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The Dynamics of Undersea Cables: Emerging Opportunities and Pitfalls

Michael Sechrist
Belfar Center for Science &
International Affairs
Harvard University

Chintan Vaishnav
Engineering Systems Division
Massachusetts Institute of Technology

Daniel Goldsmith
Sloan School of Management
Massachusetts Institute of Technology

Nazli Choucri
Political Science Department
Massachusetts Institute of Technology

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I. INTRODUCTION

Cyberspace is built on physical foundations that support the "virtual" manifestations we know of and use in everyday computing. Physical infrastructure can include wired, fiber optic, satellite and microwave links, as well as routing equipment. An often overlooked but critical part of the Internet infrastructure is undersea communication cable links. Undersea cables are the technology of choice to move large amounts of data around the world quickly. In the U.S., approximately 95% of all international Internet and phone traffic travel via undersea cables. Nearly all government traffic, including sensitive diplomatic and military orders, travels these cables to reach officials in the field.[2]

The problem, however, is that the undersea cable infrastructure is susceptible to several types of vulnerability, including: rising capacity constraints, increased exposure to disruption from both natural and mad-made sources, and emerging security risks from cable concentration in dense geographical networks (such as New York and New Jersey, and places like Egypt/Suez Canal.) Moreover, even under normal working conditions, there is a concern whether governance-as-usual can keep up with the future growth of Internet traffic. *In this paper, we explore the impact of these problems on the dynamics of managing undersea cable infrastructure.*

This paper proceeds as follows: first, we introduce the underpinnings of the undersea cable infrastructure and describe the source of vulnerabilities in cable operations; second, we evaluate the explore of dependency among actors in this space and describe the various modes of governance over undersea cables in particular and Internet infrastructure in general; third, we present a causal framework for capturing the key pitfalls and potential opportunities in managing undersea cables; fourth, we present a formalized simulation model of the causal structure designed to provide further insight into the core dynamics; fifth, we present simulation output for analysis; and sixth, we develop high-leverage policy recommendations to address key challenges.

II. BACKGROUND: UNDERSEA COMMUNICATION CABLES

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[1] This work is funded by the Office of Naval Research under award number N00014-09-1-0597. Any opinions, findings, and conclusions or recommendations expressed in this publication are those of the author(s) and do not necessarily reflect the views of the Office of Naval Research.

[2] Sechrist, Michael, "Cyberspace in Deep Water: Protecting Undersea Communications Cables By Creating an International Public-Private Partnership," A Report, Belfer Center for Science and International Affairs, Harvard University, 2010. Available at http://belfercenter.ksg.harvard.edu/experts/2223/michael_sechrist.html

Undersea cables are the technology of choice to move large amounts of data around the world quickly.[3] Some of the most important data to traverse these cables is financial. The Society for Worldwide Interbank Financial Telecommunication (SWIFT), which describes itself as "the global provider of secure financial messaging services," uses undersea fiber-optic communications cables to transmit financial data to more than 8,300 banking organizations, securities institutions, and corporate customers in 195 countries.[4]

In 2004 alone, 9 million messages and approximately $7.4 trillion in transactions were traded every day on this network.[5] By 2011, nearly 15 million messages a day are sent over it. The CLS Bank, which "operates the largest multi-currency cash settlement system," trades over 1 million transactions and over $4.7 trillion dollars a day over the same undersea cables.[6] In addition, "the U.S. Clearing House Interbank Payment System processes in excess of $1 trillion a day to more than 22 countries for investment companies, securities and commodities exchange organizations, banks, and other financial institutions."[7]

Nearly all U.S. government traffic, including sensitive diplomatic and military orders, travels these cables in order to reach officials in the field. Companies use them to transfer trillions of dollars every day. And other companies, many foreign owned, operate most of them.[8] According to the Office of the Assistant Secretary of Defense for Homeland Defense and Americas' Security Affairs, "the private sector owns the preponderance of [U.S.] critical infrastructure -- estimates range from 85 percent to 95 percent."[9] For undersea cables, the figure is closer to 100%.

Description of Undersea Communications Cable

Underse cables range in diameter from 17 millimeters to 69 millimeters[10]; that width places them between the size of a human thumb and a human wrist. Within 2,000 meters of a coastline, cables are typically armored, or even double-armored,

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[3] Douglas Burnett, "Cable Vision," 2011 Proceedings, U.S. Naval Institute. Accessed at www.usni.org

[4] Douglas Burnett, "Cable Vision," 2011 Proceedings, U.S. Naval Institute. Accessed at www.usni.org

[5] Address by Stephen Malphrus, ROGUCCI conference

[6] Ibid.

[7] Burnett, Cable Vision.

[8] Sechrist, 2010

[9] Anne La Lena, "PCII & You," *DCIP News*, November 2009. Accessed at http://policy.defense.gov/sections/policy_offices/hd/assets/downloads/DCIP%20Newsletter_November%202009.pdf

[10] See Kordje Bedourma, Memorandum to African Development Bank Regarding GHANA & NIGERIA: MAIN ONE SUBMARINE CABLE, January 6, 2009. Accessed at http://www.afdb.org/fileadmin/uploads/afdb/Documents/Environmental-and-Social-Assessments/30776237-EN-ESIA-REPORT-MAIN-ONE-SYSTEM-POSTING-JAN-09.PDF. Also see 2008 *Guardian (UK)* map, accessed at http://image.guardian.co.uk/sys-images/Technology/Pix/pictures/2008/02/01/SeaCableHi.jpg

and are buried upwards of 3 meters of seabed (see cable diagram below).[11] These measures protect the cable from fisherman trawling and ships anchoring around the shore. Outside of 2,000 meters, some cables may be buried in the seabed further, but they typically are unarmored in a Kevlar-coating.[12]

Many times though, the unarmored cable sits unprotected on the ocean floor. In this state, they can stretch for thousands of miles across the ocean floor, upwards of 12,000 kilometers in some cases, carry up to 10 terabytes per second of data and ensure traffic availability 99.999% of the time.[13] Cables can be laid to water depths of 8,000 meters and can withstand pressure of 10,000 psi.[14]

For much of the past decade, 10 gigabyte per second (10G) wavelengths were deployed within undersea cable systems. In 2010, only about 21.7%, a fraction of those 10G wavelengths, were lit in these cables. More recently, fiber-optic cables have moved to 40G wavelengths. On average worldwide, 40G wavelengths are lit at a lower percentage, somewhere around 13.7%. [15] Table 1 shows an example of the unlit v. lit ratio, which comes from Terabit Consulting's 2011 Undersea Cable Report. The "Fill" percentages equate to lit capacity on regional cable systems.

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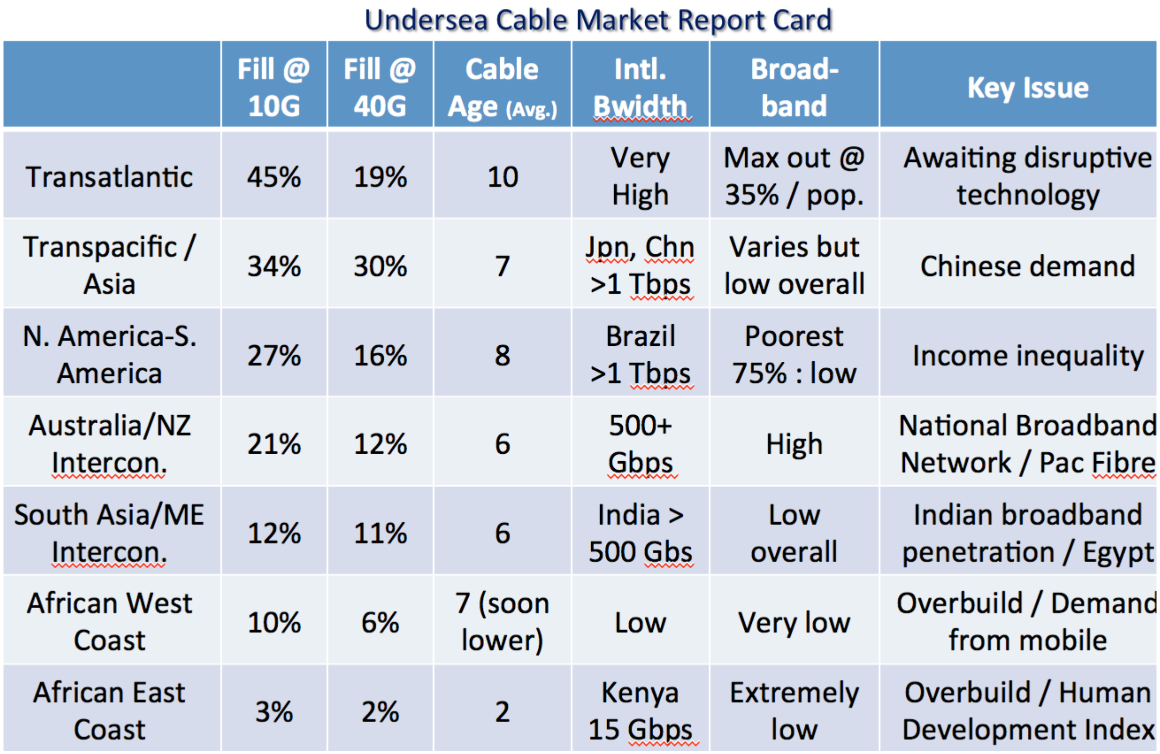
[11] "Framework for Burial Depth Specifications," Submarine Cable Improvement Group (SCIG). Accessed at http://www.scig.net/Section05.pdf

[12] Cathy Holding, "A global cable network of fragile links," *The Independent (UK)*, March 10, 2009. Accessed at http://www.independent.co.uk/news/business/sustainit/a-global-cable-network-of-fragile-links-1640448.html

[13] Laurie Doyle presentation, PTC 2007 conference.

[14] Maurice E. Kordahi, Seymour Shapiro, Gordon Lucas and Kelvin Moore, "International Standards For Undersea Cable System Testing," Submarine Cable Improvement Group (SCIG), http://www.scig.net/Section11b.pdf

[15] Michael Ruddy, The Submarine Cable Industry at a Crossroads: A Macroeconomic Evaluation of the Industry's Future, ICPC 2011, April 2011.



Undersea Cable Market Report Card

	Fill @ 10G	Fill @ 40G	Cable Age (Avg.)	Intl. Bwidth	Broad-band	Key Issue
Transatlantic	45%	19%	10	Very High	Max out @ 35% / pop.	Awaiting disruptive technology
Transpacific / Asia	34%	30%	7	Jpn, Chn >1 Tbps	Varies but low overall	Chinese demand
N. America-S. America	27%	16%	8	Brazil >1 Tbps	Poorest 75% : low	Income inequality
Australia/NZ Intercon.	21%	12%	6	500+ Gbps	High	National Broadband Network / Pac Fibre
South Asia/ME Intercon.	12%	11%	6	India > 500 Gbs	Low overall	Indian broadband penetration / Egypt
African West Coast	10%	6%	7 (soon lower)	Low	Very low	Overbuild / Demand from mobile
African East Coast	3%	2%	2	Kenya 15 Gbps	Extremely low	Overbuild / Human Development Index

Table 1 An example Undersea Cable Report Card

It can take at least 3-4 months to lay an undersea cable, depending on distance. But it can take a company or consortium of companies several years before it reaches the point to build. Drafting the construction and maintenance agreement and receiving the necessary permits from federal, state, and local officials fills much of that time. Moreover, it costs generally $500 million to lay a new trans-oceanic cable system today.

We next present a case study highlighting the key characteristics, and the scale and scope of a typical undersea cable vulnerability.

Case study – Taiwan, 2006

On December 26, 2006, a seminal event occurred in the undersea cable industry. An earthquake of at least 6.7 magnitude triggered submarine landslide near the junction of the Eurasian and Philippine tectonic plates. Termed the Hengchun earthquake, the epicenter of the event landed directly in the middle of the heavily cabled Luzon Strait, off the coast of Taiwan. Ten aftershocks greater than 4.7 magnitude also hit the region.[16] From the timing of the breaks, a turbidity current averaging a speed of approximately 20km/hour traveled over 330 km.[17]

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[16] 2006 Hengchun earthquake, Wikipedia entry, accessed at http://en.wikipedia.org/wiki/2006_Hengchun_earthquake

[17] ICPC, "Critical Infrastructure: Submarine Telecommunication Cables," Accessed at www.iscpc.org/publications/Critical_Infastructure_2009_V2.pps

Undersea landslides severed 9 out of 11 cables in the area, moving cables far away from their original routes. Only Asia Netcom's EAC and the Guam-Philippines cable were left online.[18] A total of 21 faults were discovered in the 9 damaged cable systems.[19] The damage extended to water depths of 4000 meters and covered many in tons of mud.[20] It took 11 cable ships (over 40% of the world's entire fleet) until February 15th – a total of 49 days or seven weeks to complete the cable repair work.[21]

The day after the earthquake, most people in Hong Kong were without connection to the Internet, or as one New York Times writer commented, "just twiddling their thumbs."[22] Taiwan's international calling capacity to the U.S. was down to 40% its normal capacity.[23] Ninety-eight percent of Taiwan's communications with Malaysia, Singapore, Thailand and Hong Kong was also disrupted.[24] Internet access to China, Hong Kong, Vietnam, Taiwan, Singapore, Japan and the Philippines was seriously impaired. Banking, airline bookings, email & other services in many of these countries, particularly Taiwan and Singapore, were either stopped or delayed.[25]

Financial markets and general commerce were disrupted. A South Korean domestic bank reported that "trading of the Korean won has mostly halted due to the communication problem."[26] Other "securities traders in Hong Kong and Singapore were unable to obtain prices and complete orders… [and] dealers in the region said

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[18] Alin Popescu, Todd Underwood, Earl Zmijewski, "Quaking Tables: The Taiwan earthquakes and the Internet Routing Table," Rensys Corporation. Presentation delivered to APRICOT Bali, 2007. Accessed at http://www.renesys.com/tech/presentations/pdf/Plenary2-Underwood.pdf

[19] Ryan Singel, "Fiber Optic Cable Cuts Isolate Millions From Internet, Future Cuts Likely," *Wired Magazine*, January 31, 2008. Accessed at http://www.wired.com/threatlevel/2008/01/fiber-optic-cab/

[20] Ibid.

[21] Ibid.

[22] Seth Mydans, "The Day the Pixels Froze: When a Digital World Was Stopped by a Natural Disaster," *The New York Times*, December 28, 2006. Accessed at http://www.nytimes.com/2006/12/28/business/28connect.html

[23] Sumner Lemon, "Earthquake disrupts Internet access in Asia," *Computer World Magazine*, December 27, 2006. Accessed at http://www.computerworld.com/s/article/9006819/Earthquake_disrupts_Internet_access_in_Asia?intsrc=news_ts_head

[24] Ibid.

[25] "Taiwan quake causes net blackout," *Reuters*. December 28, 2006. Accessed at http://www.smh.com.au/news/wireless--broadband/taiwan-quake-causes-net-blackout/2006/12/28/1166895395104.html

[26] "Asia communications hit by quake," *BBC News*, December 27, 2006. Accessed at http://news.bbc.co.uk/2/hi/asia-pacific/6211451.stm

they have had difficulties accessing international news providers for information."[27] Customers also had trouble looking up various "stock prices online."[28]

Some traffic that couldn't be carried on the two remaining undersea cable systems needed to find a different route in order to reach North and South America. One solution was to re-route traffic over terrestrial cables across Asia and through Europe. Despite these ad-hoc arrangements, some delay in Internet traffic was still apparent even 2 months after the earthquake.

This event forced communication carriers to avoid cable-laying in seismically active areas. A new alliance of communication carriers, called the Pacific Partner Members Committee No. 2, was created after the crisis to deal with the aftermath of the event and how to prevent a future one.

III. CURRENT GOVERNANCE OF UNDERSEA COMMUNICATION CABLES

Cable architecture spans the globe and acts as the arteries of the global digital infrastructure. No one nation or company can truly ensure high-level security, unless all are committed to doing so. This interdependence is one reason why cybersecurity problems are so frustratingly complex and difficult to solve; the solution resides in near seamless state and non-state actor collaboration.

Currently, undersea communication cables are governed by a patchwork solution among governments and private sector actors. The U.S. cable permitting process, for instance, highlights this point. In the U.S., the FCC approves all submarine cable licenses after reviewing the license application. This authority has been delegated via Presidential Executive Order 10530, Section 5.[29]

In order to make a full inter-agency decision, however, the FCC is required to send all cable licenses to the Committee of Foreign Investment in the United States (CFIUS) for review first. Within CFIUS, a "Team Telecom" studies undersea cable landing license applications for national security purposes, particularly to ensure that foreign ownership of telecom companies does not provide other governments' access to U.S. national security information.[30] Team Telecom is comprised of officials from the Departments of Defense, State, Justice, Homeland Security, Central

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[27] Choe Sang-Hun and Wayne Arnold, "Asian Quake Disrupts Data Traffic," *The New York Times*, December 28, 2006. Accessed at http://www.nytimes.com/2006/12/28/business/worldbusiness/28quake.html?pagewanted=all

[28] Ibid.

[29] See E.O. 10530 at http://www.archives.gov/federal-register/codification/executive-order/10530.html

[30] Kent Bressie, "More Unwritten Rules: Developments in U.S. National Security Regulation of Undersea Cable Systems," Presentation made to the 2009 PTC conference, January 18, 2009. Accessed at http://www.harriswiltshire.com/siteFiles/News/7DF1C8D035660E8FBEF0AAC7BA8DA103.pdf

Intelligence Agency, National Security Agency and the Office of the Director of National Intelligence.[31]

In addition to receiving, Team Telecom, CFIUS and FCC approval, a cable cannot land in the U.S. without some sort of approval from the U.S. Army Corps of Engineers, the Department of State, the National Oceanic and Atmospheric Administration and the U.S. Coast Guard at the federal level. It is an uncoordinated mess essentially.

At the state and local level, cable companies need to receive zoning and environmental approvals as well. For instance, in states, such as New Jersey, California and Florida, environmental requirements are stiff, and permitting can hold the cable development process up to a year. The uneven permit process is a constant complaint among cable operators. It is also uneven when applying for permits to repair cables within states' maritime boundaries. Some states take weeks to do so and charge high fees to enter their waters.

In sum, we argue undersea cables architecture are governed under an ad-hoc, haphazard model on the national and international level. Also, while the above discussion focuses on the specifics of undersea cable permits in the United States, a similar complex web of decision processes pervade in general.

IV. THE DYNAMICS OF MANAGING UNDERWATER SEA CABLES

The foregoing discussion highlights several facts about the *dynamics* of managing undersea cable infrastructure: its critical nature given the Internet's growing reliance on it; its vulnerability to natural and human-made disruptions and the associated impact; and the growing complexity of its governance with increasing number of stakeholders. Moreover, the ad-hoc governance of undersea cables shows how these changes have occurred faster than the ability of the governing institutions to understand their ramifications. The result is a disconnect between critical challenges facing the management of undersea cable infrastructure and the tools available for it. The goal of this and the following section is to reduce this disconnect by providing a causal framework that describes the dynamics of undersea cables, by showing critical linkages among underwater sea cable actors, actions, and impacts.

We do so by using system dynamics modeling at three levels:

1. We begin with identifying causal structures at two levels: (a) at a high level, focusing on the structure behind technological growth and current governance (Figure 2); and (b) at a detailed level, focusing on the structure

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[31] Kent Bressie, "New Barriers to U.S. Market Entry for Undersea Cable Operators: Recent Developments with 'Team Telecom'," Presentation to the 2008 PTC conference, January 13, 2008. Accessed at www.ptc.org/ptc08/participants/speakers/papers/BressieFinalSlides.pdf

behind managing capacity, utilization, and vulnerability (Figure 3 -Figure 6).

2. As we are interested in understanding the implications of the structure, we develop a single stock and flow model that focus on the crux of the governance and capacity management dilemmas.
3. We then perform analysis on the model developed in step 2 and draw conclusions on policy implications for managing undersea cables.

High-Level: Dynamics of Technological Growth and Governance

In section II, we discussed the importance of lit v. unlit capacity of the undersea cable. At the highest level, used international bandwidth serves as a proxy for the undersea cable lit capacity. Figure 1 shows data on the growth of used international bandwidth of the undersea cables. This growth is representative of the increasing use of undersea cables. Most fundamentally, it shows the exponential nature of technological growth and our increasing reliance on it.

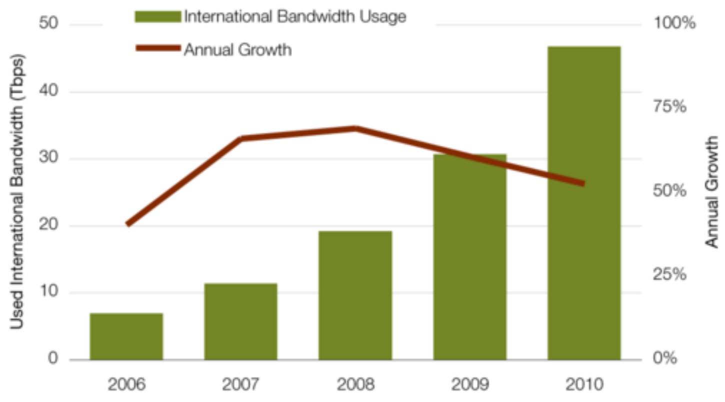

Figure 1 Growth of Used International Bandwidth

We capture the above high-level dynamics in Figure 2 with the help of three structures. Loop labeled "R1: Technological Growth" shows how the increased availability of Internet Technology – including physical infrastructure such as undersea cables as well as the applications and end devices that operate over it – increases the reliance of various activities on it. These activities may originate in commercial, military, academic, or entertainment realm. Such increasing reliance increases investment in Internet technology, including investment in undersea cables, which produces more technology. Such a structure would argue for the exponential growth in the production and utilization of Internet technology, which is something we are currently witnessing.

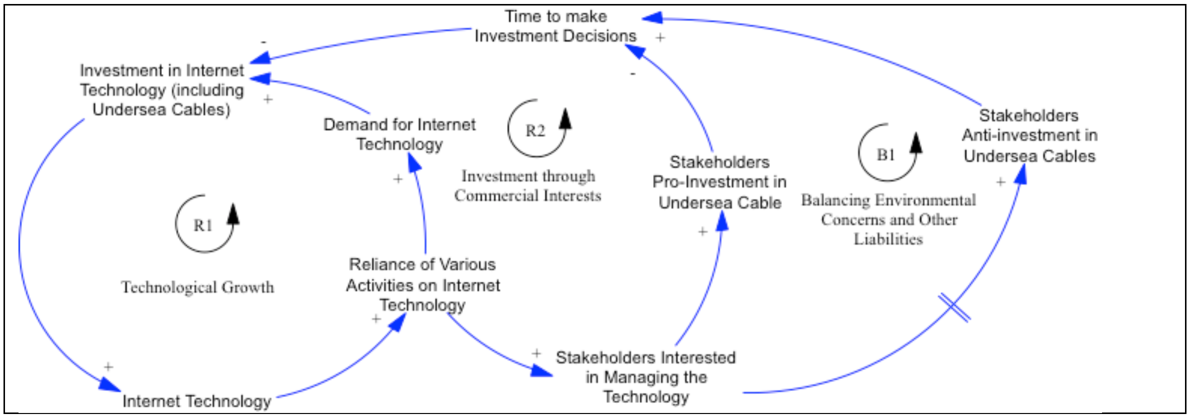

Figure 2 Technological Growth and Governance

Increased reliance on Internet technology has propelled two governance structures. Both structures originate as increased reliance on technology leads to more stakeholders interested in managing technology. Loop labeled “R2: Investment through Commercial Interests” shows the increasing in investment due to commercial interest, which typically occurs first. In the management of undersea cables, the investment of last two decades, where security and other environmental concerns were secondary, could be explained by this structure.

As major activities begin to utilize the technology, various other concerns come in focus. For example, in the case of undersea cables today, these concerns are the security of communications infrastructure on one side, and the environmental impact of laying undersea cables on the other. These interests complicate investment decisions, and slow down the rate of investment in Internet technology as shown by the Loop labeled “B3: Balancing Environmental Concerns and Other Liabilities.” The above dynamics are relevant for most technologies that become ubiquitous, but they are urgent in the case of Internet and undersea cables because of the rapid technological change as well as the rapid growth of global activity on it.

Detailed-level: Dynamics of Capacity, Utilization, and Vulnerabilities

We now turn to the causal formulations that explain the dynamics of undersea cables capacity, utilization, and vulnerabilities. We will develop this formulation over Figure 3 through Figure 6.

Figure 3 presents feedback loop labeled “B1: Capacity expansion” which describes the balancing operations of expanding capacity to meet demand. This feedback loop can be entered with the core concept of the “Under Sea Cable Capacity Gap,” the difference between the available capacity and he demand for capacity.

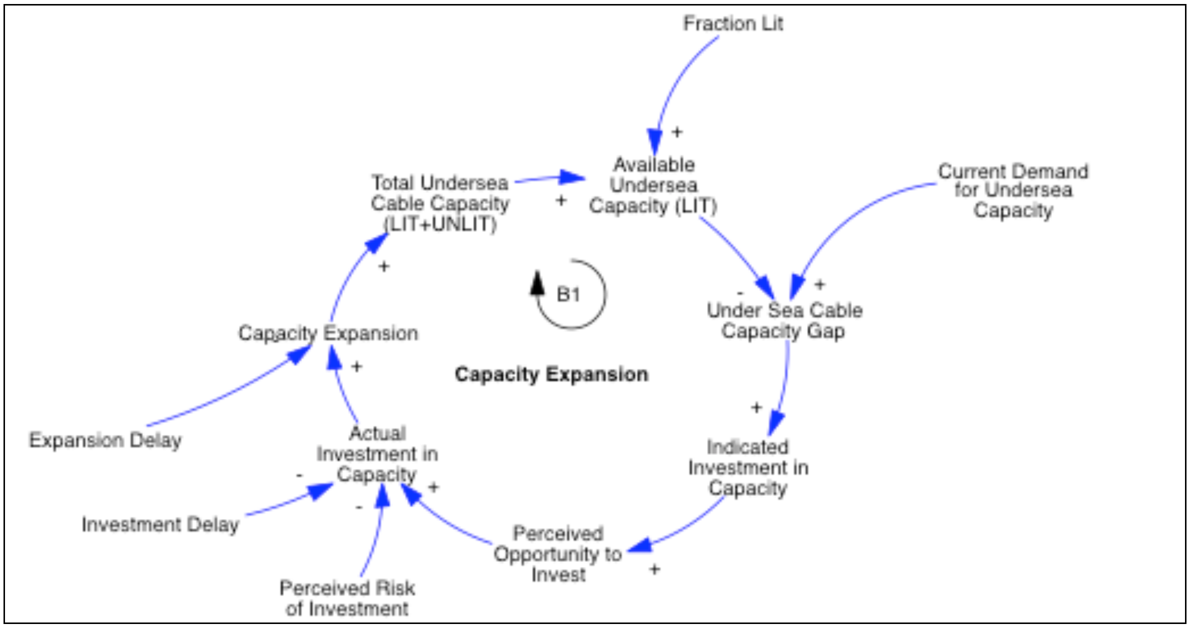

Figure 3 Capacity Expansion

If the “Undersea Cable Capacity Gap” were to rise (as signaled in Figure 1), it would create an implied level of investment in capacity necessary to close the gap (the “indicated investment in capacity”.) As this rises, it would be increasingly be perceived as an opportunity to invest, ultimately driving investment in capacity. The level of investment would be mediated, however, by the perceived risk of investment and the timing effects of investment (for example, the longer the delay to invest, the lower the level of investment.)
Overtime, this investment would be converted into an expansion in capacity, increasing both the total undersea cable capacity and ultimately the available lit capacity, closing the balancing loop.

Next, we expand on Figure 3 Capacity Expansion by adding an addition feedback loop that describes the effects of declining service quality on overall demand.

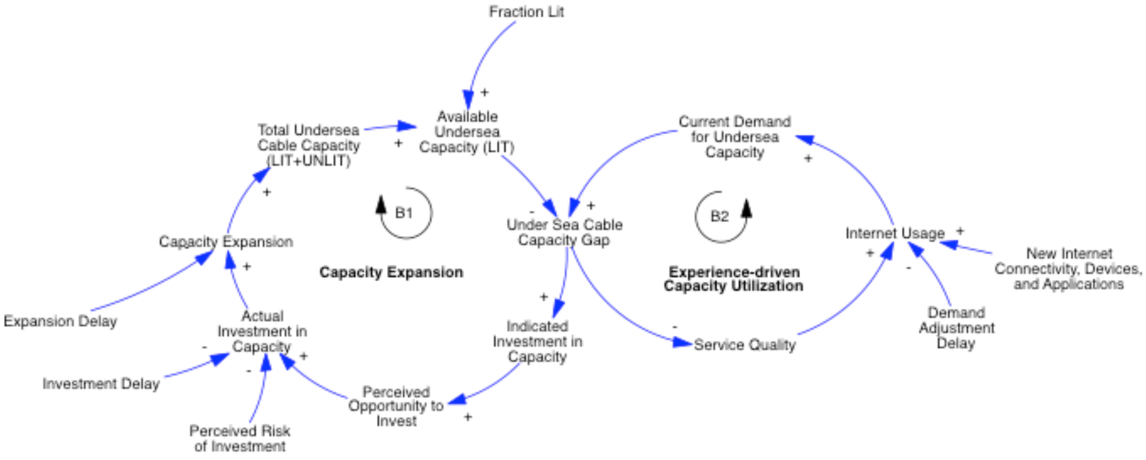

Figure 4 Experience Driven Capacity Utilization

Figure 4 adds loop "B2: Experience-driven Capacity Utilization," which describes the consequences of a failure of the dynamics in loop B1 to provide for expanded undersea capacity. If the required capacity does not exist, Internet users will experience a loss in service quality as Internet availability and speeds are reduced. Overtime, this has the potential to reduce Internet usage, balancing demand, albeit at a cost of Internet activity and its implied benefits.

Next, we examine cases in which efforts to expand capacity to meet demand can unintentionally create additional risks to the underlying cable infrastructure. Figure 5 shows two additional loops, both describing the ways in which capacity expansion can serve to increase the likelihood of disruption. Loop R1 describes risk created from geographical concentration, the collocation of new capacity that has the potential to create capacity loss from man-made disruptions. For example, a network served by a dense series of cables is more prone to capacity loss from intentional (non-state actor attacks, for example) and unintentional human interference (such as a shipping accident). Additionally, this concentration poses additional susceptibility from natural disasters (Loop R2), such as earthquakes and tsunamis.

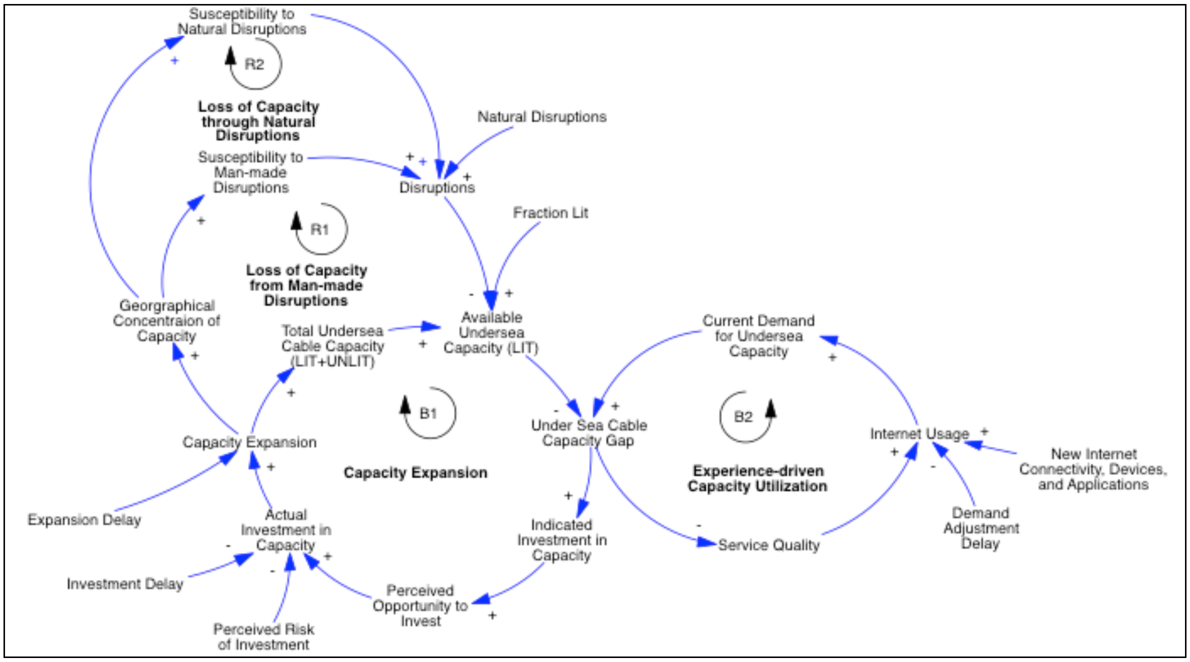

Figure 5 Capacity Utilization

Finally, we present a dynamic buffering against disruptions: unlit capacity, the quantity of cable capacity that is available but not currently in use. Because a significant amount of the cost of installing cables is the installation and connection of cables, operators often install more fiber than is needed for current demand, to provide for future expansion and have redundancy in case cable failure. Loop B3 of Figure 6 shows the dynamics of utilizing unlit capacity. If capacity is constrained, it will increase pressure to utilize unlit capacity (although this comes at a cost to the operator) to increase the overall capacity in use. Figure 6 explains the reason why those managing undersea cables focus on maintaining the necessary unlit capacity margin so as to cope with the increases in used international bandwidth or the loss of bandwidth due to disruptions.

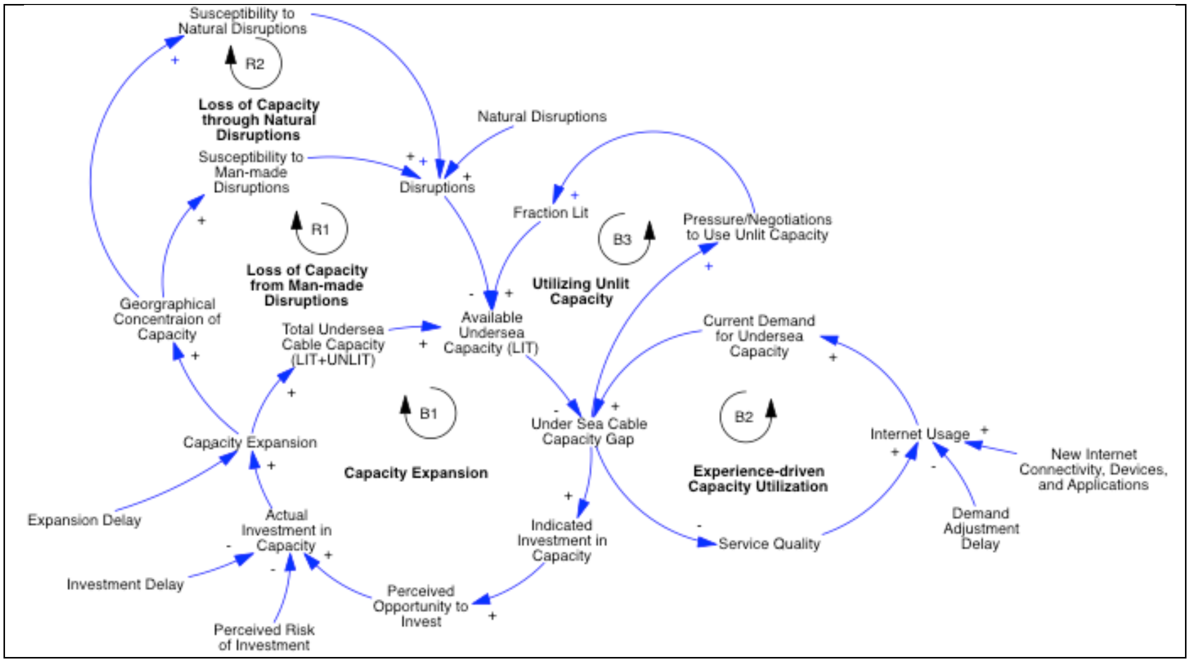

Figure 6 Utilizing Unlit Capacity

Having described in causal structure the core dynamics of undersea capacity expansion, given several contingencies, we will next explore these dynamics at a greater depth in a stock-flow model.

IV. SIMULATION MODELS

In this section we discuss a stock-flow model for the causal structures above. We first describe the model formulations, then the assumptions behind the model and their implications, and finally show how the model calibrates with the available data.

Debates about undersea cables can get very involved to micro-level details such as cables per landing station, pairs of fibers per cable, capacity of each fiber pair, and so on. We present here a parsimonious model, as we wish to rise above these details and to highlight higher level issues in managing undersea cables, of course while still staying true to the issues we identified in the above section.

Model Formulations

Table 2 shows the list of model parameters, corresponding symbols and units.

Variable Name	**Symbol**	**Unit**
Used International Bandwidth	T	Tbps[32]
Undersea Cable Total Capacity	C	Tbps
Investment in Undersea Cable	I	Dollar
Stakeholders in Undersea Cable Governance	S	Stakeholder
Time to Invest in Undersea Cables	τ_i	Month
Normal Time to Invest in Undersea Cables	$\tau_i^{'}$	Month
Time to Install Unit Undersea Cables	τ_n	Month
Fractional Utilized (Lit) Capacity	c_{lit}	Dimensionless[33]
Fractional Unutilized (Unlit) Capacity	c_{unlit}	Dimensionless[34]
Desired Fractional Unutilized (Unlit) Capacity	c_{des}	Dimensionless[35]
Available Undersea Cable Capacity	C_{avail}	Tbps
Disruption	δ	Month
Fractional Loss of Used Capacity	c_{lost}	Dimensionless[36]
Duration of Disruption	δ_t	Month
Additional Total Unutilized (Unlit) Capacity Required	C_{add}	Tbps
Additional Investment Required	I_{add}	Dollar
Average Investment in Undersea Cables	I_{avg}	Dollar
Actual Investment in Undersea Cables	$I_{C\ t}$	Dollar
Unit Technology Investment Yield	θ	Tbps/Dollar
Percentage Monthly Change in Internet Traffic due to Current Internet Activity	γ	%/Month

Table 2 Model Parameters, Symbols, and Units

We will now discuss the formulations for the complete model in the the following subsections: used international bandwidth (i.e., lit capacity), investment in undersea cables, building total undersea cable capacity (i.e., lit + unlit capacity), disruptions and available capacity, and the connection between utilization and investment.

Used International Bandwidth Formulations

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[32] Tera bits per second. 1 Tbps = 10^{15} bits per second.

[33] Equivalent of %/100

[34] ibid.

[35] ibid.

[36] ibid.

Figure 1 showed the growth of used international bandwidth. We formulate the this growth in bandwidth usage as follows:

$$\frac{dT_{t+1}}{dt} = d\gamma T_t + T_0$$

T_0 is the initial bandwidth usage at time 0 (in year 1990 when the Internet went commercial) the The above function approximates bandwidth usage to an exponential rize (or decline depending upon γ). Later in this section, we will see how it calibrates with Figure 1

Undersea Cable Investment Formulations

Investment in undersea cable occurs in two ways. First, Average Investment in Undersea Cables, which is the investment that takes place merely to keep up with the expected growth even though the desired fraction of unutilized (unlit) capacity may still be available. Second, Additional Investment Required, when capacity must be built rapidly as the margin of suplus ulit capacity may be depleting. The equation below reflects this situation:

$$I_{act} = I_{avg} + I_{add}$$

Here, I_{avg} is used as an exogenous variable to calibrate the historical trend of investment in undersea cable. I_{add} is determined endogenous to the model as shown below after we discuss the capacity formulations.

We can now formualte Investment in Undersea Cables:

$$\frac{dI}{dt} = d\frac{I_{act}}{\tau_i}$$

Where, τ_i is the Time to Invest in Undersea Cables, which is formulated as a function of Normal Time to Invest in Undersea Cables, $\tau_i^{'}$, and a function *f* of the total Number of Stakeholders in Undersea Governance, *S*.

$$\tau_i = \tau_i^{'} f(S)$$

The function *f*, above, produces a multiplier indicating how number of stakeholders affect time to invest in undersea cables. Figure 7 shows the table function for *f*. *Please note that there are no real world measurements of such a table function, but the trend is quite clear—the larger number of stakeholders in the process, the longer it takes to make investment decisions.*

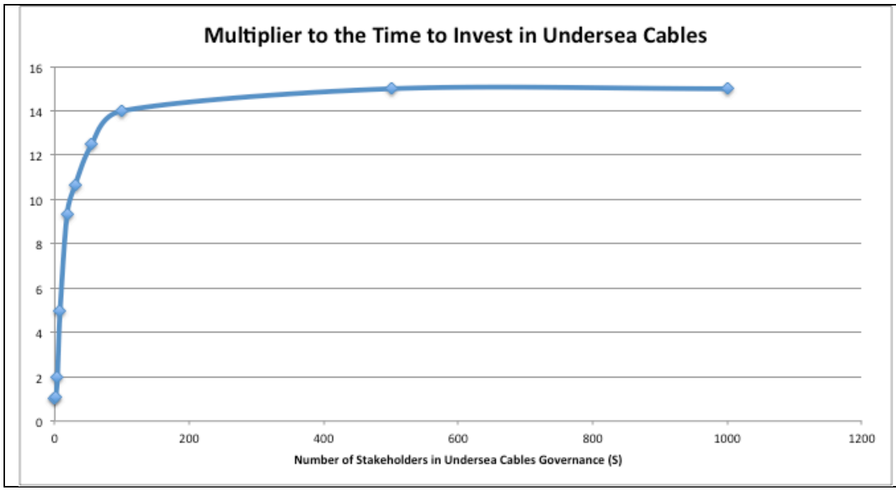


Figure 7 Table Function: Impact of Number of Stakeholders on Time to Invest in Undersea Cables

Undersea Cable Capacity Formulations

The Undersea Cable Total Capacity depends upon investment in undersea cables, how much that investment yields, and the time it takes to install a unit capacity, as shown below:

$$\frac{dC}{dt} = \frac{\theta \cdot I}{\tau_n} + C_0$$

Where C_0 is the undersea cable total capacity available in 1990. Here, Unit Technology Investment Yield, θ, indicates how much capacity can be built for a dollar. In the real world, this number exists but is not discussed as such. Also, its value has consistently gone down as technology gets cheaper. In the model, this variable is exogenous and is used for calibration purposes as discussed later.

Disruption and Available Capacity Formulation

Disruption, δ, is formulated as total or fractional loss of utilized capacity, c_{loss}, for a some duration, δ_t.

$$\delta = 1 - c_{loss} \cdot \delta_t$$

Available Undersea Cable Capacity, then, is a function of total capacity less disrupted capacity.

$$C_{avail} = \delta \cdot C = C - C \cdot c_{loss} \cdot \delta_t$$

Formulations Connecting Capacity and Investment

The ratio in the total available capacity of undersea cables vs. its usage gives us the Fraction of Utilized (or Lit) Capacity, c_{lit}. The MIN function below prevents the lit capacity from going above 1, which would be unreal.

$$c_{lit} = MIN\ (1, \frac{T}{C_{avail}})$$

Having formulated for the lit capacity, we can now find out the Fraction of Unutilized (or Unlit) Capacity, c_{unlit}.

$$c_{unlit} = 1 - c_{lit}$$

All of the above leads to the important formulation that connects additional investment required in undersea cable, C_{add}, when the unlit capacity falls below the desired margin, c_{des}.

$$C_{add} = \frac{C}{\theta}\ MAX\ (0, c_{des} - c_{unlit})$$

As we discussed towards the end of last section, c_{des}, Desired Fractional Unutilized (Unlit) Capacity, is a critical factor determined by those in governance of undersea cable in order to maintain a "safe margin" of unlit capacity. Today, this parameter ranges around 0.9 (i.e., 90% capacity is unlit). When bandwidth utilization rises and the margin falls below this value, additional investment is initiated.

Assumptions and Implications

The above model reflects several assumptions that we will now discuss. It is clear that these assumptions prevent us from building a model that is less-than-all-encompasing. That said, these assumptions allow us to keep the model parsimonious—the need for which has already been discussed—without compromising the lessons we want to and have learned from it.

The major assumptions embedded in this model are as follows:

1. The formulations for undersea cable investment, capacity, and utilization can only let them grow—not deplete. On one hand, in the real world, so far these quantities have only grown and are also expected to keep growing. On the other hand, there is no law that requires Internet traffic to keep growing for ever. Also, technological innovation could produce options other than undersea cables for international communications, thereby reducing their utilization. We think it is reasonable to exclude such hypothetical possibilities from the model.
2. Unlimited investment is available for undersea cables in this model. There may be a case to be made for limited funds since both public and private actors have shown some hesitation in investing in undersea cables because of the uncertainty about who should have responsibility when disruptions take place. We have not analyzed these dynamics. Nonetheless, regardless of the underlying reasons, having less than required funds would only make the results discussed in this paper worse.
3. There is no clear measurement of what causes the number of stakeholders in the governance process to grow. However, one corrilation is clear, the greater the investment, the greater is the number of stakeholders. We do not

know if the above corrilation is also causation. Even so, we have approximated this situation with an operational variable, Average Undersea Cable Investment per Stakeholder. This variable allows us to endogenize the number stakeholders. The results, as we shall discuss, are qualitatively different when the model is run with stakeholders as exogenous vs. endogenous. The exact value of the parameter, Average Undersea Cable Investment per Stakeholder, is irrelevant.

4. As noted earlier, the exact nature of the impact of number of stakeholders on the time (more accurately, delay) in investing in undersea cables is unknown. Again, the correlation is there: more the number of stakeholders, longer it takes to invest. We have approximated this situation in table function in Figure 7. The exact shape of this function may be different in that it could be more or less concave, but we are sure it cannot be convex, and so we can live with this approximation.
5. This is a model at a global scale in its capacity and utilization. As a result, it is not clear whether there is redundant unlit capacity available everytime there is disruption, since regions differ in their redundant capacities. We have therefore limited the notion of disruption to that where a spare capacity to migrate traffic is unavailable.

Parameterization and Calibration

We will now discuss how we calibrated the model to the real world data, and what the parameterization turned out to be as a result. As the model in the Appendix A shows, there are several switches included in the model for isolating various segments for calibration purposes. The calibration involved three phases that we discuss next.

Calibrating Utilization of International Bandwidth

We first calibrated the Utilization of International Bandwidth, T, by setting two parameters: Percentage Monthly Change in Internet Traffic due to Current Internet Activities, γ, and Initial Bandwidth Usage, T_0. γ was set to 5.02 %/month, to meet an average annual growth of Bandwidth Usage of 61%, as shown in Figure 1 T_0 was set to 290 Mbps, which would indicate what the International internet bandwidth usage ought to have been in 1990 so as to have a good calibration. Figure 8 shows the model run with the same data as in Figure 1.

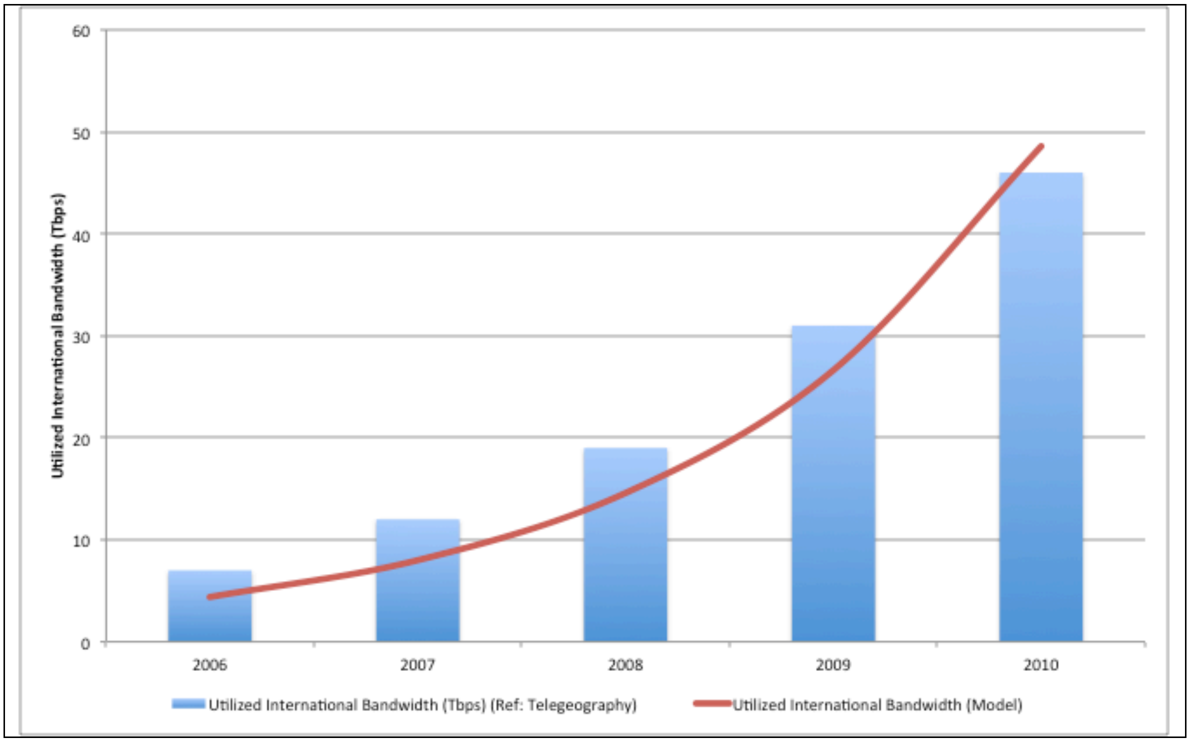


Figure 8 Calibration with Utilized International Bandwidth

Calibration of Investment in Undersea Cables

We next calibrated the Investment in Undersea Cables, I, by adjusting Average Investment in Undersea Cables, I_{avg}. According to Michael Ruddy of Terabit Consulting in his 2010 Undersea Cable Report, approximately $51 Billion have been invested in undersea cable infrastructure in the past two decades ($27 billion in the last decade alone). Figure 9 shows this data.

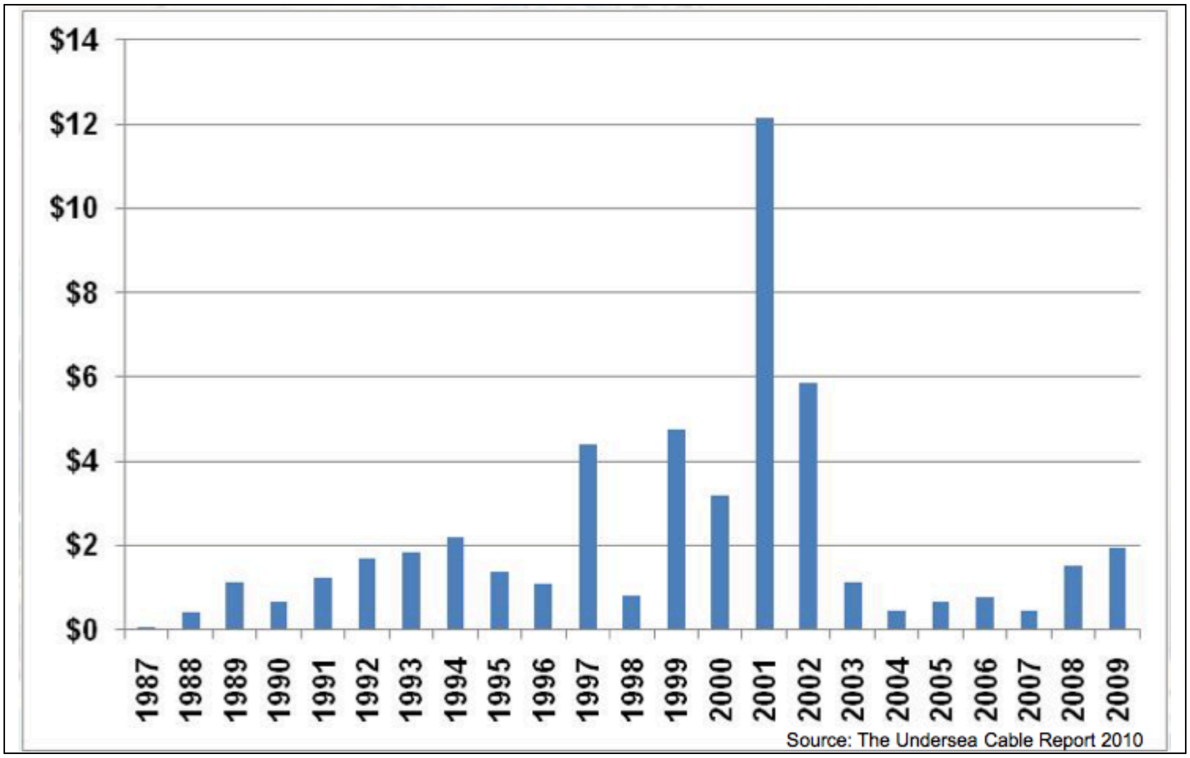


Figure 9 Investment in Undersea Cables

We calibrate this model to have an investment of \$51 Billion by the year 2011. A \$51 Billion investment is achieved when I_{avg} is set to \$1.2 Billion, which in effect is the investment done over the Time to Invest in Undersea Cable, τ_i. Figure 10 shows the outcome.

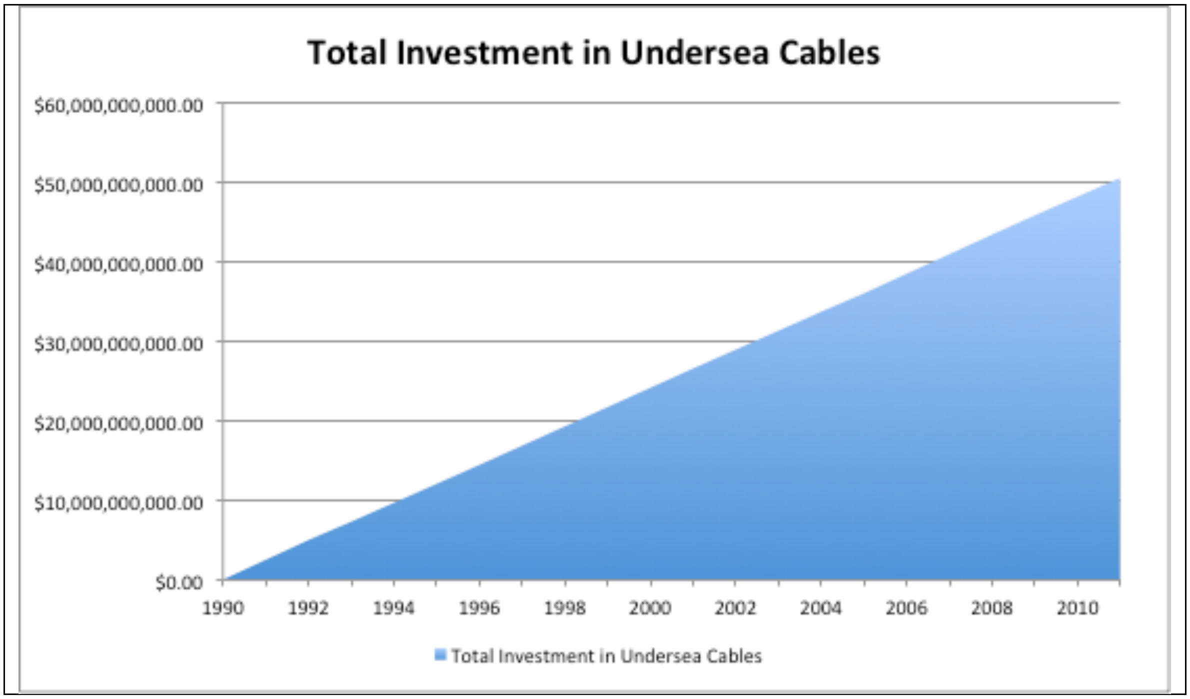


Figure 10 Total Investment in Undersea Cable Calibrated to $51 Billion by Year 2011

Calibration of Undersea Cable Total Capacity

Finally, we calibrate the Undersea Cable Total Capacity, C, such that the utilization remains under 10% (i.e., Fractional Utilized (Lit) Capacity, c_{lit}, remains under 0.1), until after year 2012—the year we are in—given the balance of capacity and utilization. This condition lets us keep the Fractional Unutilized (Unlit) Capacity, c_{unlit}, under the Desired Fractional Utilization (Unlit) Capacity, c_{des}, which is set to 0.9 (i.e., 90%). We achieve this calibration by tuning Unit Technology Investment Yield, θ, to 900bps/Dollar. This is approximately how much installed bandwidth a dollar buys. Unfortunately, we cannot verify how close this number is to its real world equivalent. However, setting it as such allows us to study the trends until 2011 as we know them, and then study the implications of the model for the future.

Model Parameterization

The above calibration leaves us with the following summary of all parameter settings:

Variable Name	**Symbol**	**Value**
Normal Time to Invest in Undersea Cables	τ_i'	6 Month
Time to Install Unit Undersea Cables	τ_n	6 Month
Desired Fractional Unutilized (Unlit) Capacity	c_{des}	0.9
Fractional Loss of Used Capacity	c_{lost}	0.5
Duration of Disruption	δ_t	6 Month

Average Investment in Undersea Cables	I_{avg}	$1.2 Billian
Unit Technology Investment Yield	θ	9E-10 Tbps/Dollar
Percentage Monthly Change in Internet Traffic due to Current Internet Activity	γ	5.02 %/Month
Average Undersea Cable Investment per Stakeholder	η	4E+13

Table 3 Model's Initial Parameterization

V. MODEL ANALYSIS AND RESULTS

We now perform model analysis discuss the result. The discussion that follows is written from two perspectives. First, from the perspective of validating whether the model behaves as expected. Second, from the perspective of what it teaches us. Our focus is necessarily on dynamic issues that would be hard to comprehend in the absence of such a model.

Steady State Error Between Desired and Actual Unlit Capacity and the Complexity of Eliminating It

Figure 11 shows a growth in Utilized International Bandwidth, T, that causes the Fractional Unutilized (Unlit) Capacity, c_{unlit}, to drop, and the subsequent response of building Undersea Cable Total Capacity, C. The same phenomena can be seen more clearly in Figure 12, which magnifies the period of year 2009 to 2015**.**

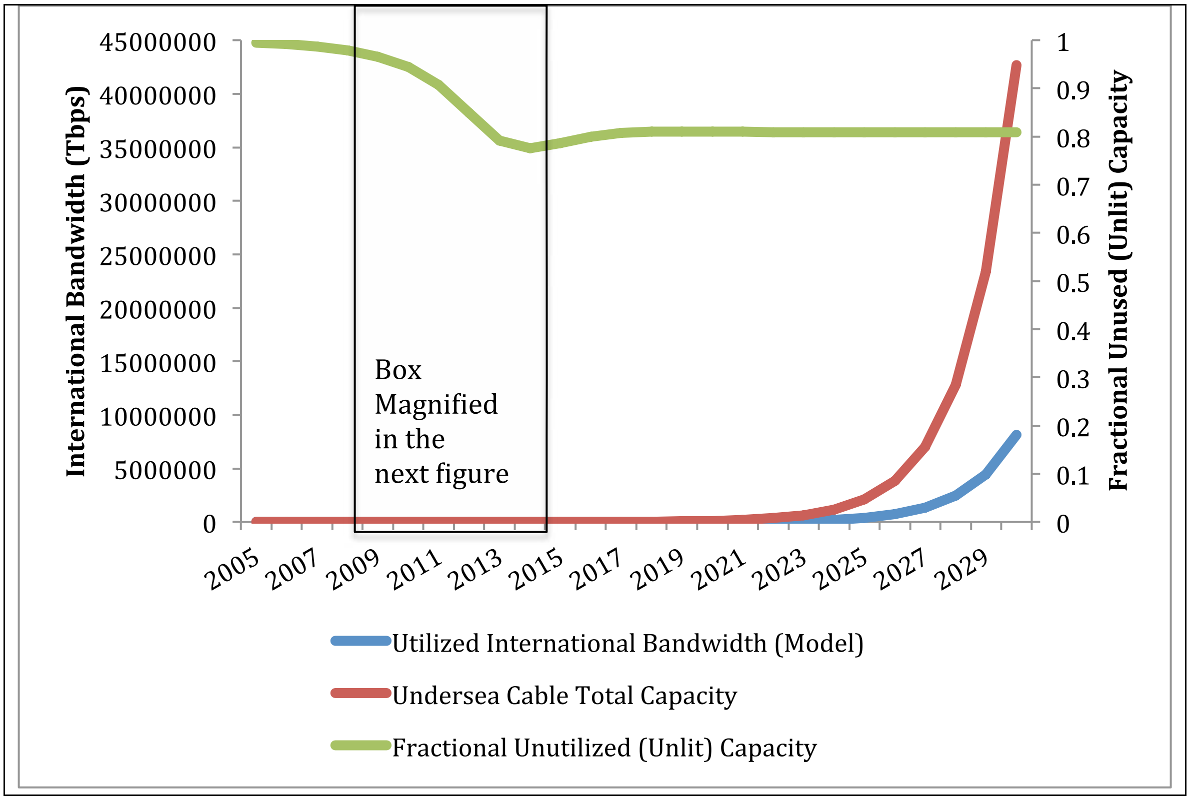


Figure 11 Base Run: Growing Bandwidth Utilization, drop in Unlit Capacity, and Building of New Capacity

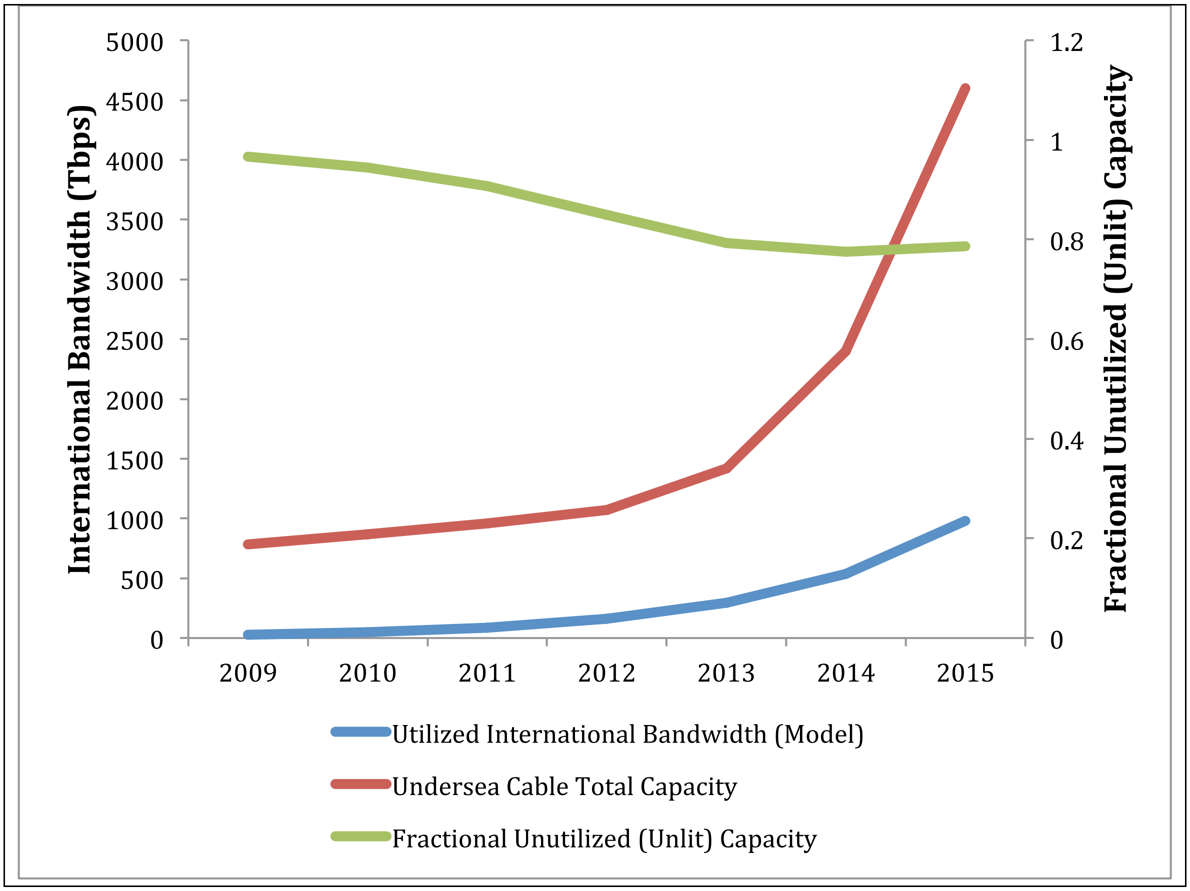


Figure 12 Utilized bandwidth, Unutilized Capacity, and Total Capacity (Figure 10 Zoom-in)

A longer and different view of the above situation is shown in Figure 13. Here, as the Fractional Unutilized (Unlit) Capacity, c_{unlit}, falls below the Desired Fractional Unutilized (Unlit) Capacity, c_{des}, Additional Investment in Undersea Cables, I_{add}, kicks into build Additional Fractional Unutilized Cable Capacity Required, c_{add}. These trends indicate that the model behaves as expected: when utilized bandwidth grows rapidly and the unutilized margin falls, additional invest occurs to build capacity.

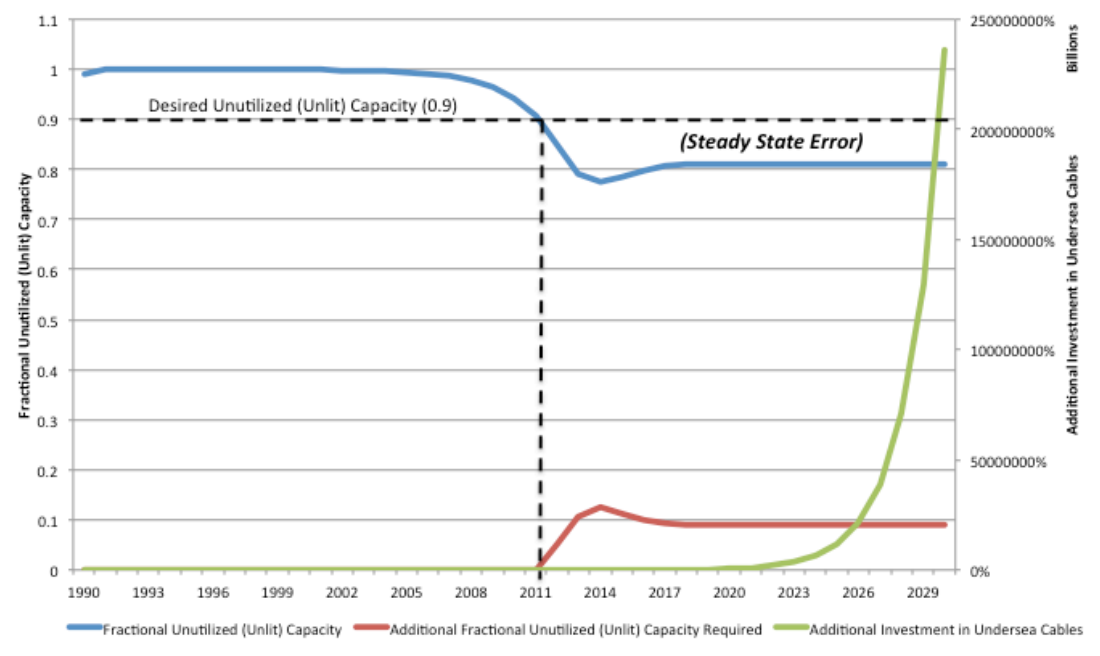


Figure 13 Base Run: Desired Unlit Capacity and Effect on Additional Investment

Let us now turn to analyzing what the above trend teach us. Figure 13 shows something peculiar. When fractional unlit capacity falls under the desired margin, new capacity is indeed built, but there is a *steady state error* that prevents the fractional unlit capacity to rise back above the desired margin despite additional investment. Why is that?

The reason for the steady state error is two material delays: the delay in investing in undersea cables,τ_i, and the delay in installing undersea cable capacity, τ_n. These delays prevent the additional investment in undersea cables from materializing into additional capacity so as to keep up with the growth in bandwidth utilization. The longer these delays, the larger the steady state errors ought to be, which is something we will analyze in the next subsection.

Can we eliminate this steady state error? *It is possible to eliminate the steady state error in theory, but very complex to do in the real word.* The model we have built would suggest that if we invest *more than* the required additional investment (I_{add}) indicated by the falling margin of unlit capacity available, we will ultimately catch-up and eliminate the steady state error. However, in real life, calculating what that extra investment ought to be has grave dynamic complexity owing to changes in at least four factors: bandwidth utilization (because of changing Internet traffic), time to invest (because of changing stakeholder investment), technology yield of investment (because of changing cost of technology), and available capacity (because of natural and man-made disruptions).

High-level: Implications of Time to invest in Undersea Cables on Safety Margin and Infrastructural Costs

We now turn to sensitivity analysis for some important parameters. The finding in this subsection relates to the high-level technology and governance causal structure showed in Figure 2. Figure 14 shows the impact of Normal Time to Invest in Undersea Cables, $\tau_i^{'}$, on Additional Fractional Unlit Capacity Required $(c_{des} - c_{unlit})$ to maintain the desired margin, which in our simulation runs was set to 0.9 (or 90%), and total investment necessary to build this capacity. This figure is a phase plot; meaning, each data point here is generated from a single simulation run. In each simulation run, the normal time to invest in undersea cable parameter is set to a value between 1 month and 36 months (see x-axis), and the corresponding value of the two parameters of interest on the y-axis are recorded in the equilibrium. A single simulation run generates tree values, one for x-axis, and two for the two y-axes, and a single plot is created from multiple such simulation runs.

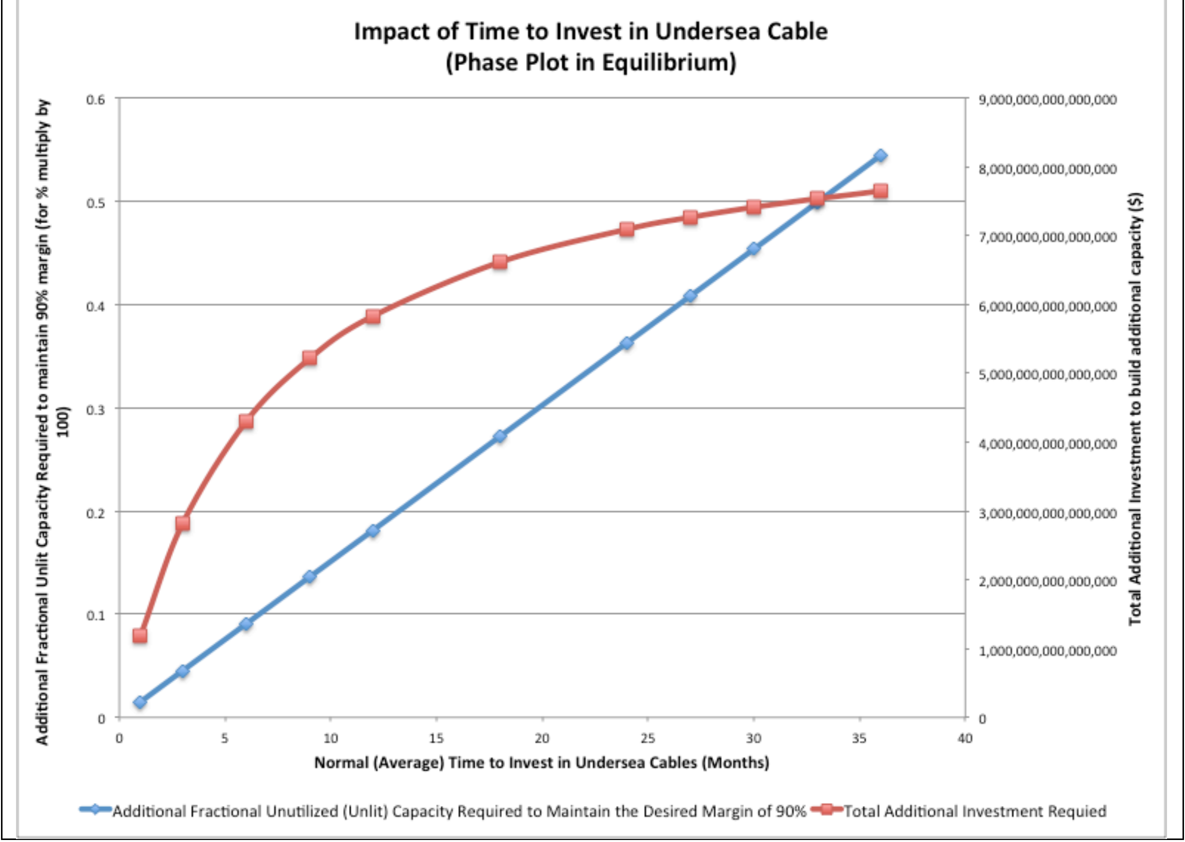


Figure 14 Implications of Time to Invest in Undersea Cables

We are interested in studying the model behavior in response to changing time to invest in undersea cables as this is the parameter delays in governance decisions affect the most. As we have conjectured, growing number stakeholders, or growing disagreement in stakeholders, can lengthen the time to invest in undersea cables. We vary this parameter between 1 and 36 months (three years), which, in the model, traslates to 4 months to 12 years to realize 95% of intended investment in the undersea cables, to capture what happens in the real word in international governance.

The result shows that as the delays grow in investing in undersea cables, far more capacity has to be built to maintain the desired margin of unutilized capacity, and to keep up with the growing bandwidth usage. As shown in Figure 14, up to 50% more of unutilized capacity may be required when delays in investment are very large.

An associated lesson shown in Figure 14 is that the additional investment required to build this additional capacity also rises; however, it rises at a deminishing rate. This outcome may be counter intuitive, and may even mislead investment policies. The indicated additional investment required does not rise linearly with additional capacity required as the steady state error is rising non-linearly. In other words, as the investment delays become longer, ivestment decisions that are based upon curent capacity are smaller than necessary. This situation exacerbates the issue of steady state error, as policymakers end up committing less investment than necessary, leading to growing gap between capacity and utilization.

Detailed-level: Disruption That Looks the Same May Have Very Different Dynamic Implications

The second set of sensitivity analysis is to understand the impact of disruption. Imagine that we lose 50% of used the used international bandwidth for a period of six months. Figure 15 shows the impact of such a disruption, if it were to take place in year 2000, 2010, and 2020. At one level, the lesson is obvious: the total data lost—more accurately, the total data that could not be transmitted—is far different in 2000, 2010, and 2020. Showing how same magnitude and duration of disruption can mean different impact at different times. This happens as the Internet traffic keeps growing.

At a deeper level, this chart indicates that we are only going to be more and more dependent upon the international Internet backbone. We have to find ways to both minimize the occurance of disruptions as well as the impact they can have on Internet activities. This final chart, which in some sense could be the first chart in this paper, is the reason for undertaking this study of the dynamics of undersea cables.

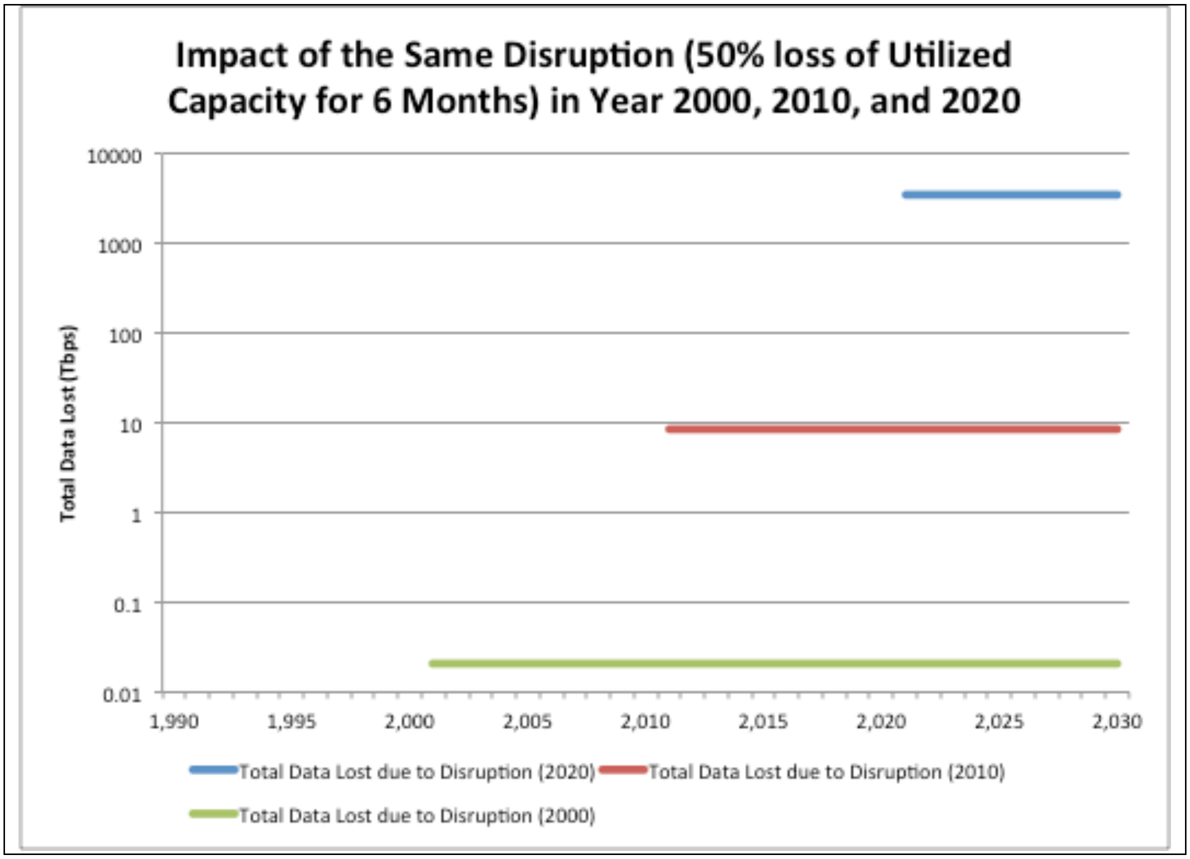


Figure 15 Impact of the same disruption in years 200, 2010, and 2020

VI. POLICY RECOMENDATIONS

In this paper, we highlighted the critical importance of undersea cable infrastructure for international communications over the Internet. With the help of a short case and related discussion, we first introduced several dynamic challenges in managing undersea cable infrastructure, including: rising capacity constraints, increased exposure to disruption from both natural and mad-made sources, emerging security risks from cable concentration in dense geographical networks, and the complex web of governance processes. We then offered causal formulations, a formal stock-flow model, and model analysis to understand in greater depth the opportunities and pitfalls facing policymakers when managing the undersea cable infrastructure in future. In this section, we conclude with a summary of policy lessons that follow from synthesizing lessons learned at each of the above steps.

At the highest level, opportunities for managing the undersea cables more efficiently lie along at least three dimensions: reducing the time to make investment decisions about the undersea cables, reducing the install and upgrade time for undersea cable systems, and reducing the load on undersea cable systems. The recommendations below are more specific manifestations of three classes of policy options:

1) Customers, companies or governments in need of more bandwidth quickly should choose cable systems being deployed by fewer owners, *not more*. When weighing bandwidth purchases on two systems, clients should choose the system with less number of owners in order to ensure faster decision-making processes and easier permit clearances. This insight is counterintuitive in the face of much excitement for cost sharing among larger number of partners.

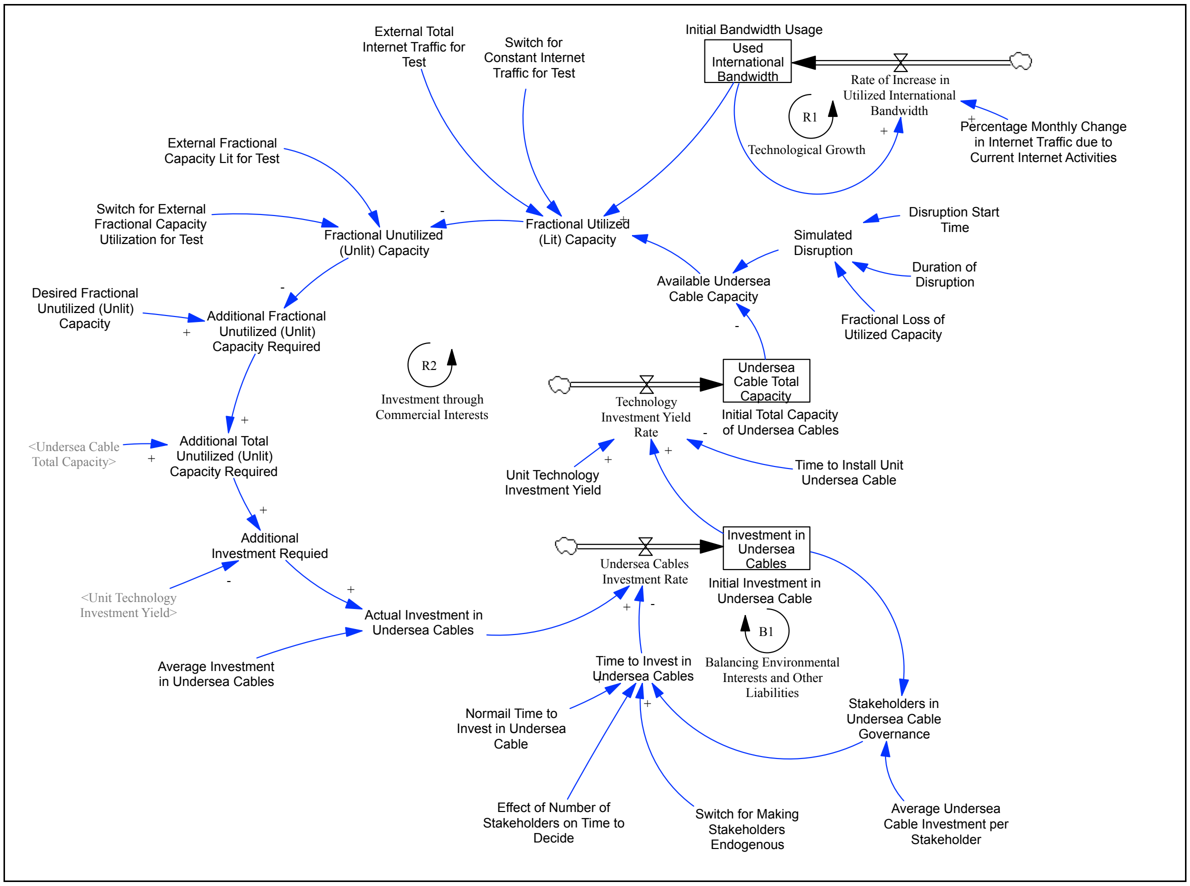
2) Fiber pairs on legacy systems can now be upgraded without upgrading the entire system. This dynamic will reduce time to install in our model, but it is unclear whether such upgrades will be possible past the 100G mark. To the extent it were though, such measures reduce the steady state error between capacity and utilization.

3) Nations that are connected at their borders via roadways and railways ought to lay fiber connectivity when new road and railways infrastructure is built. Such connectivity could come through international mandate. Today, in many places those nations that are connected by land still exchange traffic through undersea cables for historical reasons. Developing alternatives to undersea cables in such places would help in two ways: by reducing the utilization of undersea cables, and by reducing the reliance on undersea cables for intra-continental traffic when disruptions occur. Of course, such an option is more relevant for developing nations where new infrastructure investments are being made.

On the side of pitfalls, the most major ones for managing undersea cable are structural. At the highest level, the interplay between technological growth and the cable governance structure determines investments in additional capacity. This interplay exposes a competition between exponentially rising demands met with an increasingly sluggish response. This situation can only lead to demand surpassing capacity, or at least encroaching upon the “safe margin” of unutilized capacity. The situation is worse than it may appear because we do not fully comprehend the bewildering dynamic complexity of global growth in traffic, combined with distributed nature of investment, capacity building, and management of vulnerability. These dynamics conspire to prevent all key actors involved from collectively understanding the urgency of improved undersea cable management. Of course, as we have shown in this paper, even if these pitfalls were recognized, fully addressing them is not simple.

In sum, new usage patterns from the “Internet of Things,” coupled with changes from IPv6, will push bandwidth expansion exponentially in next 10-15 years. It is unclear whether legacy governance systems and cable ownership processes can keep up with this hunger for bandwidth. However, it is clear that with our research, we may have taken the first step in understanding the dynamics challenges involved in managing undersea cables and in identifying classes of policy decisions that may begin to address these challenges.

APPENDIX A
Model



```
Rate of Data Loss=
	Rate of Increase in Utilized International Bandwidth * (1 -
Simulated Disruption)
	~	Tbps/Month
	~	Rate of data loss.
	|

Total Impact of Disruption= INTEG (
	Rate of Data Loss,
		0)
	~	Tbps
	~	Total data loss due to disruption
	|

Actual Investment in Undersea Cables=
	Average Investment in Undersea Cables + Additional Investment
Requied
	~	Dollar
	~	Currently set to be the same as Actual Investment
	|

Technology Investment Yield Rate=
```

```
      Investment in Undersea Cables * Unit Technology Investment Yield
/ Time to Install Unit Undersea Cable
      ~     Tbps/Month
      ~     Total Undersea Cable Capacity Acquired Per Month
      |

Months per Year=
      12
      ~     Month/Year
      ~           |

Available Undersea Cable Capacity=
      Undersea Cable Total Capacity * Simulated Disruption
      ~     Tbps
      ~     Available capacity given disruptions.
      |

Average Investment in Undersea Cables=
      1.2e+09
      ~     Dollar
      ~     Exogenous Investment in Underseacable
      |

Average Undersea Cable Investment per Stakeholder=
      4e+13
      ~     Dollar/Stakeholder
      ~     Average spending that generates an additional stakeholder
      |

Base Year=
      1990
      ~     Year
      ~     Year of Starting the Simulation
      |

Switch for Constant Internet Traffic for Test=
      0
      ~     Dmnl [0,1,1]
      ~    When set to 1, a constant external Internet traffic is used.
      |

Disruption Start Time=
      120
      ~     Month
      ~     When does the disruption begin. Currently initialized to
year 10 (month \
            120).
      |

Duration of Disruption=
      6
      ~     Month
      ~     Duration of Disruption at year 10.
      |

Initial Total Capacity of Undersea Cables=
      0.029
      ~     Tbps
```

```
      ~     10 times the 1990 Traffic, given that 90% is unlit capacity
      |

External Fractional Capacity Lit for Test=
      0.8
      ~     Dmnl [0,1]
      ~     External Capacity Utilization for testing
      |

External Total Internet Traffic for Test=
      20
      ~     Tbps
      ~     External Traffic, currently set to the global Internet
traffic in 2010.
      |

Additional Investment Requied=
      "Additional Total Unutilized (Unlit) Capacity Required"/Unit
Technology Investment Yield
      ~     Dollar
      ~     Total additional investment required
      |

Fractional Loss of Utilized Capacity=
      0
      ~     Dmnl
      ~     Fraction of Utilized Capacity Lost due to Disruption.
Initialized to 0, so \
            no disruptions in the normail case.
      |

"Fractional Unutilized (Unlit) Capacity"=
      1 - (Switch for External Fractional Capacity Utilization for Test
* External Fractional Capacity Lit for Test\
             + (1 - Switch for External Fractional Capacity Utilization
for Test) * "Fractional Utilized (Lit) Capacity"\
            )
      ~     Dmnl
      ~     What fraction of undersea cable capacity is unutilized
      |

"Fractional Utilized (Lit) Capacity"=
      MIN (1, ((Switch for Constant Internet Traffic for Test *
External Total Internet Traffic for Test
       + (1 - Switch for Constant Internet Traffic for Test) * Used
International Bandwidth\
            )/Available Undersea Cable Capacity))
      ~     Dmnl
      ~     What fraction of Undersea Cable Capacity is Utilized
      |

Initial Bandwidth Usage=
      0.00029
      ~     Tbps
      ~           |

Initial Investment in Undersea Cable=
      1.2e+08
```

```
	~	Dollar
	~	Total Investment in Undersea Cable in 1990
	|

Switch for Making Stakeholders Endogenous=
	0
	~	Dmnl [0,1,1]
	~	When set to 1, Number of Stakeholders impact the decision 
process
	|

Simulated Disruption=
	1 - Fractional Loss of Utilized Capacity * PULSE( Disruption 
Start Time , Duration of Disruption\
		 )
	~	Dmnl
	~	Disruption that leads to capacity loss. 1 indicates no 
disruption (all of \
		the capacity is available). Less than 1 indicates the 
correspoing fraction \
		of capacity lost.
	|

Time to Install Unit Undersea Cable=
	6
	~	Month
	~	1/3rd of the Average Installation Time
	|

Time to Invest in Undersea Cables=
	(1 - Switch for Making Stakeholders Endogenous) * Normail Time to 
Invest in Undersea Cable\
		 + Switch for Making Stakeholders Endogenous * Normail Time 
to Invest in Undersea Cable\
		 * Effect of Number of Stakeholders on Time to 
Decide(Stakeholders in Undersea Cable Governance
	)
	~	Month
	~	Time to make investment decision
	|

Switch for External Fractional Capacity Utilization for Test=
	0
	~	Dmnl [0,1,1]
	~	When set to 1, external capacity utilization is used for 
testing purposes.
	|

Year=
	Base Year + (Time/Months per Year)
	~	Year
	~	Current Year
	|

Stakeholders in Undersea Cable Governance=
	Investment in Undersea Cables/Average Undersea Cable Investment 
per Stakeholder
	~	Stakeholder [1,36,1]
```

```
	~	Total Stakeholders in the Decision Process
	|

"Additional Fractional Unutilized (Unlit) Capacity Required"=
	MAX ( 0 , ("Desired Fractional Unutilized (Unlit) Capacity" - 
"Fractional Unutilized (Unlit) Capacity"\
		) )
	~	Dmnl
	~	When unutilized capacity is less than desired, use that 
value to build \
		additional capacity. When there is sufficient unutilized 
capacity, do \
		nothing.
	|

"Additional Total Unutilized (Unlit) Capacity Required"=
	"Additional Fractional Unutilized (Unlit) Capacity Required" * 
Undersea Cable Total Capacity
	~	Tbps
	~	Build the required additional capacity
	|

"Desired Fractional Unutilized (Unlit) Capacity"=
	0.9
	~	Dmnl
	~	What fraction of Undersea Cable Capacity do those in 
governance want to \
		maintain as unutilized
	|

Effect of Number of Stakeholders on Time to Decide(
	[(0,0)-
(1000,20)],(0,1),(2,1.1),(4,2),(8,5),(18.3299,9.33333),(30.5499,10.6667
),(54.9898\
		,12.4762),(100,14),(500,15),(1000,15))
	~	Dmnl
	~	Multiplier to normail time for decision as stakeholders 
grow
	|

Percentage Monthly Change in Internet Traffic due to Current Internet 
Activities=
	5.02
	~	1/Month
	~	Percentage monthly grwoth or decline in the Internet 
Traffic Parameter for \
		tuning the experimental exponential growth in Internet 
Traffic.
	|

Investment in Undersea Cables= INTEG (
	Undersea Cables Investment Rate,
		Initial Investment in Undersea Cable)
	~	Dollar
	~	Total investment in Undersea Cables
	|

Normail Time to Invest in Undersea Cable=
```

```
      6
      ~     Month
      ~     Normail time it takes to invest the required amount in
undersea cable
      |

Rate of Increase in Utilized International Bandwidth=
      Used International Bandwidth * Percentage Monthly Change in
Internet Traffic due to Current Internet Activities\
            /100
      ~     Tbps/Month
      ~     Total monthly increase in Internet Traffic
      |

Used International Bandwidth= INTEG (
      Rate of Increase in Utilized International Bandwidth,
            Initial Bandwidth Usage)
      ~     Tbps
      ~     Total Internet Traffic
      |

Undersea Cable Total Capacity= INTEG (
      Technology Investment Yield Rate,
            Initial Total Capacity of Undersea Cables)
      ~     Tbps
      ~     Total Global Capacity of the Undersea Cable.
      |

Undersea Cables Investment Rate=
      Actual Investment in Undersea Cables/Time to Invest in Undersea
Cables
      ~     Dollar/Month
      ~     Average Investment in Undersea Cable per Month
      |

Unit Technology Investment Yield=
      9e-10
      ~     Tbps/Dollar
      ~     What capacity can be installed for a dollar
      |

********************************************************
      .Control
********************************************************~
            Simulation Control Parameters
      |

FINAL TIME  = 480
      ~     Month
      ~     The final time for the simulation.
      |

INITIAL TIME  = 0
      ~     Month
      ~     The initial time for the simulation.
      |

SAVEPER  =
```

```
        TIME STEP
      ~     Month [0,?]
      ~     The frequency with which output is stored.
      |

TIME STEP  = 0.0625
      ~     Month [0,?]
      ~     The time step for the simulation.
      |
```

APPENDIX B
How to Generate Model Runs of this Paper

1. Figures 8, 10, 11, 12, 13. Execute the base run of the model as per Table 3 (which is the same as the submitted model)
2. Figures 14, set…
   a. Switch for Making Stakeholders Endogenous = 0
   b. Perform a simulation run each with Normal Time to Invest in Undersea Cable = 1, 3, 6, 9, 12, 15, 18, 21, 24, 27, 30, 33, 36
   c. Record the final value of the two parameters of interest for each simulation run
3. Figure 15, set…
   a. Fractional loss of Utilized Capacity = 0.5
   b. Duration of Disruption = 6 months
   c. Perform simulation runs with Disruption Start time = 120 (for year 2000), 240 (for 2010) and 360 (for 2020).
   d. Record value of stock, "Total Impact of Disruption," on view 2.