Improving the Chilean Internet Robustness: Increase the Interdependencies or Change the Shape of the Country?

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Abstract. This work addresses the study of Chilean Internet robustness in how an outage at the physical layer (Internet backbone) affects the upper layer (BGP network) that routes from/to Internet Service Providers. We propose a novel way to model the Internet physical and logical networks coupled as an interdependent system, and study the effect of the shape in which the physical network is built and the interconnection level on the robustness of the whole interdependent system. We study three cases of simulated Internet structures with width and length proportions ranging from 1:1 to 1:25, where each case has the same overall area. Here 1:25 corresponds to the proportions of Chile, while 1:1 represents a square space. For each case we studied five scenarios of interdependent connections in order to determine the relation between network robustness, and its shape and interconnections. Our main findings are: (1) the shape area where physical network is located affects the overall robustness making the interdependent networks more fragile as the shape becomes narrower, and (2) this effect can be diminished on interdependent systems increasing the number of inter-links.

1 Introduction

Chile is a country with a long history of strong earthquakes. One of the most destructive ones at 9.5 on the Mw scale happened in 1960 in Valdivia, south of the country. Again, in 2010, another very strong earthquake struck Cobquecura, at 8.8 Mw. These are both on the top 10 strongest earthquakes ever recorded, with Valdivia being number one. This puts a lot of pressure on communications networks, with some of the nodes failing at different times. Chile's peculiar geography makes studying physical networks important to ensure the robustness of the internet/cellphone networks.

In fact, after the 8.8 Mw earthquake a one day Internet outage was checked and reported [18], and since then one of our institute's main objectives has been to study and improve our national communication networks infrastructure.

In order to understand what would happen to the Internet under different failure scenarios it's necessary to study its robustness. Here, we consider that Internet robustness refers to the ability to keep the users connected in case of

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failure. However, to understand the Internet robustness we must first understand the underlying structures that compose it [22]. On the one hand there is the physical Internet network comprised by cables, antennas, routers, etc. On the other hand there is the logical Internet network comprised by autonomous systems (AS) [1] which are connected following the BGP protocol [2]. These networks interact with each other allowing for the Internet to properly function.

This work addresses the study of Chilean Internet robustness in how an outage at the physical layer (Internet backbone) affects the upper layer (BGP network) that routes from/to Internet Service Providers. Then we generalized to geographies not similar to that of Chile, varying the width:height ratio of them in order to better understand if the geography is a key factor in the Internet robustness.

We characterized the Internet following the recommendations of Willinger and Roughan [22], as an interdependent network comprised by the physical Internet network and the logical Internet network. Here, each layer is characterized and modelled as well as the interactions between them (Sect. 3) based on the model presented by Parandehgheibi et al. [15]. In Sect. 4 we simulate Internet interdependent systems and then in Sect. 5 we study other two kinds of physical spaces, thus we explore the effect on the interdependent system of three physical spaces whose width and length proportions range from 1:1 to 1:25. In Sect. 6 we analyze the results of our experiments. Finally, in Sect. 7 we present the conclusions of this work.

Our finding suggests that a mixture of the shape and the inter-link connections have an effect over the overall robustness making the interdependent networks more fragile as the shape becomes narrower and as the amount of inter-connection becomes lower.

2 Related Work

The area of interdependent networks studies systems composed of two or more interacting networks, with behaviours produced by such interactions that are not usually present on single networks. The study of the robustness of interdependent networks is a problem that has been explored in the last decade, leading to the development of several frameworks to tackle it. Among these frameworks we can find the "*one to one*" model presented by Buldyrev et al. [3], where they consider two interacting networks where each node depends on exactly one node in the other network with mutual dependency, this means that if a node fails then necessarily its interdependent neighbour will fail.

Variations of this 'one to one' model can be found on literature, such as the work of Wang et al. [20] which considers a one to one model with loads within each network, or the work presented in [8] where is not required that each node is interconnected to other node. We can also find "*many to many*" kind of models, where each node may be interconnected to 0 or more nodes in the other network [4,6,14,16,19]. In these models dependencies may be directed or undirected. The models have different rules for how many of a node's interdependencies have to fail for the node to fail.

Other models focus more on specific characteristics of the system that want to be represented. Examples of this are the works presented in [9,13,15] where the main purpose of the model is to represent a power grid network coupled with their control network, or the work of Li et al. [11] where main feature of the model is to represent spatially constrained networks.

In order to measure the robustness of interdependent networks different indexes and metrics are used. Some of these include the size of the giant mutually connected component [10,11,21,24], the percolation threshold [3,5,12], the time delay of information transmission [23], etc.

Up to the authors knowledge, the work presented here is the first one modeling the Internet as an interdependent network comprised by the logical and physical Internet networks, and studying its robustness.

3 Internet Modeling

It is worth mentioning that modelling the Internet as a single network of autonomous systems (ASs) has received criticism in the past:

> "*(...) the traditional approach of modeling the AS-level Internet as a simple connected di-graph is an abstraction incapable of capturing important facets of the rich semantics of real-world inter-AS relationships, including different interconnections for different policies and/or different interconnection points (...) The multiple nature of such connections leads this to being a multigraph, as it is very common for two ASes to be connected by multiple links and in different geographic locations.*" (Internet Topology Research Redux, by Willinger and Roughan) [22].

Therefore, following Willinger and Roughan recommendations, in this work we will consider other participating structures influencing the logical Internet network. In our case we consider the physical structures related to the logical network and the interactions between them. We model the interdependent system mixing different previous models for the interdependencies, the physical network, and the logical network. For the interdependencies we follow the model presented in [15], here we include the interdependencies' behaviour as well as the consumer-provider behaviour presented in the paper. As for the physical network, it is modeled using a modification of the relative neighbourhood model presented in [21]. Finally, the logical network is modeled as a Power-law network [7]. The models for the interdependencies, the logical network, and the physical network will be discussed in the following sections.

3.1 Physical Network

The physical network is responsible of transferring and distributing the information through physical means such as cables, optical fibers, routers, and antennas. Here, processing and redistributing information equipment such as servers, routers, or antennas correspond to the nodes of the network. In this work, we considered the Internet backbone as the physical Internet network. It is important to notice that in Chile in particular (and Latin America and some other countries in general) the Internet backbone network follows the highways topology. This information is relevant to properly model the physical Internet network.

In this network the information flow is bidirectional between each pair of nodes, thus, the links of the network are undirected links. Additionally, this network has characteristics specific to its physical nature such as distances and failure probability given their geographic location, for example, due to natural catastrophes. Finally, each node must have a path to a node that can provide Internet access, that is, a path to a physical counterpart of an Internet service provider, and to an International gateway.

The model for the physical network is a modification of the relative neighbourhood model presented in [21] for interdependent networks, which describes the conditions to inter-connect a pair of nodes where each belong to a different physically embedded network.

We have adapted this model to build a single physical layer instead of an interdependent network. In our adaptation, given a finite 2-dimensional space with a certain shape and a number of nodes N_p, each node is randomly allocated in the space. Two nodes u and v get to be connected if there is no other node in the intersection area of the circles centered at u and v, each of radius $d(u, v)$, where $d(u, v)$ is the euclidean distance between node u and v. This can be interpreted as follows: two nodes will get to be connected if there is no other node closer to them in the area between them.

This way, the adapted relative neighbourhood model creates a network where 2 nodes are connected if there is no other node close enough in the direction where they face each other, which captures a physical Internet network built with finite resources, and where longer links have a higher cost relative to shorter links.

3.2 Logical Network

The logical network maps communication routes among the ASes. An AS is a subnetwork that autonomously manages the routing within itself. On the logical network each AS represents a node while each connection given by the BGP between nodes represent a link. In this network the information flow is bidirectional, hence the links in this network are undirected. Additionally, in order for a node to have access to the Internet service it must be connected through at least one path to a Internet Service Provider (ISP), and to an International gateway to have access to the worldwide network.

The logical network is modeled as a network with Power-law degree distribution using appropriate λ values [7] as it has been widely used to model BGP networks.

3.3 Interdependencies and Consumer-Provider Behaviour

The physical and the logical network interact with each other, i.e., they are interdependent networks. These interactions are mutual.

On the one hand, we have that each ASes node in the logical network may be allocated in one or more nodes in the physical network. If a node in the physical network doesn't have a path to an ISP or gateway counterpart node (logical networks), then it will not have access to Internet service. As for the dependence, if all the physical nodes where a logical node is allocated fail, then the logical node will also fail, as none of its physical systems is able to communicate.

On the other hand, we have that a physical node may route a set of ASes. Hence, if all the logical nodes allocated in it fail, then the physical node won't be able to answer to any other node within the physical network, so we consider that it failed too.

This way the dependencies between networks are established as "many to many" in a bidirectional fashion, with the condition that if all of the interdependent nodes of a particular node fail, then it fails.

Based on the model presented by Parandehgheibi et al. [15] we considered an interdependence model where each node in each network can be inter-connected to 0 or more nodes bidirectionally to the other network. Here, if a node looses all of its inter-connections then it fails. In order for the logical network to work as described in Sect. 3, each node in the logical network must be inter-connected to at least one node in the physical network. In our adaptation of the Parandehgheibi model, we set a maximum amount of inter-connections I_{max} for the logical network nodes, rather than a fixed amount of inter-connections. This way, each logical node u will be connected to $I_u \in [1, 2, \ldots, I_{max}]$ nodes in the physical network, where I_u is selected at random from the set $[1, 2, \ldots, I_{max}]$. Each of these I_u inter-connections is randomly established between u and a node in the physical network, and u must be inter-connected to exactly I_u nodes in the physical network.

As for the consumer-provider nature of the interdependent networks described in Sect. 3, we model it as described in [15], that is, within a network some nodes are considered to be providers and the rest of them are considered to be consumers. In order for a consumer node to be able to function there must be a path between it and a provider node.

In our model we consider that there is a fixed amount of provider nodes P_l in the logical network (there are six Internet Service Providers, ISP, in Chile). To model realistic Internet providers, these provider nodes must have the highest amount of inter-connections possible among the logical nodes, that is, the logical nodes whose I_u is the closest to I_{max}. As for the physical network, is considered that each node inter-connected to a provider node in the logical network will become a provider node in the physical network. In our adaptation of the model, we interpreted provider nodes as ISPs and International gateways. This way, a consumer node will stay functional if there's a path from it to the a provider node, and if it has at least one inter-connection with the other network.

4 Chilean Infrastructure

Our objective is to study the effect on the robustness of the shape in which the Internet physical network is built in, specifically for the case of a Chile-like geography (see Fig. 1).

Fig. 1. Continental Chilean geography. The width (E-W) to length (N-S) proportion of Chile is 1:25.

To study the robustness of interdependent networks we must first define what does it mean to be robust in the context considered. In this work the robustness has a user based perspective, that is, given two interdependent systems, in case of fail the system that has more users with Internet access will be the most robust. To observe the users' ability to access the Internet in our model, we must observe if the logical network contains the ISPs ASes, which in fact give to the final users' the Internet access. Therefore, in our model we define G_L as measure of robustness, with $G_l = \frac{N_l^f}{N_l}$, where N_l is the amount of nodes in the logical network (all initially functional), and N_l^f is the amount of functional nodes (with Internet access) of the logical network after an attack.

For the interdependent networks used for experiments we considered logical networks with $\lambda = 2.5$ [7]. The physical network was built in a rectangular space with a width to length ratio of 1:25 in order to simulate a space with Chile-like proportions. For the experiments was considered $P_l = 6$ the amount of logical provider nodes following the amount of providers of the Chilean Internet network, and $I_{max} \in [1, 3, 5, 7, 10]$ the maximum amount of inter-connections for logical nodes. For each I_{max} we simulated and tested 10 interdependent systems to appreciate their average behaviour. On each experiment, each layer had a single connected component. Thus, the interdependent physical nodes of two nodes connected by a path in the logical network are also connected through a path in the physical network.

To study the robustness of the interdependent systems we tested random attacks over the physical network. For each interdependent system 100 iterations of each kind of attack were considered to get the final results.

Finally, the logical network was simulated with 300 nodes, and the physical network with 2000 nodes, in order to follow the Chilean proportions of nodes in both networks.

As a general result we found that G_L presents a continuous decay under random attacks on each attack case studied, meaning that no abrupt collapse is observed on the logical network under random attacks. We also found that the I_{max} value did have a strong impact on the overall robustness, by increasing the robustness as the I_{max} gets higher.

In Fig. 2(a) we show the fraction of nodes lost in the logical network when up to 15% node fails at the physical network, for each I_{max}. Notice that the *one to one* case ($I_{max} = 1$) shows higher fragility in contrast to the cases with lager values of I_{max}. It can also be appreciated that the larger the I_{max} value, the more robust is the network. This can be further observed in Fig. 2(b), where we can see the effect on the G_L of the fractional amount of nodes removed from the physical network. Overall, in Fig. 2(a), (b) we can see that there is a great difference on the robustness for each I_{max}. However, the most notorious differences are seen for $I_{max} = 1$ and $I_{max} = 10$ relative to $I_{max} \in [3, 5, 7]$.

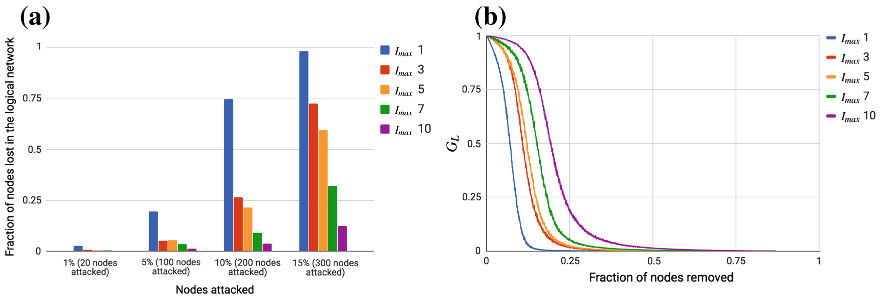

Fig. 2. (a) Fraction of nodes lost in the logical network for the Chile like interdependent system under attacks over the physical network. (b) G_L for the Chile like interdependent system under attacks over the physical network.

So far we have seen the effect of a Chile-like geographic environment on the robustness, given different I_{max} values. However, there remains to be determined whether this behaviour has any relation with the shape of the space in which the physical network was built in, and if there is any relation, which kind of relation it is.

5 Exploring Other Geographies

To fully understand the effects of the geography (physical network) on the robustness of the Internet as modeled in this work we studied two other space shapes to build the physical network in. This shapes represent a range between a Chile-like shape and a square shape.

Similar to Sect. 4 we consider G_L as robustness measure and 10 iterations per I_{max} and shape studied. The shapes considered have width to length ratios in $\{1 : 25, 10 : 125, 1 : 1\}$, where 10:125 represents a space whose shape is in between a Chile-like space and a square space (1:1). As for the rest of the parameters we consider $\lambda = 2.5$, $P_l = 6$, $I_{max} \in [1, 3, 5, 7, 10]$, and each network having a single connected component containing all the nodes. This way, the robustness behaviour of all the space shapes can be compared.

From the experiments performed we found that the shape in which the physical Internet network is built in has an effect on the robustness of the interdependent system, where the narrower the shape, the lower the robustness. Also, notice that this effect can be reduced by increasing the number of inter-dependent links (I_{max}).

In Fig. 3 can be seen the fraction of functional nodes in the logical network G_L versus the I_{max} value, when the different interdependent systems have lost 1, 5, 10, and 15% of the nodes at the physical network. On Fig. 3 we can appreciate that the most fragile shape to build the physical network in is the Chile-like shape, while the closer the shape gets to a square the more robust it gets. This phenomena can be appreciated in the fact that the higher the I_{max} the higher the G_L for the same amount of nodes removed.

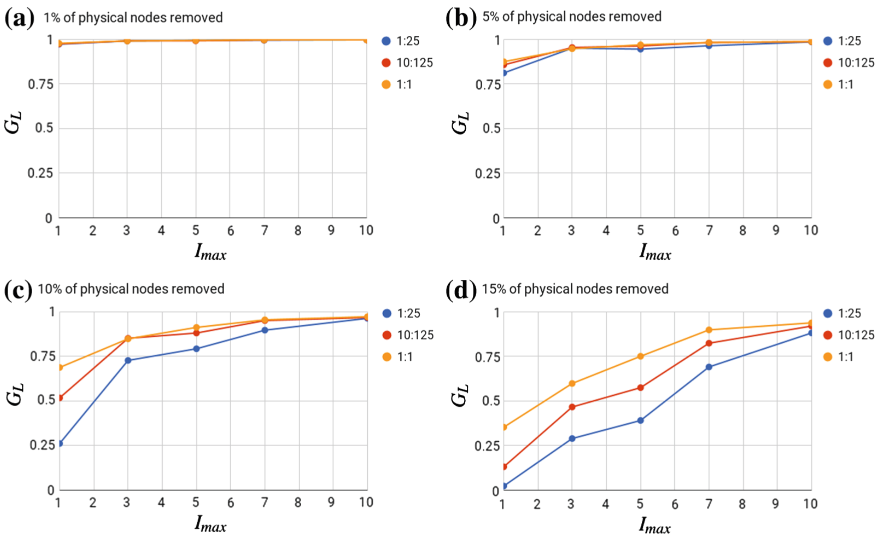

Fig. 3. (a–d) G_L versus I_{max} for each shape with width to length ratios in [1:1,10:125,1:25], given a fixed amount of nodes removed from the physical network.

On Fig. 3 we can also appreciate the effect of the I_{max} value on the differences of robustness for each kind of shape: in Fig. 3(a) is shown that for a small node loss there is almost no difference on the robustness of each shape. However, as the amount of nodes lost in the physical network increases the differences in robustness among the shapes become more evident.

Moreover, in Fig. 3(b)–(d) is shown that the higher the I_{max} value the more robust are the interdependent network pairs, and not only that, but as the I_{max}

gets higher the differences on the robustness among the shapes decreases. The latter behaviour can be appreciated in the fact that the lines get closer to each other as the I_{max} value gets higher.

6 Discussion

From the results exposed in Sects. 4 and 5 we observe that the shape in which the Chilean physical Internet network is built in is by itself a risk factor for the Chilean Internet robustness, as other shapes are more robust under the same conditions.

This phenomena occurs due to the restrictions imposed on the width and length. The restrictions for the Chile-like shape, that is, a really narrow and long shape, mean that randomly allocated nodes have a high probability of being close to each other on the narrower axis and far from each other on the longer axis.

This, in turn, causes that nodes get connected with higher probability with those really close to them rather than those further away, since if a node is further away in the longer axis, then in order to establish a connection between them there could not be any other node in the whole area between them. If there was a node in the area between the pair of nodes considered, then they would connect to that node rather to each other because of the really long and narrow nature of the Chile-like shape.

Therefore, as nodes are more likely to be far away since an axis is 25 times longer than the other, the links among the nodes on the physical network will be sparse in comparison to a more square like shape, and thus, the physical network ends up having fewer redundant paths among nodes.

Having fewer redundant paths means that it is easier to loose paths to a provider, and therefore it is easier to loose Internet connection. As these nodes fail they trigger the loss of their interdependent links to the logical nodes, thus lowering the overall robustness.

Of course, if we build the physical network on a square space and then we moved them on to the Chile-like space maintaining the link structure, then the negative effect on the robustness of our Internet interdependent model would not be present anymore. However, that would not capture the real conditions under which the Chilean physical network was built. Let us remember that our model to build the physical network is meant to represent a network that is built under the condition of finite resources, where adding links between a pair of nodes is not always allowed, and where links costs are proportional to distance between them.

An interesting behaviour noted from the results was that the negative effect of the Chile-like space shape on the robustness can be diminished by increasing the robustness of the interdependent networks.

The increased robustness results in a lower difference on the amount of nodes lost among the different shapes explored to build the physical network in. This increase on the robustness can be attained by increasing the I_{max} value as seen in Sect. 4, that behavior is explained by the nature of the interdependencies between the physical and the logical network. As stated in Sect. 3.3, in order for a node to fail due to inter-connection loss it must loose *all* its interdependencies.

A higher I_{max} means that the average amount of inter-links of a logical node is higher, therefore, on average, more links must be removed from a logical node to fail due to inter-connection loss. Similar results have been shown by Radicchi et al. [17] for redundant interdependencies in multiplex networks where having more layers, and therefore having more inter-connections, improves the robustness of the system.

Another consequence of having a higher I_{max} is that the amount of inter-links of the logical provider nodes, given how they were selected, is equivalent or really close to the I_{max} value, causing the provider nodes on the logical network to be particularly robust against failure due to inter-link loss. These consequences of having a higher I_{max} explain why the robustness increases as the I_{max} value increases.

Our findings suggest that although the shape of the space in which the physical network is built in influences the robustness of the interdependent network composed by the Internet logical network and the Internet physical network, this effect can be diminished by increasing the amount of inter-links between the networks. This suggests that there is no need to re-structure the topology of the physical network. Thus, an improvement to the robustness problem of the Internet interdependent system studied may not require the great investment that would be required to modify a physical network topology.

7 Conclusions

In this work we proposed a novel way to model the Internet as the interdependent system comprised by the Internet logical network and the Internet physical network. We used this model to build interdependent networks that resemble the Internet interdependent system, and studied the effect of the shape of the physical network on the robustness of the simulated interdependent networks. In particular, the robustness was studied from a users' base perspective, that is, the capability of a node to reach an Internet Service Provider.

Our findings show that there is a positive relation between the amount of inter-links and the robustness of the interdependent system based in our model. We found that the closest to a Chile-like shape the space is, the less robust is the interdependent system.

Moreover, the negative effects on the robustness of the space shape in which a physical network is built can be diminished by increasing the upper limit of inter-links that a logical node can have I_{max}. This offers a way of improving the robustness of these kind of interdependent networks that would cost less than to modify the physical network topology.

A problem that remains to be studied that is of particular interest for a country prone to natural catastrophes such as Chile is what would happen on these kind of interdependent networks under attacks that affect a specific area on the physical Internet network (localized attacks). Studying these kind of attacks would give us further insight on the natural catastrophes' effect over the Internet network.

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