HOW RESILIENT IS THE GLOBAL SUBMARINE CABLE NETWORK?

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Abstract: An understanding of marine-based risk can influence many decisions affecting the profitability of submarine cable investments. Yet reliability information is rarely made available in a way that can be quantified and understood in a regional or global context. This paper takes data from more than 1,000 worldwide marine cable faults spanning a seven-year period as inputs to a numerical model that allows estimation of resilience and availability for existing cables, planned cables, and mesh networks.

While there always will be cables that do not fit the model, this paper illustrates the vast regional differences in network resilience as a consequence of marine faults and available redundant paths. The findings presented should enable smarter investment decisions for new system builds, improved budgeting of network operating costs and greater understanding of network resilience (and conversely, vulnerability) by stakeholders at many levels.

1. INTRODUCTION

Previous studies have examined cable fault statistics in terms of their cause [1], geographic distribution, and time to repair [2] [3]. This study analyses the impact that the 150 marine repairs which occur on average every year [4], have on regional and global submarine telecoms reliability and resilience.

Unless an end point loses all connectivity, typically as a result of multiple concurrent faults on several cable systems, services are restored in the blink of an eye and the end customer is usually oblivious to a fault occurring. However, in the wake of several high-profile outages [5], many governments [6], content providers, and carriers have become increasingly concerned about the diversity of submarine cables. Network operators, on the other hand, regard statistics on the reliability of each individual cable as commercially sensitive, so are not forthcoming with information. Without publicly available fault data, assessing even in broad terms the true resilience of the global submarine cable network has therefore been an impossible task.

At SubOptic 2013, Palmer-Felgate et al [2] presented anonymised repair statistics from the Maintenance Zone Agreements. The statistics were subsequently updated with data from the Private Maintenance Agreements [3]. The 1,020 worldwide cable repairs occurring between 2008 and 2014 were characterised in terms of repair commencement time, repair-ship transit time and approximate fault location by jurisdiction. The jurisdictional information stated whether a fault occurred within a country's Territorial Waters (TW, in most cases the 12-mile limit), Exclusive Economic Zone (EEZ, the 200-mile limit) or beyond the EEZ in the High Seas (HS). This paper uses these recent statistics to analyse how marine faults impact the cost and connectivity of the global network.

2. METHOD

The marine repair statistics from [3] were used to create a mathematical model that can simulate the reliability, availability and repair-ship utilization of any submarine cable route worldwide, whether existing or planned. The model also allows estimation of the number of diverse paths required to provide certain resilience to a network.

All cable length measurements were performed as database queries using the Global Marine Cables Database of as-laid cable positions and the Maritime Boundaries Database. The exercise was automated using Intergraph Geomedia® (a Geographical Information System).

Firstly, three parameters are calculated for each maritime jurisdiction (Jurisdiction) by averaging the cable-repair data [3] over the total length of cables covered by the Maintenance Agreements within each Jurisdiction (the Total Lengths). The parameters are:

<u>Repairs/km/yr</u> (r):

$$r = \rho / L$$

where ρ = repairs/yr for the Jurisdiction [3] and L = Total Lengths within the Jurisdiction.

<u>Outage/km/yr</u> (o) in days:

$$o = r(0.62m + T)$$

where m = Mean Time to Commence Repair for the Jurisdiction [3], 0.62 is the percentage (62%) estimated from [3] to be traffic impacting faults, and T = time to restore traffic from arrival at the repair ground. T is estimated as follows: 3 days for repairs in the TW, 4 days for repairs in the EEZ and 5 days for repairs in the HS.

<u>Repair Ship Utilization/km/yr</u> (u) in days:

$$u = r((T + 2t) + 2)$$

where t = Mean Transit Time for the Jurisdiction [3]. An estimated two days are added for loading and offloading of spares and/or post-repair burial works.

o, r & u are calculated for the TW and EEZ of each of the 76 countries where ρ, m & t were available, and the HS.

Results specific to any Cable Route are calculated from the length portions within each Jurisdiction and the corresponding values for o, r & u:

<u>Repairs per year</u> (R):

$$R = \sum_{i=n}^{n} (rc)$$

where c = length of the Cable Route within a Jurisdiction and n is the number of Jurisdictions the route transects.

<u>Outage per year</u> (Ω) in days:

$$\Omega = \sum_{i=n}^{n} (oc)$$

<u>Repair Ship Utilization per year</u> (U) in days:

$$U = \sum_{i=n}^{n} (uc)$$

The probability of node isolation (Network Outage) is modelled by multiplying the outage probability of each route constituting diverse paths of the network.

<u>Network Outage per year</u> (N) in days:

$$N = 365(\left(\frac{\Omega_1}{365}\right)\left(\frac{\Omega_2}{365}\right)\left(\frac{\Omega_3}{365}\right)\ldots)$$

where Ω_1, Ω_2 and Ω_3 refer to the Ω values of each diverse path of the network.

For the purpose of this study, it is assumed that diverse paths between common end points have the same Ω value, so the equation is simplified to:

$$N = 365\left(\left(\frac{\Omega}{365}\right)^{D}\right)$$

where *D* is the number of diverse paths.

Knowing Ω and the desired *N* value, this equation can be rearranged to give the required number of diverse paths:

$$D = \frac{\log N}{\log\left(\frac{\Omega}{365}\right)}$$

Improvements to the model to reflect that multiple faults can be caused by single events such as earthquakes [5], ships dragging their anchors [4], or turbidity currents [7] are required in areas with the least separation between cables. As such, the model presently overestimates network resilience due to the assumed random fault distribution. Locations that have proven to be single points of failure [5] [6] [7] are depicted in Figure 1.

3. RESULTS & DISCUSSION

The model was applied to a series of hypothetical routes bisecting actual routes on the most densely populated submarine cable arteries as shown in Figure 1. It was tested against known historical data and was generally found to be representative of the mean for routes served by multiple cables. In some situations, the effect of averaging over areas of starkly differing risk (predominantly resulting from large water depth variations) biased the results by ±20%. This limitation is caused by the resolution of the input data from [3].

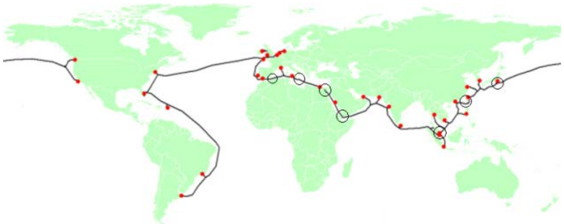

Figure 1: *Routes and end points used in the simulation. Circles indicate historically proven single points of failure [5], [6], and [7].*

The repair rate per km per year by Jurisdiction (*r*) ranges from 0.00004 in the High Seas to 0.02 in Singapore's TW, yet such figures only come into significance when applied to entire cable routes. Figure 2 shows route distance vs. the number of cable faults (*R*) and outage (Ω) for 277 point to point links. The correlation is very poor (R^2 = 0.1), showing that length is a small contributor to a cable's overall risk profile. All cables are exposed in varying degrees to anthropogenic hazards in shallow waters, geological hazards and shortcomings with system design, manufacture and installation. It is these highly variable factors that lead to disparate performance of cables of equal length.

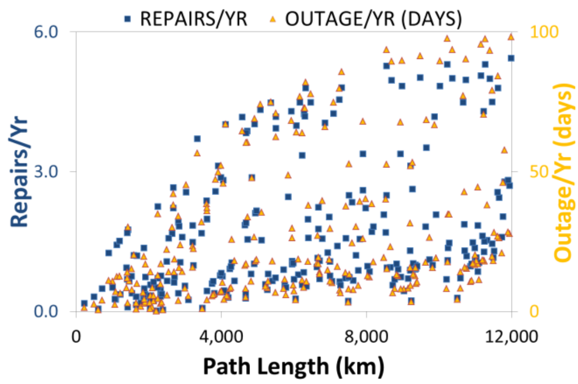

Figure 2: *Projected cable faults/yr and outage time/yr vs. cable length for 277 cable routes of varying length.*

Table 1 shows the annualised repair (*R*), outage (Ω) and repair ship utilization (*U*) predictions from the model for fifteen of the cable routes shown in Figure 1. Terrestrial faults are not considered in the analysis but are necessary to calculate end-to-end availability. For this reason Table 1 refers to cables terminating in Egypt, but not to routes traversing Egypt.

Table 1 indicates that cables in regions with expansive shallow seas tend to be less reliable than cables elsewhere, irrespective of their length. This is predominantly due to heightened risk from human activities such as fishing and anchoring [1]. In parts of Asia, the problem is exacerbated by intensive and seabed intrusive fishing methods [8], whilst a UK based study has revealed a critical threat from ships that are underway and unaware that their anchor is deployed [4].

With knowledge of each repair costing $1M to $3M [4], it is possible to forecast the estimated total marine repair costs for a planned cable based on the past performance of cables in close proximity. Table 1 shows projected annual repair costs derived from the forecasted repair-ship utilization assuming $1M per repair for the average repair lasting 15 days.

Similarly, the predicted outage per year listed in Table 1 can be used to forecast the cost of restoring traffic via other routes whilst connectivity is lost. This is heavily impacted by lengthy permitting times for repairs, e.g., typically seven weeks in Hong Kong TW.

In some cases the repair and restoration costs will make up a significant proportion of the total cost of ownership and therefore substantially impact the return on investment. The model takes repair commencement times from all of the Cable Maintenance Agreements, but with specific cable and vendor inputs, the cost effectiveness of any marine maintenance solution can be more precisely predicted.

ROUTE	Repairs per yr	Outage (days/yr)	Availability (%)	Ship utilization (days/yr)	Repair cost ($M/yr)
BRAZIL - MIAMI	0.2	3.4	99.1	3.7	0.3
PUERTO RICO - NY	0.1	0.9	99.7	1.7	0.1
NEW YORK - LONDON	0.5	6.0	98.4	7.3	0.5
UK - IRELAND	0.2	1.4	99.6	1.7	0.1
NETHERLANDS - LISBON	1.6	14.1	96.1	15.3	1.0
MARSEILLES - EGYPT	0.4	3.8	99.0	3.9	0.3
EGYPT - UAE	0.6	9.0	97.5	9.8	0.7
UAE - MUMBAI	0.2	3.8	91.8	3.4	0.2
MUMBAI - SINGAPORE	1.0	26.6	92.7	20.5	1.4
SINGAPORE - HONG KONG	2.6	45.5	87.5	33.4	2.2
PHILIPPINES - TAIWAN	2.7	42.8	88.3	29.7	2.0
SHANGAI - JAKARTA	4.6	78.3	78.6	56.8	3.8
HONG KONG - TOKYO	2.1	37.8	89.7	25.0	1.7
TOKYO - LOS ANGELES	0.5	8.4	97.7	8.4	0.6
SHANGHAI - USA/CANADA	1.0	18.4	94.9	13.8	0.9

Table 1: *Repair and outage/availability results simulated from the model for a selection of high-capacity routes.*

A prediction of the frequency and water depth at which faults occur can help estimate how much repair cable will be added over the system life. This is useful for determining the end-of-life performance margin, planning wet plant spares purchases and depot locations.

Knowledge of the approximated risk profile for any given route is also useful for quantitatively determining the number of diverse paths required in a network. Table 2 shows the minimum number of diverse paths required to provide a consistent level of availability or resilience on the routes listed in Table 1.

The availability objective used is 99.999% or 'five nines' (referred to as carrier-grade availability [9]). A network consisting of the minimum number of diverse routes to achieve this standard would have avoided any node isolation during all catastrophic outage events in the last decade. The calculations assume the routes are fully diverse and have no single points of failure, such as common landing points.

The results show that short shallow water routes require just as much diversity as long deep ocean routes - sometimes more. The advantage of having restorative routes is evident by referencing the availability figures in Table 1 achieved by single spans on the same routes.

Table 2 shows that all routes west of India have potential to achieve 99.999% or greater network availability if operated as part of a mesh network with ample capacity. East of India, the situation is more variable, with Mumbai to Singapore and routes to Indonesia having the least potential availability. This situation is partially a result of very long repair commencement times in Indonesian and Indian Waters. Routes west and south of Singapore have until very recently been severely impacted by such delays, but policy changes being implemented in Indonesia are helping to alleviate the situation. There are also new cables under construction on these underserved routes.

The Mumbai to Singapore route could achieve the same resilience with one less cable if national regulations permitted the commencement of repairs within five days.

The maximum possible availability utilising all existing diverse routes (listed in Figure 2) highlights the vast regional differences in resilience. Where ample choice of routes is available, the risk of node isolation can be minimised by utilising cables which have the greatest physical separation between them, thus avoiding single points of failure.

ROUTE	Route distance (km)	Min. diverse routes*	Existing diverse routes	Max. 'Nines' availability
BRAZIL - MIAMI	9,238	3	5	10
PUERTO RICO - NY	3,475	2	4	10
NEW YORK - LONDON	5,783	3	12	20
UK - IRELAND	224	3	8	15
NETHERLANDS - LISBON	2,551	4	5	7
MARSEILLES - EGYPT	2,817	3	5	9
EGYPT - UAE	5,220	4	6	9
UAE - MUMBAI	2,132	3	6	10
MUMBAI - SINGAPORE	4,911	5	3	3
SINGAPORE - HONG KONG	3,032	6	9	8
PHILIPPINES - TAIWAN	2,674	6	6	5
SHANGAI - JAKARTA	6,170	8	4	2
HONG KONG - TOKYO	3,607	6	7	7
TOKYO - LOS ANGELES	9,038	4	8	13
SHANGHAI - USA/CANADA	6,632	5	5	6

Table 2: *The number of diverse paths needed for 99.999% availability*, the number of existing paths and the availability when using all available routes are shown for a selection of major routes. Low capacity (pre-1999) cables are excluded as these are unsuitable for protecting newer cables.*

The simulation has focussed on the main arterial routes connecting major economies, where the submarine network is mostly well built out. Having the required diversity is however meaningless unless adequate reserve lit capacity is available for restoration purposes. Developing nations with few cables will inevitably have far less resilience to events that may occur many thousands of miles from their shores.

Lastly, the model can quantify the advantages and disadvantages of various system designs. Figure 3 illustrates three ways in which three countries can be connected and the resulting predicted performance and cost impacts are shown in Table 3.

The model has been used to calculate the repairs, outage (node isolation), ship repair days and repair costs for each design over a 25 year design life.

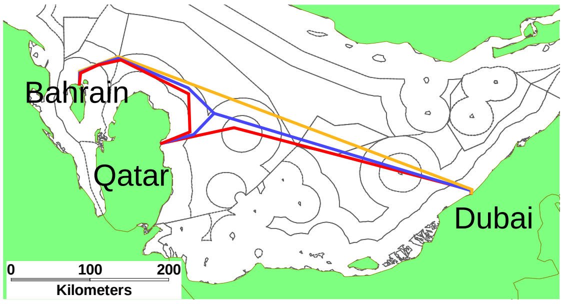

Figure 3: *Three example routes: i) festoon (red), ii) collapsed ring (blue), iii) ring (orange and red). Grey lines depict the Maritime Boundaries.*

A ring system will require the most cable and incur more repairs than the alternatives. As such, the ring architecture will be more expensive to build and maintain. It will, however, offer a level of resilience ~80 times greater than the alternatives. A festoon design requires more cable than the collapsed ring and is less reliable, but may require the least capital investment because it doesn't require a branching unit and may not require electrically-powered repeaters.

	Ring	Collapsed Ring	Festoon
Total Length (km)	1112.7	581.1	607.1
Repairs in 25yrs	47.5	24.5	27.7
Outage days "	1.8	143.9	163.2
Ship repair days "	372.6	193.6	221.9
Repair cost "	$24.8M	$12.9M	$14.8M

Table 3: *Outputs from the model for three system designs connecting Dubai, Qatar and Bahrain over a 25 year design life.*

When capital costs and external restoration costs are factored in, the total cost of ownership can predicted and compared for each of the three options.

4. CONCLUSIONS

The method and results presented herein open the door for stakeholders to gain a general understanding of the resilience of a network on which they purchase communication services. If that network is to be newly constructed, investment can be aligned with required availability.

The methodology enables the network architect to achieve the desired level of resilience. It also allows the financial planner to assess the approximate total cost of ownership of any cable, including restoration and marine repair costs. Both of these can have a significant bearing on investment viability and likely return.

In many cases, it may not be possible for a single entity to acquire capacity on all desired routes. This can result in new cables being constructed, not only to meet capacity demand, but also to provide diversity from existing routes. The model shows that new cables are needed between India and Japan (and countries en route).

A cost-efficient global network should provide ample capacity *and* a consistent level of resilience. Capital expenditure on diversity should be targeted accordingly. This is not necessarily where the fewest cables are available, but where a network is least resilient. Such locations are most evident in parts of Asia where the seas are already densely populated with submarine cables yet the network is most vulnerable to outages. Choke points and high demand for the lowest-latency routes serve to hinder physical separation and further increase the catastrophic outage potential.

As improvements are continually being made to cable and repeater design, route planning and installation methods, it is logical to anticipate that submarine systems will become more reliable over time. Furthermore, efforts by industry bodies to encourage governments to expedite repair permits are already reducing repair commencement times and increasing availability. The methods presented here provide the means by which to measure these changes.

Ultimately, the model could be integrated into a Software Defined Network (SDN) control plane and refined in real-time as the input parameters change and marine faults occur. The SDN controller routing and protection algorithms would use the real-time data to ensure that sufficient diversity is available to meet customers' requirements during multiple faults.

It is inherently expensive to operate a mesh network in a high-risk region, where lit capacity is available to fully restore over many diverse paths. Hence, one of the greatest risks to network resilience is a commercial one: How much resilience does the customer demand, and at what price?

5. REFERENCES

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