	1	0.8
Benin	Togo	1	78.9573
Bermuda	United States	2	2.82
Bermuda	Venezuela	1	0.1865
Brazil	Argentina	3	102.9973
Brazil	Bermuda	1	0.1865
Brazil	Dominican Republic	1	50
Brazil	Trinidad & Tobago	1	10
Brazil	United States	3	292
Brazil	Uruguay	2	230.4585
Brunei	Indonesia	1	0.1399
Brunei	Malaysia	1	24.9506
Brunei	Singapore	1	28
Brunei	Vietnam	1	28.8
Cambodia	Malaysia	2	110
Cameroon	Brazil	1	32
Cameroon	Equatorial Guinea	1	24
Cameroon	Gabon	2	20.8
Cameroon	Nigeria	2	27.3
Canada	United States	3	128.584
Cape Verde	Brazil	1	72

Continued on next page

Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
Cayman Islands	Costa Rica	1	0.9225
Cayman Islands	Honduras	1	140.4585
Chile	Colombia	2	24.04
Chile	Peru	1	108
Chile	United States	1	72
Main land, China	Brunei	3	56.9399
Main land, China	Malaysia	1	0.5
Main land, China	Singapore	3	70.96
Main land, China	United States	2	105.6
Main land, China	Vietnam	5	421.84
Christmas Island	Singapore	1	60
Cocos (Keeling) Islands	Oman	1	39
Colombia	Jamaica	1	12.8
Colombia	United States	9	289.0075
Comoros	Djibouti	2	152.2585
Congo, Dem. Rep.	Congo, Rep.	2	154.9585
Congo, Rep.	Angola	2	154.9585
Cook Islands	Niue	1	10
Costa Rica	Honduras	1	0.9225
Costa Rica	Mexico	1	3.2
Costa Rica	Nicaragua	1	8.4
Croatia	Italy	1	0.0331
Cyprus	Egypt	3	48.72
Cyprus	Greece	1	187.338
Cyprus	Italy	1	0.0025
Cyprus	Turkey	4	42.9968
Denmark	Faroe Islands	1	0.0075
Denmark	Iceland	1	5.1
Denmark	Netherlands	1	44.385
Denmark	Norway	4	2095.025
Denmark	United Kingdom	1	105.3101
Djibouti	Cyprus	1	0.1399
Djibouti	Egypt	5	591.2641
Djibouti	Jordan	1	187.338
Djibouti	Kenya	3	244
Djibouti	Tanzania	3	159.5385
Djibouti	Turkey	1	18.7069
Dominica	Trinidad & Tobago	2	2.1501
Dominican Republic	Chile	1	19.2
Dominican Republic	Colombia	1	50
Dominican Republic	Haiti	1	7.2
Dominican Republic	Jamaica	1	2.5
Dominican Republic	Turks and Caicos Islands	1	8.4
Dominican Republic	United States	2	140.5371
Ecuador	Guatemala	2	127.2

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Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
Ecuador	Panama	2	185.4585
Egypt	Algeria	1	30
Egypt	France	3	444.5841
Egypt	Greece	4	760.1399
Egypt	Italy	5	80.8773
Egypt	Libya	1	3.84
Egypt	Malta	1	16
Egypt	South Africa	2	147.7385
Equatorial Guinea	Nigeria	1	20
Equatorial Guinea	Sao Tome & Principe	1	105.3101
Estonia	Sweden	2	0.2307
Faroe Islands	Iceland	2	0.0275
Fiji	New Caledonia	1	105.3101
Fiji	New Zealand	2	94
Fiji	Samoa	1	17.6
Fiji	Tonga	1	7.8844
Fiji	Vanuatu	1	0.32
Finland	Estonia	4	0.4248
Finland	Germany	1	144
Finland	Sweden	5	44.549
France	Ghana	1	20
France	Jersey	1	0.5903
France	Morocco	1	1.4006
France	Spain	1	480
France	United Kingdom	8	2655.0382
France	United States	1	250
French Polynesia	Cook Islands	1	10
Gabon	Benin	1	78.9573
Gabon	Equatorial Guinea	1	20
Gabon	Nigeria	2	141.2585
Gambia	Senegal	1	20
Georgia	Bulgaria	1	12.6
Georgia	Russia	1	0.0025
Germany	Denmark	5	1.4331
Germany	Netherlands	1	5.2
Ghana	Portugal	1	10
Ghana	Spain	4	175.7585
Gibraltar	Portugal	1	3.84
Greece	Albania	1	0.0006
Greece	Italy	9	1346.4782
Greece	Libya	1	1.2
Greenland	Canada	1	2.56
Grenada	Antigua & Barbuda	2	2.1501
Guatemala	Mexico	3	198.8585
Guinea	Guinea-Bissau	1	20

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Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
Guinea-Bissau	Mauritania	1	20
Guyana	Barbados	1	44.385
Guyana	Trinidad & Tobago	2	188.618
Haiti	Bahamas	1	1.0501
Haiti	Jamaica	1	7.2
Honduras	Belize	1	8.4
Honduras	Guatemala	1	140.4585
Honduras	Mexico	1	0.9225
Iceland	Greenland	1	2.56
India	Maldives	3	452.4241
India	Mauritius	1	0.44
India	Oman	5	497.378
India	Pakistan	5	224.7087
India	Saudi Arabia	1	7.28
India	United Arab Emirates	1	0.5
Indonesia	Christmas Island	1	60
Indonesia	Malaysia	6	82.7576
Indonesia	Singapore	17	1088.356
Indonesia	United States	1	24.9506
Indonesia	Vietnam	1	0.1399
Iran	Bahrain	2	53.76
Iran	Kuwait	1	0.0025
Iraq	Comoros	1	140.4585
Iraq	Yemen	1	2.56
Ireland	Canada	2	78
Ireland	Iceland	1	18
Ireland	United States	2	137.199
Isle of Man	Ireland	1	105.3101
Israel	Cyprus	4	231.6519
Israel	Italy	1	12.8
Italy	Algeria	1	480
Italy	Belgium	1	0.1399
Italy	France	4	289.368
Italy	Gabon	1	140.4585
Italy	Monaco	1	0.0006
Italy	Tunisia	4	28.4315
Italy	United Kingdom	1	0.5
Jamaica	Cayman Islands	1	8.4
Jamaica	Cuba	1	5.12
Jamaica	United States	1	12.8
Japan	Canada	1	105.3101
Japan	Philippines	4	242.559
Japan	Russia	2	1.28
Japan	South Korea	10	388.7199
Japan	Taiwan, China	2	247.338

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Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
Japan	United States	7	224.2199
Jersey	Guernsey	2	0.6234
Jordan	Egypt	2	0.6049
Jordan	Israel	1	187.338
Kazakhstan	Azerbaijan	1	105.3101
Kenya	Cyprus	1	16
Kenya	Egypt	1	192
Kenya	Mozambique	3	159.5385
Kiribati	Australia	1	72
Kuwait	Madagascar	1	140.4585
Kuwait	Saudi Arabia	2	53.76
Latvia	Sweden	2	0.0356
Lebanon	Cyprus	1	0.0006
Lebanon	Egypt	1	3.323
Liberia	Sierra Leone	1	20
Libya	Italy	1	0.12
Libya	Monaco	1	3.84
Lithuania	Latvia	1	0.0442
Lithuania	Sweden	2	18.7855
Madagascar	Saudi Arabia	1	140.4585
Madagascar	Somalia	1	11.8
Madagascar	South Africa	1	24
Malaysia	Bangladesh	1	249.8641
Malaysia	India	1	0.44
Malaysia	Myanmar	2	258.7069
Malaysia	Sri Lanka	1	55
Malaysia	Thailand	8	394.2272
Maldives	Oman	1	2.56
Maldives	Pakistan	1	249.8641
Malta	France	1	16
Malta	Italy	5	16.5782
Marshall Islands	Micronesia	1	3.323
Mauritania	Gambia	1	20
Mauritius	Madagascar	2	25.28
Mauritius	South Africa	1	0.44
Micronesia	Palau	1	24.9506
Micronesia	United States	1	3.323
Monaco	United Kingdom	1	3.84
Montserrat	Saint Kitts & Nevis	1	1.0501
Morocco	Portugal	2	480.1399
Mozambique	Egypt	1	7.28
Mozambique	Sudan	2	152.2585
Myanmar	Bangladesh	1	18.7069
Myanmar	India	2	320
Myanmar	Sri Lanka	1	0.1399

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Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
Namibia	Congo, Dem. Rep.	1	14.5
Namibia	Nigeria	1	12
Netherlands	Belgium	2	105.3126
Netherlands	United Kingdom	6	4084.3937
New Caledonia	Australia	1	0.64
New Zealand	Australia	4	349
New Zealand	Kiribati	1	72
Nicaragua	Honduras	1	8.4
Nigeria	Benin	1	0.8
Nigeria	France	1	140.4585
Nigeria	Ghana	1	10
Nigeria	Saint Helena	1	12
Nigeria	Sao Tome & Principe	1	20
Nigeria	Togo	1	14.5
Nigeria	United Kingdom	1	2.5
Niue	Samoa	1	10
Northern Mariana Islands	United States	2	7.2786
Norway	Canada	1	187.338
Norway	Ireland	2	309.0631
Norway	United Kingdom	2	216.1399
Oman	Iran	2	13.7958
Oman	Saudi Arabia	3	444.898
Oman	Seychelles	1	140.4585
Oman	Somalia	1	24.9506
Oman	United Arab Emirates	9	214.0068
Pakistan	Oman	5	240.5853
Pakistan	Saudi Arabia	1	249.8641
Pakistan	Seychelles	1	16
Pakistan	United Arab Emirates	3	196.1103
Palau	Indonesia	1	144
Palau	Philippines	1	24.9506
Panama	Cayman Islands	2	141.381
Panama	Costa Rica	2	11.6
Panama	Mexico	1	20
Papua New Guinea	Indonesia	1	44.385
Papua New Guinea	United States	1	8.4
Peru	Ecuador	2	127.2
Peru	Panama	1	4.84
Philippines	Main land, China	8	271.7399
Philippines	Indonesia	3	399.6266
Philippines	United States	3	269.8192
Poland	Denmark	1	0.0025
Poland	Sweden	1	0.005
Portugal	Cape Verde	2	86.5
Portugal	Liberia	1	20

Continued on next page

Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
Portugal	Senegal	3	151.2585
Qatar	Bahrain	3	141.7585
Qatar	Iran	2	53.76
Qatar	Saudi Arabia	1	80
Romania	Bulgaria	1	0.0012
Russia	Finland	1	0.1865
Russia	Ukraine	1	10.5159
Saint Helena	Portugal	1	12
Saint Kitts & Nevis	Saint Martin	2	8.9345
Saint Kitts & Nevis	Sint Maarten	1	1.1
Saint Lucia	Saint Vincent & Grenadines	2	2.1501
Saint Martin	United States	3	6.0526
Saint Pierre and Miquelon	Canada	1	33.2781
Saint Vincent & Grenadines	Dominica	2	2.1501
Saint Vincent & Grenadines	Grenada	1	44.385
Samoa	Wallis and Futuna	1	17.6
Sao Tome & Principe	Benin	1	20
Saudi Arabia	Djibouti	7	706.022
Saudi Arabia	Egypt	1	0.7873
Saudi Arabia	Iraq	2	53.76
Saudi Arabia	Jordan	1	0.5
Saudi Arabia	Lebanon	1	3.323
Saudi Arabia	Somalia	2	332.4585
Saudi Arabia	Sudan	2	5.7121
Saudi Arabia	Yemen	2	98.7069
Senegal	Cape Verde	1	16
Seychelles	Somalia	1	16
Seychelles	Tanzania	1	5.9114
Seychelles	United Arab Emirates	1	140.4585
Sierra Leone	Guinea	1	20
Singapore	India	2	89.12
Singapore	Malaysia	11	866.5363
Singapore	Myanmar	1	140.4585
Singapore	Thailand	3	284.03
Singapore	United States	5	946.0141
Sint Maarten	Anguilla	1	1.1
Sint Maarten	Saint Martin	1	0.0025
Solomon Islands	Australia	1	20
Somalia	Comoros	1	11.8
Somalia	Djibouti	2	52
Somalia	Iraq	1	140.4585
Somalia	Yemen	1	192
South Africa	Angola	1	0.8
South Africa	Cameroon	1	20
South Africa	Congo, Dem. Rep.	1	140.4585

Continued on next page

Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
South Africa	Namibia	2	26.5
South Korea	Main land, China	1	0.5
South Korea	Taiwan, China	8	359.4199
Spain	Morocco	3	485.1237
Spain	Portugal	5	179.5985
Spain	United States	2	305.3101
Sri Lanka	India	7	509.3113
Sri Lanka	Maldives	2	80.3578
Sri Lanka	Pakistan	1	18.7069
Sudan	Egypt	2	143.0185
Sudan	South Africa	1	11.8
Suriname	Guyana	2	188.618
Sweden	Denmark	12	15.3295
Syria	Cyprus	1	0.0006
Syria	Egypt	1	0.005
Syria	Lebanon	1	0.0786
Taiwan, China	Main land, China	7	315.9914
Taiwan, China	Philippines	5	348.388
Taiwan, China	United States	1	60
Tanzania	Kenya	3	159.5385
Thailand	Bangladesh	1	0.7873
Thailand	India	1	0.5
Thailand	Myanmar	2	80.1399
Thailand	Sri Lanka	1	200
Thailand	United States	1	28.8
Timor-Leste	Indonesia	1	187.338
Togo	Ghana	1	14.5
Togo	Morocco	1	78.9573
Trinidad & Tobago	Grenada	2	2.1501
Trinidad & Tobago	Venezuela	1	10
Tunisia	Algeria	1	0.7873
Turkey	Egypt	2	18.8468
Turkey	Greece	1	38.4
Turkey	Romania	1	0.0012
Turkmenistan	Azerbaijan	1	105.3101
Turks and Caicos Islands	Colombia	1	8.4
United Arab Emirates	Iran	1	0.0186
United Arab Emirates	Kenya	1	1.28
United Arab Emirates	Qatar	7	275.5385
United Arab Emirates	Saudi Arabia	7	219.2971
United Kingdom	Faroe Islands	2	0.59
United Kingdom	Ghana	2	142.9585
United Kingdom	Gibraltar	1	3.84
United Kingdom	Guernsey	3	5.1705
United Kingdom	Ireland	11	135.8518

Continued on next page

Table 8.2 – continued from previous page

Country_From	Country_To	Num	Sum bandwidth(Tb/s)
United Kingdom	Isle of Man	5	106.7584
United Kingdom	Jersey	1	0.0002
United Kingdom	Morocco	1	0.1399
United Kingdom	Spain	3	109.6501
United Kingdom	United States	6	166.3865
United States	American Samoa	1	67
United States	Bahamas	3	22.8
United States	Cuba	2	63.0919
United States	Ecuador	2	185.4585
United States	French Polynesia	1	0.64
United States	Guatemala	1	50
United States	Mexico	1	105.3101
United States	Panama	4	96.1225
United States	Peru	2	24.04
United States	Tokelau	1	72
Uruguay	Argentina	4	234.8912
Venezuela	Chile	1	4.84
Venezuela	Colombia	1	0.1865
Venezuela	Dominican Republic	1	8.4
Venezuela	Jamaica	1	5.12
Venezuela	United States	1	10
Vietnam	Cambodia	1	80
Vietnam	Singapore	6	370.7799
Virgin Islands (U.K.)	Aruba	1	45
Virgin Islands (U.K.)	Bermuda	1	2.5
Virgin Islands (U.K.)	Dominican Republic	1	2.5
Virgin Islands (U.S.)	Dominican Republic	1	140.4585
Virgin Islands (U.S.)	United States	1	0.0786
Yemen	Djibouti	4	290.7401
Yemen	Sudan	1	2.56

8.5 STC vulnerable countries

Table 8.3: STC vulnerable countries

Country	Continent	Sum bandwidth(Tb/s)
Romania	Europe	0.0012
Albania	Europe	0.0031
Syria	Asia	0.0056
Poland	Europe	0.0075
Croatia	Europe	0.0338
Latvia	Europe	0.0798
Vanuatu	Oceania	0.32
Faroe Islands	Europe	0.5975

Continued on next page

Table 8.3 – continued from previous page

Country	Continent	Sum bandwidth(Tb/s)
Jersey	Europe	0.6234
Haiti	North America	1.0501
Montserrat	North America	1.0501
Anguilla	North America	1.1
Sint Maarten	North America	1.1025
Antigua & Barbuda	North America	2.1501
Dominica	North America	2.1501
Saint Lucia	North America	2.1501
Marshall Islands	Oceania	3.323
Lebanon	Asia	3.4023
Gibraltar	Europe	3.84
Monaco	Europe	3.8406
Northern Mariana Islands	Oceania	7.2786
Greenland	North America	7.36
Nicaragua	North America	8.4
Turks and Caicos Islands	North America	8.4
Bonaire, Sint Eustatius and Saba	North America	9.285
Costa Rica	North America	9.3225
Cook Islands	Oceania	10
Niue	Oceania	10
Saint Kitts & Nevis	North America	10.0345
Ukraine	Europe	10.5159
Bahamas	North America	11.8501
Saint Helena	Africa	12
Bulgaria	Europe	12.6012
Georgia	Asia	12.6025
Saint Barthelemy	North America	12.8844
Saint Martin	North America	12.8869
Wallis and Futuna	Oceania	17.6
Lithuania	Europe	18.8297
Gambia	Africa	20
Guinea	Africa	20
Guinea-Bissau	Africa	20
Liberia	Africa	20
Mauritania	Africa	20
Solomon Islands	Oceania	20
Sierra Leone	Africa	20
Mayotte	Africa	23.9869
Reunion	Africa	25.72
Namibia	Africa	26.5
Samoa	Oceania	30.0915
Saint Pierre and Miquelon	North America	33.2781
Belize	North America	33.3506
Cocos (Keeling) Islands	Asia	39
Aruba	North America	45.1

Continued on next page

Table 8.3 – continued from previous page

Country	Continent	Sum bandwidth(Tb/s)
Barbados	North America	46.5351
Grenada	North America	46.5351
Saint Vincent & Grenadines	North America	46.5351
Tonga	Oceania	47.8844
Christmas Island	Asia	60
Guadeloupe	North America	65.299
Cuba	North America	68.2119
American Samoa	Oceania	69.4915
Kiribati	Oceania	72
Tokelau	Oceania	72
Micronesia	Oceania	72.6586
Cambodia	Asia	80
Togo	Africa	93.4573
Benin	Africa	99.7573
Azerbaijan	Asia	105.3101
Kazakhstan	Asia	105.3101
Turkmenistan	Asia	105.3101
Belgium	Europe	105.5526
New Caledonia	Oceania	105.9501
Sao Tome & Principe	Africa	125.3101
Virgin Islands (U.S.)	North America	140.5371
Honduras	North America	149.781
Cayman Islands	North America	149.781
Congo, Dem. Rep.	Africa	154.9585
Congo, Rep.	Africa	154.9585
Mozambique	Africa	159.5385
Seychelles	Africa	162.3699
Palau	Oceania	168.9506
Timor-Leste	Asia	187.338
Jordan	Asia	187.9429
Suriname	South America	188.618
Iraq	Asia	194.2185
French Guiana	South America	207.338
Guyana	South America	233.003
Bangladesh	Asia	269.3584

8.6 STC robust countries

Table 8.4: STC robust countries

Country	Continent	Remaining	Lost 1st	Lost 2ed	Lost 3rd
Estonia	Europe	0.2639	0.1865	0.0442	0.0331
Bermuda	North America	5.32	2.5	2.5	0.32
Guernsey	Europe	5.7583	3.3	1.868	0.5903

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Table 8.4 – continued from previous page

Country	Continent	Remaining	Lost 1st	Lost 2ed	Lost 3rd
Libya	Africa	8.363	3.84	3.323	1.2
Martinique	North America	21.1	10	10	1.1
Iceland	Europe	23.12	18	5.1	0.02
Venezuela	South America	23.52	10	8.4	5.12
Tunisia	Africa	28.3873	18	9.6	0.7873
Jamaica	North America	28.4	12.8	8.4	7.2
Mauritius	Africa	33.28	24	8	1.28
Virgin Islands (U.K.)	North America	50	45	2.5	2.5
Turkey	Asia	61.539	38.4	18.7069	4.4321
Iran	Asia	61.6444	51.2	7.8844	2.56
Curacao	North America	63.4	45	10	8.4
Sweden	Europe	67.524	44.385	18.7069	4.4321
Papua New Guinea	Oceania	74.9009	44.385	20	10.5159
Cameroon	Africa	76	32	24	20
Brunei	Asia	81.7506	28.8	28	24.9506
Malta	Europe	89.2247	59.199	16	14.0257
Cape Verde	Africa	102.5	72	16	14.5
Isle of Man	Europe	106.7293	105.3101	1.4006	0.0186
Fiji	Oceania	144.9101	105.3101	22	17.6
Germany	Europe	150.2501	144	5.2	1.0501
Sudan	Africa	156.6906	140.4585	11.8	4.4321
Tanzania	Africa	159.5385	140.4585	11.8	7.28
French Polynesia	Oceania	160.4585	140.4585	10	10
Ghana	Africa	162.9585	140.4585	20	2.5
Comoros	Africa	163.1654	140.4585	18.7069	4
Nigeria	Africa	173.2585	140.4585	20	12.8
Madagascar	Africa	176.2585	140.4585	24	11.8
Senegal	Africa	176.4585	140.4585	20	16
South Africa	Africa	184.4585	140.4585	24	20
Peru	South America	186.399	108	59.199	19.2
Finland	Europe	188.5715	144	44.385	0.1865
Kenya	Africa	192.4585	140.4585	36	16
Bahrain	Asia	194.2185	140.4585	51.2	2.56
Kuwait	Asia	194.2185	140.4585	51.2	2.56
Angola	Africa	194.9585	140.4585	40	14.5
Dominican Republic	North America	198.8585	140.4585	50	8.4
Chile	South America	199.2	108	72	19.2
Somalia	Africa	201.409	140.4585	36	24.9506
Trinidad & Tobago	North America	204.538	187.338	10	7.2
Denmark	Europe	208.8941	105.3101	59.199	44.385
Russia	Asia	227.3422	104	78.9573	44.385
Netherlands	Europe	228.6524	105.3101	78.9573	44.385
Uruguay	South America	234.8906	140.4585	90	4.4321
Colombia	South America	235.4585	140.4585	50	45
Israel	Asia	238.538	187.338	38.4	12.8

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Table 8.4 – continued from previous page

Country	Continent	Remaining	Lost 1st	Lost 2ed	Lost 3rd
Cote D'Ivoire	Africa	239.4157	140.4585	78.9573	20
Gabon	Africa	239.4157	140.4585	78.9573	20
Cyprus	Asia	241.738	187.338	38.4	16
Panama	North America	257.4585	140.4585	72	45
Equatorial Guinea	Africa	269.7686	140.4585	105.3101	24
Qatar	Asia	271.6585	140.4585	80	51.2
Vietnam	Asia	274	140	80	54
United Arab Emirates	Asia	275.4585	140.4585	80	55
South Korea	Asia	278	144	80	54
Yemen	Asia	290.7069	192	80	18.7069
Ecuador	South America	293.4585	140.4585	108	45
Mexico	North America	295.7686	140.4585	105.3101	50
Guatemala	North America	298.4585	140.4585	108	50
Main land, China	Asia	300	140	80	80
Argentina	South America	309.4157	140.4585	90	78.9573
Myanmar	Asia	338.7069	240	80	18.7069
Brazil	South America	372.4585	160	140.4585	72
Taiwan, China	Asia	372.6481	187.338	105.3101	80
New Zealand	Oceania	379	240	72	67
Canada	North America	386.9955	187.338	140.4585	59.199
Philippines	Asia	406.2953	187.338	140	78.9573
Thailand	Asia	420	200	140	80
Oman	Asia	420.4585	200	140.4585	80
Ireland	Europe	433.1742	249.8641	105.3101	78
Japan	Asia	467.7965	187.338	140.4585	140
Pakistan	Asia	470.3226	249.8641	140.4585	80
Maldives	Asia	528.8214	249.8641	200	78.9573
Sri Lanka	Asia	528.8214	249.8641	200	78.9573
Malaysia	Asia	529.8641	249.8641	200	80
Algeria	Africa	550	480	40	30
Morocco	Africa	564.0773	480	78.9573	5.12
Australia	Oceania	567.7965	240	187.338	140.4585
Indonesia	Asia	567.7965	240	187.338	140.4585
Singapore	Asia	571.338	240	187.338	144
Egypt	Africa	590.3226	249.8641	200	140.4585
Saudi Arabia	Asia	590.3226	249.8641	200	140.4585
Djibouti	Africa	590.3226	249.8641	200	140.4585
India	Asia	590.3226	249.8641	200	140.4585
Greece	Europe	627.338	360	187.338	80
Norway	Europe	653.2022	249.8641	216	187.338
United States	North America	677.338	250	240	187.338
Italy	Europe	687.7965	360	187.338	140.4585
Portugal	Europe	692.4585	480	140.4585	72
Spain	Europe	1140	480	460	200
United Kingdom	Europe	2604.4585	2400	140.4585	64

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Table 8.4 – continued from previous page

Country	Continent	Remaining	Lost 1st	Lost 2ed	Lost 3rd
France	Europe	2837.2022	2400	249.8641	187.338

8.7 Country degree centrality

Table 8.5: Country degree centrality

Country	Continent	Degree Centrality
India	Asia	0.4635
Singapore	Asia	0.4325
Japan	Asia	0.3696
Saudi Arabia	Asia	0.2289
Brazil	South America	0.2164
United States	Central America	0.1946
France	Europe	0.1905
Indonesia	Asia	0.1626
United Arab Emirates	Asia	0.1562
Pakistan	Asia	0.0894
Egypt	Africa	0.0843
United Kingdom	Europe	0.0741
Italy	Europe	0.0696
South Korea	Asia	0.0638
Main land, China	Asia	0.0525
Oman	Asia	0.0428
Taiwan, China	Asia	0.0402
Nigeria	Africa	0.0381
Colombia	South America	0.0335
Greece	Europe	0.0283
Kenya	Africa	0.026
Bahamas	North America	0.0222
Cyprus	Europe	0.0219
Qatar	Asia	0.0214
Cape Verde	Africa	0.0214
Malaysia	Asia	0.0204
Philippines	Asia	0.0195
Spain	Europe	0.019
Mexico	Central America	0.019
Portugal	Europe	0.0161
Fiji	Australia	0.0161
Maldives	Asia	0.0159
Australia	Australia	0.0144
Kuwait	Asia	0.0107
Israel	Asia	0.0107
Dominican Republic	North America	0.0103
Somalia	Africa	0.01

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Table 8.5 – continued from previous page

Country	Continent	Degree Centrality
Cameroon	Africa	0.0095
Guatemala	Central America	0.0089
Bahrain	Asia	0.0089
Sri Lanka	Asia	0.008
Sudan	Africa	0.0074
Saint Vincent & Grenadines	Central America	0.0073
Tanzania	Africa	0.0071
Venezuela	South America	0.0058
Jamaica	North America	0.0058
Papua New Guinea	Australia	0.0058
Denmark	Europe	0.0046
Ireland	Europe	0.0043
Honduras	Central America	0.0042
Belgium	Europe	0.004
Libya	Africa	0.0034
Trinidad & Tobago	North America	0.0027
Benin	Africa	0.0027
Grenada	North America	0.0025
New Zealand	Australia	0.0025
Panama	Central America	0.0024
Saint Martin	North America	0.0024
Morocco	Africa	0.0022
South Africa	Africa	0.0019
Angola	Africa	0.0019
Sao Tome & Principe	Africa	0.0018
New Caledonia	Australia	0.0018
Comoros	Africa	0.0018
Iraq	Asia	0.0018
Djibouti	Africa	0.0018
Albania	Europe	0.0018
Cayman Islands	North America	0.0016
Greenland	Central America	0.0016
Uruguay	South America	0.0015
Turkey	Europe	0.0015
Mozambique	Africa	0.0015
Iran	Asia	0.0015
Equatorial Guinea	Africa	0.0015
Syria	Asia	0.0013
Solomon Islands	Australia	0.0013
Norway	Europe	0.0013
Isle of Man	Europe	0.0013
Algeria	Africa	0.0013
Vietnam	Asia	0.0012
Seychelles	Africa	0.0012
Palau	Australia	0.0012

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Table 8.5 – continued from previous page

Country	Continent	Degree Centrality
Cuba	North America	0.0012
Republic of Congo	Africa	0.0012
Mauritius	Africa	0.001
Sint Maarten	North America	0.0009
Gibraltar	Europe	0.0009
Costa Rica	Central America	0.0009
Thailand	Asia	0.0007
Iceland	Europe	0.0007
Federated States of Micronesia	Australia	0.0007
Saint Barthelemy	North America	0.0007
Togo	Africa	0.0006
Northern Mariana Islands	Australia	0.0006
Jordan	Asia	0.0006
Democratic Republic of the Congo	Africa	0.0006
Bangladesh	Asia	0.0006
Antigua & Barbuda	North America	0.0004
Netherlands	Europe	0.0003
Malta	Europe	0.0003
Lebanon	Asia	0.0003
Haiti	North America	0.0003
Belize	Central America	0.0003
Yemen	Asia	0.0001
Timor-Leste	Asia	0.0001
Suriname	South America	0.0001
Romania	Europe	0.0001
Madagascar	Africa	0.0001
Guinea-Bissau	Africa	0.0001
The Gambia	Africa	0.0001
Faroe Islands	Europe	0.0001
Dominica	North America	0.0001
Christmas Island	Australia	0.0001
Curaçao	North America	0.0001
Cocos Islands	Australia	0.0001
Barbados	North America	0.0001

8.8 LandingPoint degree centrality

Table 8.6: LandingPoint degree centrality

LandingPoint	Country	Degree Centrality
Mumbai	India	0.4284
Shima	Japan	0.2529
Jeddah	Saudi Arabia	0.2088
Marseille	France	0.1895

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Changi North	Singapore	0.1714
Tuas	Singapore	0.1624
Fujairah	United Arab Emirates	0.1547
Fortaleza	Brazil	0.1487
Piti	United States	0.1113
Changi South	Singapore	0.0952
Karachi	Pakistan	0.0892
Mazara del Vallo	Italy	0.0669
Busan	South Korea	0.0635
Rio de Janeiro	Brazil	0.0595
Maruyama	Japan	0.0595
Suez	Egypt	0.0589
Bude	United Kingdom	0.0571
Dumai	Indonesia	0.0521
Chikura	Japan	0.0479
San Juan	United States	0.0455
Lagos	Nigeria	0.0381
Toucheng	Taiwan, China	0.0375
Chennai	India	0.0333
Cartagena	Colombia	0.0292
Chania	Greece	0.026
Mombasa	Kenya	0.026
Yeroskipos	Cyprus	0.0219
Barka	Oman	0.0214
Doha	Qatar	0.0208
Cancún	Mexico	0.0187
Tanjung Pakis	Indonesia	0.0178
Chongming	Main land, China	0.0178
Suva	Fiji	0.0161
Chung Hom Kok	Main land, China	0.0156
Wall Township	United States	0.0149
Port Said	Egypt	0.0143
Hulhumale	Maldives	0.0141
Jakarta	Indonesia	0.0134
Praia	Cape Verde	0.0134
Medan	Indonesia	0.0134
Duba	Saudi Arabia	0.0112
Tseung Kwan O	Main land, China	0.0107
Tel Aviv	Israel	0.0107
Ras Ghareb	Egypt	0.0107
Kuwait City	Kuwait	0.0107
Isla Verde	United States	0.0107
Al Seeb	Oman	0.0107
Kribi	Cameroon	0.0095
Sesimbra	Portugal	0.0089

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Puerto Barrios	Guatemala	0.0089
Yanbu	Saudi Arabia	0.0089
Batam	Indonesia	0.0083
Nassau	Bahamas	0.008
Port Sudan	Sudan	0.0074
Virginia Beach	United States	0.0071
Salalah	Oman	0.0071
Mogadishu	Somalia	0.0071
Melaka	Malaysia	0.0071
Dar Es Salaam	Tanzania	0.0071
Nanhui	Main land, China	0.0071
Punta Cana	Dominican Republic	0.0067
Manama	Bahrain	0.0067
Kingstown	Saint Vincent & Grenadines	0.0067
Perth	Australia	0.0067
Southport	United Kingdom	0.0054
Matara	Sri Lanka	0.0054
Makassar	Indonesia	0.0054
Alta Vista	Spain	0.0054
Hawksbill	Bahamas	0.0054
Santos	Brazil	0.0052
Penang	Malaysia	0.0048
Okinawa	Japan	0.0048
Manado	Indonesia	0.0048
Blackpool	United Kingdom	0.0048
Sao Pedro	Cape Verde	0.0045
Port Moresby	Papua New Guinea	0.004
Ostend	Belgium	0.004
Morib	Malaysia	0.004
Blaabjerg	Denmark	0.004
Barranquilla	Colombia	0.004
Sydney	Australia	0.0037
Timika	Indonesia	0.0036
Sorong	Indonesia	0.0036
Puerto Plata	Dominican Republic	0.0036
Puerto Cortes	Honduras	0.0036
Granadilla	Spain	0.0036
Dublin	Ireland	0.0036
Singapore	Singapore	0.0036
Santa Cruz de La Palma	Spain	0.0027
Porthcurno	United Kingdom	0.0027
Ocho Rios	Jamaica	0.0027
Mt. Lavinia	Sri Lanka	0.0027
Davao	Philippines	0.0027
Cotonou	Benin	0.0027

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Terempa	Indonesia	0.0024
Tanjung Pandan	Indonesia	0.0024
Sandy Point	Bahamas	0.0024
Roxas City	Philippines	0.0024
Punto Fijo	Venezuela	0.0024
Point Salines	Grenada	0.0024
Pesaren	Indonesia	0.0024
Cat Island	Bahamas	0.0024
Batu Prahu	Indonesia	0.0024
Maria Chiquita	Panama	0.0022
Fangshan	Taiwan, China	0.0022
Chaguaramas	Trinidad & Tobago	0.0022
Amwaj Island	Bahrain	0.0022
Whitesands Bay	United Kingdom	0.0018
Tarrafal—Santiago	Cape Verde	0.0018
Sao Tome	Sao Tome & Principe	0.0018
San Jose	Philippines	0.0018
Palembang	Indonesia	0.0018
Oxford Falls	Australia	0.0018
Moroni	Comoros	0.0018
Montego Bay	Jamaica	0.0018
Kuching	Malaysia	0.0018
Haramous	Djibouti	0.0018
Graciosa	Portugal	0.0018
Genoa	Italy	0.0018
Durres	Albania	0.0018
Cagayan de Oro	Philippines	0.0018
Banjarmasin	Indonesia	0.0018
Ancol	Indonesia	0.0018
Al Faw	Iraq	0.0018
Tétouan	Morocco	0.0013
Taytay	Philippines	0.0013
Tartous	Syria	0.0013
St. Louis	Saint Martin	0.0013
Muntok	Indonesia	0.0013
Melkbosstrand	South Africa	0.0013
Maputo	Mozambique	0.0013
Maldonado	Uruguay	0.0013
Magen's Bay	United States	0.0013
Kristiansand	Norway	0.0013
Jacksonville	United States	0.0013
Honiara	Solomon Islands	0.0013
Bosaso	Somalia	0.0013
Bata	Equatorial Guinea	0.0013
Athens	Greece	0.0013

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Anyer	Indonesia	0.0013
Victoria	Seychelles	0.0012
Sofifi	Indonesia	0.0012
Sines	Portugal	0.0012
Sangano	Angola	0.0012
Sanana	Indonesia	0.0012
Quy Nhon	Vietnam	0.0012
Qalhat	Oman	0.0012
Port Grenaugh	Isle of Man	0.0012
Pointe-Noire	Congo, Rep.	0.0012
Oran	Algeria	0.0012
Noumea	New Caledonia	0.0012
Ngeremlengui	Palau	0.0012
Muscat	Oman	0.0012
Marmaris	Turkey	0.0012
Kitaibaraki	Japan	0.0012
Kaweni	Mayotte	0.0012
Holyhead	United Kingdom	0.0012
Highbridge	United Kingdom	0.0012
Half Moon Bay	Cayman Islands	0.0012
Guantanamo Bay	Cuba	0.0012
Governors Harbor	Bahamas	0.0012
Funchal	Portugal	0.0012
El Goro	Spain	0.0012
Dumaguete	Philippines	0.0012
Daet	Philippines	0.0012
Christchurch	New Zealand	0.0012
Brookvale	Australia	0.0012
Berbera	Somalia	0.0012
Barcelona	Spain	0.0012
Baler	Philippines	0.0012
Abu Dhabi	United Arab Emirates	0.0012
Takesung	Indonesia	0.0009
San Sebastian de la Gomera	Spain	0.0009
Saint Maarten	Sint Maarten	0.0009
Raglan	New Zealand	0.0009
Puerto Limon	Costa Rica	0.0009
Penmarch	France	0.0009
Ormoc	Philippines	0.0009
Nuuk	Greenland	0.0009
Nabire	Indonesia	0.0009
Manokwari	Indonesia	0.0009
Madang	Papua New Guinea	0.0009
Lingang	Main land, China	0.0009
Kuantan	Malaysia	0.0009

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Khasab	Oman	0.0009
Jask	Iran	0.0009
Gibraltar	Gibraltar	0.0009
Faial	Portugal	0.0009
Derna	Libya	0.0009
Coron	Philippines	0.0009
Candelaria	Spain	0.0009
Camuri	Venezuela	0.0009
Baie Jacotet	Mauritius	0.0009
West Palm Beach	United States	0.0006
Tubruq	Libya	0.0006
Tual	Indonesia	0.0006
Timpaki	Greece	0.0006
Tarakan	Indonesia	0.0006
Sriracha	Thailand	0.0006
Savona	Italy	0.0006
Porto Novo—Santo Antao	Cape Verde	0.0006
Pohnpei	Micronesia	0.0006
North Miami Beach	United States	0.0006
Nasugbu	Philippines	0.0006
Myrtle Beach	United States	0.0006
Muanda	Congo, Dem. Rep.	0.0006
Miyazaki	Japan	0.0006
Minamiboso	Japan	0.0006
Mentigi	Indonesia	0.0006
Luwuk	Indonesia	0.0006
Luanda	Angola	0.0006
Lome	Togo	0.0006
Landeyjar	Iceland	0.0006
Killala	Ireland	0.0006
Kendari	Indonesia	0.0006
Kalianda	Indonesia	0.0006
Jayapura	Indonesia	0.0006
Hithadhoo	Maldives	0.0006
Gustavia	Saint Barthelemy	0.0006
Estepona	Spain	0.0006
Cox's Bazar	Bangladesh	0.0006
Conil	Spain	0.0006
Chipiona	Spain	0.0006
Carcavelos	Portugal	0.0006
Banyu Urip	Indonesia	0.0006
Bandar Bukit Tinggi	Malaysia	0.0006
Asilah	Morocco	0.0006
Aqaba	Jordan	0.0006
Akita	Japan	0.0006

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Sidi Kerir	Egypt	0.0004
Saint Martin	Saint Martin	0.0004
Roxas	Philippines	0.0004
Port Blair	India	0.0004
Pekanbaru	Indonesia	0.0004
Pa Li	Taiwan, China	0.0004
Darwin	Australia	0.0004
Bull Bay	Jamaica	0.0004
Zawia	Libya	0.0003
Zahara de los Atunes	Spain	0.0003
Yapen	Indonesia	0.0003
Wawonii	Indonesia	0.0003
Wada	Japan	0.0003
Vitória	Brazil	0.0003
Vila do Porto	Portugal	0.0003
Velas	Portugal	0.0003
Valdemar	Denmark	0.0003
Tulum	Mexico	0.0003
Tuckerton	United States	0.0003
Trujillo	Honduras	0.0003
Toyohashi	Japan	0.0003
Tolmeta	Libya	0.0003
Tidore	Indonesia	0.0003
Tiakur	Indonesia	0.0003
Thinadhoo	Maldives	0.0003
Teping Tinggi	Indonesia	0.0003
Tebingtinggi Island	Indonesia	0.0003
Tarrafal—Sao Nicolau	Cape Verde	0.0003
Tanjung Pinggir	Indonesia	0.0003
Tanjung Bemban	Indonesia	0.0003
Taliabu	Indonesia	0.0003
Surabaya	Indonesia	0.0003
Supiori	Indonesia	0.0003
Suemlaki	Indonesia	0.0003
St. John's	Antigua & Barbuda	0.0003
São Mateus	Brazil	0.0003
Sitio	Brazil	0.0003
Sisimiut	Greenland	0.0003
Sibolga	Indonesia	0.0003
Shindu-Ri	South Korea	0.0003
Serwaru	Indonesia	0.0003
Sendai	Japan	0.0003
Sao Filipe	Cape Verde	0.0003
Salakan	Indonesia	0.0003
Saint Paul	Reunion	0.0003

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Rota	Northern Mariana Islands	0.0003
Rockly Bay	Trinidad & Tobago	0.0003
Rock Sound	Bahamas	0.0003
Riohacha	Colombia	0.0003
Riding Point	Bahamas	0.0003
Recife	Brazil	0.0003
Ras Lanuf	Libya	0.0003
Rantu Prapat	Indonesia	0.0003
Ranai	Indonesia	0.0003
Raha	Indonesia	0.0003
Puerto Lempira	Honduras	0.0003
Puerto La Cruz	Venezuela	0.0003
Puerto Cabello	Venezuela	0.0003
Porto Seguro	Brazil	0.0003
Porlamar	Venezuela	0.0003
Pointe-a-Pitre	Guadeloupe	0.0003
Pinamalayan	Philippines	0.0003
Penarik	Indonesia	0.0003
Panipahan	Indonesia	0.0003
Padang	Indonesia	0.0003
Ozamiz City	Philippines	0.0003
Ondong Siau	Indonesia	0.0003
Nova Sintra	Cape Verde	0.0003
Negril	Jamaica	0.0003
Natuna	Indonesia	0.0003
Murdeira	Cape Verde	0.0003
Morotai	Indonesia	0.0003
Morant Point	Jamaica	0.0003
Miri	Malaysia	0.0003
Milagros	Philippines	0.0003
Melonguane	Indonesia	0.0003
Mayaguana	Bahamas	0.0003
Maracaibo	Venezuela	0.0003
Maniitsoq	Greenland	0.0003
Macaé	Brazil	0.0003
Long Island	India	0.0003
Little Andaman	India	0.0003
Lisbon	Portugal	0.0003
Lingga	Indonesia	0.0003
Legazpi City	Philippines	0.0003
La Union	Philippines	0.0003
Kota Kinabalu	Malaysia	0.0003
Kolhufushi	Maldives	0.0003
Kokkini	Greece	0.0003
Kep. Aru	Indonesia	0.0003

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Kendal	Indonesia	0.0003
Karimun	Indonesia	0.0003
Kamorta	India	0.0003
João Pessoa	Brazil	0.0003
Jambi	Indonesia	0.0003
Ilhéus	Brazil	0.0003
Igneada	Turkey	0.0003
Ibaraki	Japan	0.0003
Higuerote	Venezuela	0.0003
Havelock	India	0.0003
Halul Island	Qatar	0.0003
Great Level Bay	Bonaire, Sint Eustatius and Saba	0.0003
Great Bay Beach	Saint Martin	0.0003
Güimar	Spain	0.0003
Gallows Bay	Bonaire, Sint Eustatius and Saba	0.0003
Fuvahmulah	Maldives	0.0003
Duncan Town	Bahamas	0.0003
Diba	Oman	0.0003
Dhangethi	Maldives	0.0003
Das Island	United Arab Emirates	0.0003
Current	Bahamas	0.0003
Cumaná	Venezuela	0.0003
Crown Haven	Bahamas	0.0003
Crooked Island	Bahamas	0.0003
Corvo	Portugal	0.0003
Coro	Venezuela	0.0003
Clarence Town	Bahamas	0.0003
Chichiriviche	Venezuela	0.0003
Cebu	Philippines	0.0003
Cayman Brac	Cayman Islands	0.0003
Caves Point	Bahamas	0.0003
Cape Town	South Africa	0.0003
Butuan City	Philippines	0.0003
Brega	Libya	0.0003
Boracay	Philippines	0.0003
Black River	Jamaica	0.0003
Bintulu	Malaysia	0.0003
Beverwijk	Netherlands	0.0003
Bengkalis	Indonesia	0.0003
Benghazi	Libya	0.0003
Belize City	Belize	0.0003
Baturaja	Indonesia	0.0003
Bangga	Indonesia	0.0003
Bandar Lampung	Indonesia	0.0003
Bandar Abbas	Iran	0.0003

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Baie Longue	Saint Martin	0.0003
Atafona	Brazil	0.0003
Aracaju	Brazil	0.0003
Angra do Heroismo	Portugal	0.0003
Al Daayen	Qatar	0.0003
Al Bayda	Libya	0.0003
Agats	Indonesia	0.0003
Yzerfontein	South Africa	0.0001
Yate	New Caledonia	0.0001
Wurrumiyanga	Australia	0.0001
West Island	Cocos (Keeling) Islands	0.0001
Vestmannaeyjar	Iceland	0.0001
Vao	New Caledonia	0.0001
Vanimo	Papua New Guinea	0.0001
Valverde	Spain	0.0001
Union Island	Saint Vincent & Grenadines	0.0001
Tyra	Denmark	0.0001
Trapani	Italy	0.0001
Tobelo	Indonesia	0.0001
Toamasina	Madagascar	0.0001
Tjornuvik	Faroe Islands	0.0001
Tjele	Denmark	0.0001
Tinocas	Spain	0.0001
Ternate	Indonesia	0.0001
Teluk	Indonesia	0.0001
Tarahales	Spain	0.0001
Tanjung Selor	Indonesia	0.0001
Takahagi	Japan	0.0001
Tadine	New Caledonia	0.0001
Suro	Guinea-Bissau	0.0001
Sunny Isles	United States	0.0001
Sugar Dock	Northern Mariana Islands	0.0001
Spanish River Park	United States	0.0001
Shanghai	Main land, China	0.0001
Sasanlagu	Northern Mariana Islands	0.0001
Sarmi	Indonesia	0.0001
Sapporo	Japan	0.0001
San Remigio	Philippines	0.0001
San Jose de Buenavista	Philippines	0.0001
Saint Barthelemy	Saint Barthelemy	0.0001
Saida	Lebanon	0.0001
Roseau	Dominica	0.0001
Rome	Italy	0.0001
Rayong	Thailand	0.0001
Punta del Este	Uruguay	0.0001

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Port of Spain	Trinidad & Tobago	0.0001
Port Erin	Isle of Man	0.0001
Port Elizabeth	South Africa	0.0001
Port-au-Prince	Haiti	0.0001
Playa Blanca	Spain	0.0001
Pegwell	Barbados	0.0001
Paramaribo	Suriname	0.0001
Palma	Spain	0.0001
Namlea	Indonesia	0.0001
Nador	Morocco	0.0001
Nacala	Mozambique	0.0001
Mustique	Saint Vincent & Grenadines	0.0001
Mont-Dore	New Caledonia	0.0001
Mocha	Yemen	0.0001
Merauke	Indonesia	0.0001
Mellieha	Malta	0.0001
Melbourne	Australia	0.0001
Masohi	Indonesia	0.0001
Maroochydore	Australia	0.0001
Mangalia	Romania	0.0001
Mahuma	Curacao	0.0001
Magachgil	Micronesia	0.0001
Madura	Indonesia	0.0001
Lorengau	Papua New Guinea	0.0001
Lecanvey	Ireland	0.0001
Le Porge	France	0.0001
Kokopo	Papua New Guinea	0.0001
Kismayo	Somalia	0.0001
Kimbe	Papua New Guinea	0.0001
Kiamsam	Malaysia	0.0001
Khark Island	Iran	0.0001
Kavieng	Papua New Guinea	0.0001
Kaliko	Haiti	0.0001
Kaimana	Indonesia	0.0001
Jdaide	Lebanon	0.0001
Jarry	Guadeloupe	0.0001
Invercargill	New Zealand	0.0001
Iloilo City	Philippines	0.0001
Hobyo	Somalia	0.0001
Gwadar	Pakistan	0.0001
Great Nicobar	India	0.0001
Grand Baie (Rodrigues)	Mauritius	0.0001
Gran Canaria	Spain	0.0001
George Town	Cayman Islands	0.0001
Ganaveh	Iran	0.0001

Continued on next page

Table 8.6 – continued from previous page

LandingPoint	Country	Degree Centrality
Fukuoka	Japan	0.0001
Fresh Creek	Bahamas	0.0001
Flying Fish Cove	Christmas Island	0.0001
El-Quawef	Libya	0.0001
Dunedin	New Zealand	0.0001
Dili	Timor-Leste	0.0001
Dickenson Bay	Antigua & Barbuda	0.0001
Dakhla	Morocco	0.0001
Colon	Panama	0.0001
Collo	Algeria	0.0001
Carriacou	Grenada	0.0001
Carúpano	Venezuela	0.0001
Cape D'Aguilar	Main land, China	0.0001
Canouan	Saint Vincent & Grenadines	0.0001
Calbayog	Philippines	0.0001
Cadiz City	Philippines	0.0001
Cabinda	Angola	0.0001
Butterworth	Malaysia	0.0001
Buranga	Indonesia	0.0001
Brisbane	Australia	0.0001
Bintan	Indonesia	0.0001
Bequia	Saint Vincent & Grenadines	0.0001
Banjul	Gambia	0.0001
Balluta Bay	Malta	0.0001
Bali	Indonesia	0.0001
Auckland	New Zealand	0.0001
Arawa	Papua New Guinea	0.0001
Annobon	Equatorial Guinea	0.0001
Aeng Batu Batu	Indonesia	0.0001
Aasiaat	Greenland	0.0001