Are LEO Networks the Future of National Emergency Failover? – A Quantitative Study and Policy Blueprint

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Low Earth Orbit (LEO) satellite networks are emerging as backups for national-scale outages. While they have demonstrated value in small-scale disasters such as supporting first responders during hurricanes, their effectiveness during large-scale infrastructure failures remains underexplored. This paper evaluates the capacity of LEO networks to act as national failover infrastructure using six real-world submarine cable failures. The failure capacity provided by a LEO network to a specific nation depends on a few key factors: the size of the country, the distribution of the user terminals, and the policies of the network operator for spectrum allocation and traffic engineering. We find that coordinated policies between governments and network operators, especially regarding terminal placement and spectrum use, can improve failover capacity by up to 1.8× without requiring additional infrastructure. However, even under optimistic conditions with 200,000 terminals and a dedicated failover network, LEO networks can only restore 0.9–14.7% of lost submarine cable capacity in most cases.

1 Introduction

Low Earth Orbit (LEO) satellite networks are rapidly expanding, offering global coverage and playing an increasingly important role in Internet resilience. Several providers have deployed thousands of satellites with plans for many more. LEO systems have already proven reliable during infrastructure outages [17, 46, 61, 67]. Their potential for improving network resilience has prompted governments to adopt more systematic strategies [26, 64], including NATO's satellite-based backup for submarine cable failures [5].

The performance of a LEO network in emergency scenarios is heavily dependent on the agreement between the government and the network operator, raising the question: How should such agreements be structured? Answering this requires navigating a multifaceted landscape, with constraints across the network stack (e.g., spectrum allocation, traffic engineering) and multiple stakeholders with differing priorities. These include local governments, existing LEO users, and operators themselves, each weighing deployment strategy, political sensitivities (e.g., sovereignty and data access), and service quality.

LEO viability cannot be assessed in isolation. Its value varies widely depending on one's perspective. For instance, deploying a few Starlink terminals to support first responders during a hurricane can be transformative. But whether that benefit scales to support an entire city or a nation remains unclear. LEO networks today do not yet demonstrate elastic capacity at such scales, and large-scale deployment often requires coordination far beyond local initiatives.

Compounding this is the opaqueness of LEO system design and operations, which continue to evolve rapidly as new technology and regulatory frameworks emerge [4]. Governments need better tools and data to inform infrastructure decisions. Likewise, researchers need models that bridge existing knowledge in capacity planning for terrestrial networks (e.g., cellular and submarine systems) with the novel properties of LEO networks.

This paper takes a first step in that direction by evaluating the viability of LEO networks as national-scale failover for submarine cable disruptions. National governments — because of their reach and bargaining power — are well-positioned to define failover requirements and negotiate network behavior [2, 12, 41], offering a natural setting to explore cooperative and systematic resilience planning.

Our approach combines empirical data, a realistic simulation model, and real-world submarine cable failure. We focus on six case studies — Tonga, Haiti, Lithuania, Ghana, South Africa, and Great Britain — countries recently affected by cable outages. These countries vary in terms of geographic area, population density, satellite visibility (based on latitude), and proximity to Starlink gateways. To contextualize our findings and motivate policy implications, we compare the capacity lost during each outage with the capacity Starlink could offer under different deployment scenarios. Our simulation of Starlink captures the 6,500 satellites currently deployed in space across five different shells [32] and the 198 Starlink gateways spread across 23 countries.

Our model identifies four key factors that determine the capacity available in a satellite network: the country's total area and population distribution; the deployment of user terminals; the operator's spectrum allocation policy; and its traffic engineering strategy. We also evaluate how capacity may evolve as LEO constellations expand and wireless link performance improves. Our analysis highlights critical trade-offs that governments and network operators must consider when planning for emergency connectivity. These include the effects of sovereignty-based restrictions, terminal deployment strategies, and national spectrum allocation policies. These insights offer a foundation for cooperation frameworks between governments and satellite providers.

The remainder of the main body of the paper provides an executive summary of our quantitative analysis and policy recommendations, while the appendix presents the details of our methodology and an extended analysis. Section 2 introduces key concepts and policies underlying LEO satellite networks, forming the foundation for modeling failover capacity. Section 3 examines the maximum achievable failover capacity across our case studies. Sections 4 and 5 explore the levers available to governments and LEO operators, respectively, and their impact on failover performance. Finally, section 6 projects how failover capacity evolves as LEO infrastructure scales.

2 Background

LEO Network Primer. A LEO satellite constellation consists of thousands of satellites orbiting between 200–1600 km above Earth in multiple orbital shells, defined by altitude and inclination. Lower inclinations favor coverage of densely populated regions. We show the LEO infrastructure in Figure 1. User terminals and gateways connect to satellites over radio frequency (RF) Ground-Satellite Links (GSLs), while satellites communicate with each other over laser-based Inter-Satellite Links (ISLs).

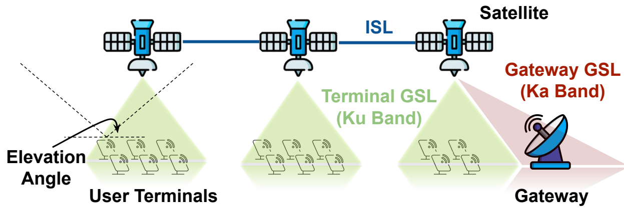


Fig. 1. LEO network infrastructure. Radio-based Ground-Satellite Links (GSLs) connect satellites to gateways and terminals. Laser-based Inter-Satellite Links (ISLs) connect satellites to each other.

RF capacity is a critical resource in a satellite network. To maximize its use, satellites divide their coverage into small hexagonal cells and illuminate only a subset of these cells using highly directional beams, as shown in Figure 2. Each beam has limited bandwidth, and the number of beams per satellite is also constrained. Efficient beam allocation must consider interference between beams and spatial separation to ensure maximum throughput without signal degradation.

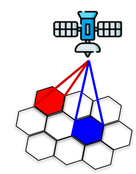


Fig. 2. A satellite can cover multiple cells using different beams.

Modeling LEO Failover Capacity. The failover capacity of a LEO network depends on a number of interconnected factors. Satellite deployment by the LEO network operator determine how many satellites and their beams can serve a region at any time. RF spectrum, jointly managed by the government and operator, determines RF bandwidth availability as well as allocation policies. However, availability doesn't guarantee usability as the placement of user terminals determines how that capacity is consumed. Clustering terminals in high-density areas can oversaturate beams and cause RF contention, while uniform distribution may underutilize available bandwidth. Hence effective deployment must align with both traffic demand and system constraints like spectrum allocation. Traffic engineering policies by the LEO operator determine how traffic is routed during emergencies. Routing decisions steer data across inter-satellite links toward operational gateways; gateway selection reflects data sovereignty norms by ensuring traffic exits only via trusted national or allied ground stations; and prioritization policies ensure critical failover traffic is served first, even if that delays routine connectivity. Taken together, these dynamics form a layered approach to resilience, and realizing the maximum failover capacity requires that governments and LEO operators manage these technical and policy levers in close coordination.

3 Failover Capacity With Current Infrastructure

We examine the maximum failover capacity LEO satellite networks can provide during national-scale submarine cable outages and the key factors that limit it (Table 1). Even under the most optimistic conditions, LEO satellite networks can only compensate less than 15% of lost submarine cable capacity in four out of the six case studies despite deploying tens or hundreds of thousands of user terminals nationally. More importantly, this is the maximum theoretical capacity assuming that terminals are uniformly distributed throughout the landmass of a country, maximizing the RF efficiency and minimizing contention for bandwidth between

	Tonga	Haiti	Lithuania	Ghana	Great Britain	South Africa
Lost Capacity because of Cable Failure	320 Gbps	320 Gbps	101 Gbps	83,700 Gbps	400,000 Gbps	31,700 Gbps
LEO Network Max Capacity (% of cable capacity)	41 Gbps (12.8%)	1,389 Gbps (434%)	2,005 Gbps (198%)	2,163 Gbps (2.6%)	3,530 Gbps (0.9%)	4,653 (14.7%)
Impact of Population Density on Network Capacity	Moderate (50%)	Significant (87.5%)	Significant (81%)	Significant (83%)	Moderate (51%)	Significant (78%)
# Terminals (for 90% of Max Capacity)	500	20,000	20,000	50,000	50,000	100,000
Bottlenecks	RF	RF	RF	Satellite Count	Satellite Count	Satellite Count

Table 1. Highlighting the maximum capacity provided a LEO network can provide (in comparison to lost submarine cable capacity), number of terminals required to achieve 90% of that capacity, bottlenecks to LEO network capacity, and the impact of population sparsity for the six case studies. Population sparsity impact refers to the impact of population being distributed in smaller pockets of the nation's landmass. RF bottleneck can be alleviated through more efficient spatial multiplexing (i.e., narrower beams and smaller coverage cells) or the allocation of more bandwidth.

terminals. Moreover, we assume that the entire satellite network dedicated solely to the affected country. While Haiti and Lithuania reasonably compensate for lost submarine cable capacity, this is largely due to relatively low capacity of their existing infrastructure.

This failover capacity is fundamentally constrained by structural bottlenecks that emerge at the national scale: limited RF spectrum and limited satellite availability, with the bottleneck largely determined by a country's land area. In smaller or densely populated countries like Tonga and Haiti, spectrum exhaustion is the primary bottleneck, since too many user terminals operate within the same satellite coverage area, saturating the finite RF capacity of that region. Once this threshold is reached, adding more terminals does not improve throughput, as they end up contending for the same limited resources. *Improving the capacity of countries with small landmasses requires using narrower beams (i.e., better RF technology) and expanded spectrum allocations (i.e., change in RF allocation policies).*

The second major constraint is the number of satellites visible from a given country at any moment, which limits how many beams can be delivered across the national footprint. Larger countries such as South Africa and Ghana face this challenge more acutely. Due to their broad land area, these nations require significantly more satellites to achieve full and consistent coverage. In practice, many regions within these countries receive only one or two beams, well below the maximum of eight, resulting in underutilized potential and reduced aggregate capacity. In section 6, we explore how an increased number of satellites may help overcome this coverage gap and increase the failover capacity of nations with large landmasses.

4 Impact of Government Policy Levers

We examine how government policy levers, specifically the placement of LEO user terminals alongwith spectrum allocation, affect failover capacity. As discussed earlier, achieving high capacity requires balancing terminal placement where it can be used effectively while maximizing the aggregate capacity. An intuitive choice is to distribute terminals by population, assuming more people means higher demand. However, this strategy can be counterproductive for LEO networks. Satellites rely on spot beams with limited RF capacity in each cell. Clustering terminals in dense areas can create RF contention, overloading some beams while leaving others underutilized. Figure 3 illustrates that aligning terminal placement with spectrum allocation can improve failover capacity by over 40 percent in the case of Great Britain. A coordinated approach places terminals where satellite beams can serve them effectively, while also allocating beams with awareness of terminal clusters to avoid interference and increase throughput.

Since governments typically oversee both terminal distribution and national spectrum licensing, this level of coordination is both feasible and impactful. *We recommend that governments develop clear policies for user terminal placement during emergencies, explicitly link spectrum licensing to failover use, and work with satellite operators to prearrange dedicated emergency capacity.* Without such coordination, even large terminal deployments may fall short in delivering meaningful connectivity.

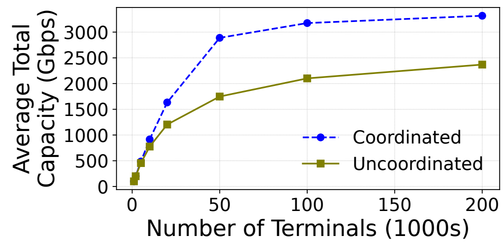


Fig. 3. Capacity of Great Britain to distribute terminals by population density, highlighting benefits of spectrum coordination and strategic deployment.

5 Impact of LEO Operator Policies

This section examines how LEO operator routing, sovereignty, and traffic prioritization policies influence national failover capacity and their broader effects. In an emergency scenario, a common assumption is that LEO satellite networks will simply route traffic through the nearest available gateway using whatever infrastructure is accessible. However, satellite networks are complex systems, constrained by shared spectrum, overlapping coverage, and competing global demand. Operator decisions around routing, gateway selection, and traffic prioritization can introduce unexpected bottlenecks or ripple effects.

Routing strategies define how traffic is directed through the network and directly determine how effectively LEO networks can support failover. Hot potato routing, which directs all traffic to the nearest gateway to avail the lowest network delay, often congests a small number of overused paths while leaving the rest of the network underutilized. In contrast, max flow routing spreads traffic across many gateways, improving load balancing and significantly boosting capacity. For example, in Great Britain, switching from hot potato to max flow routing increased failover capacity by more than five times (Figure 4). Thus, *spreading traffic across many gateways is essential to achieve higher failover capacity.*

Expanding the set of usable gateways, however, can raise data sovereignty concerns in scenarios where the satellite network routes data through untrusted or adversarial regions. If these restrictions are applied too rigidly, they can limit the resilience of the network. We illustrate this trade-off through the case study of Ghana, the only country in our analysis with a neighboring nation, Nigeria, with Starlink gateways and all other gateways farther away. To explore the policy extremes, we consider two scenarios: one where Ghana requires all traffic to route through Nigeria's gateways, and another where it excludes Nigeria's gateways entirely. As shown in Figure 5, restricting all traffic to only go through Nigeria's gateways led to a sharp decline in available capacity. But when the policy was relaxed slightly to exclude only Nigeria while permitting other

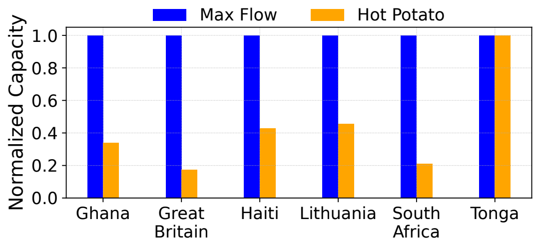


Fig. 4. Failover capacity comparison between max flow and hot potato routing.

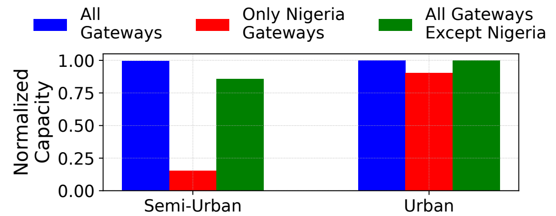


Fig. 5. Ghana's failover capacity under gateway restrictions. Data sovereignty constraints like excluding Nigeria show minimal impact.

gateways, the capacity remained nearly unchanged. This shows that *sovereignty and performance are not necessarily at odds and moderate data sovereignty policies can preserve national control without severely limiting failover effectiveness.*

Our analysis so far assumed that failover traffic was the sole user of the network, without considering the implications of having other users of the satellite network, herein referred to as incumbents. We examine an extreme case where incumbent demand is uniform across all satellites that serve countries where Starlink provides service. The priority given to failover traffic relative to incumbent traffic has a major impact on performance and cost. Prioritizing failover traffic can have far-reaching effects, straining the broader network, and affecting users far beyond the impacted region. In our simulations, when Great Britain relies on Starlink as a failover network, users across Europe and parts of Asia experience up to a 50 percent drop in available capacity (Figure 6). This degradation stems from the shared nature of satellite infrastructure. This highlights *the need for international coordination to ensure that one nation's emergency measures do not undermine connectivity for others.*

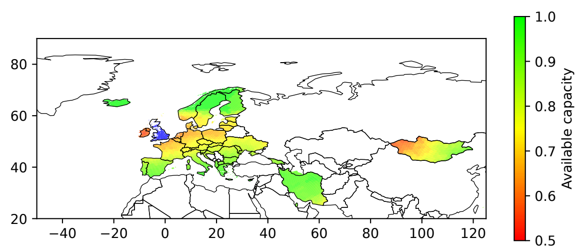
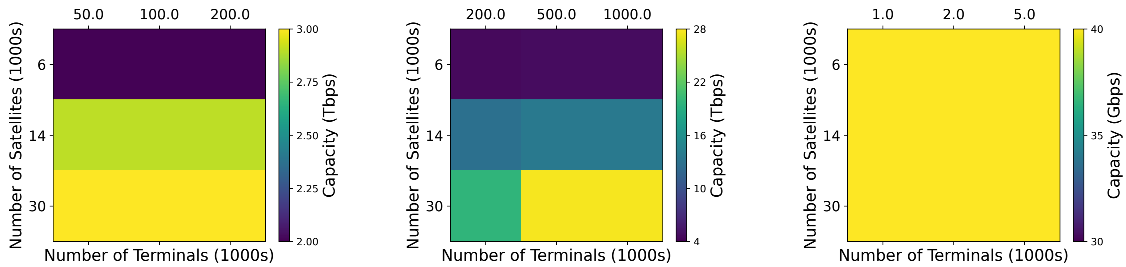


Fig. 6. Great Britain's failover traffic affects deprioritized incumbent traffic across Europe and Asia. Neighboring countries lose up to 50% of LEO capacity, showing need for international coordination during infrastructure failures.

6 Impact of LEO Network Growth

As of mid-2025, Starlink operates approximately 6,500 satellites and is on track to double that number in the next couple of years. With all pending regulatory approvals, the network could scale to more than 30,000 satellites. This growth is key to emerging government plans that incorporate LEO constellations into national resilience strategies.



(a) Lithuania (b) South Africa (c) Tonga

Fig. 7. Even with uniform terminal deployment and no caps, failover capacity plateaus due to spectrum exhaustion at or before 34k satellites as the LEO network size increases.

Increasing the number of satellites improves geographic coverage and enables denser spatial reuse of the RF spectrum. Our analysis in Figure 7 shows that such expansion significantly enhances failover capacity for large countries like South Africa. These countries benefit from improved beam availability and greater flexibility in traffic engineering. However, this growth trend does not continue indefinitely. Around 34,000 satellites, we observe a saturation point: spectrum capacity becomes the binding constraint. The network cannot activate additional beams because the available RF channels are already fully utilized.

This plateau underscores a core architectural limitation. *Simply adding more satellites will not yield higher capacity in countries with small landmasses without corresponding changes to how spectrum is managed. Even for countries with large landmasses, further capacity gains will require innovation in RF resource management, including narrower beams and expanded spectrum allocations for satellite operators.*

7 Conclusion

LEO satellite networks are often seen as a fallback for national-scale outages such as during submarine cable failures. We evaluated their viability through six case studies in various regions. In most cases, LEO networks could replace only a small share (0.9%–14.7%) of lost capacity. Our findings highlight key factors of available LEO capacity including country size, terminal density, spectrum policies, and traffic engineering. Optimizing terminal placement and spectrum allocation can improve capacity, but even under ideal conditions, LEO networks remain a supplement, not a substitute, for submarine links.

Beyond technical considerations, our results highlight the need for coordination between governments and satellite operators. Strategic agreements on failover capacity, emergency integration, and traffic prioritization are essential, improving capacity by up to 1.8× while requiring the same number of terminals or even fewer. However, prioritizing failover traffic can have unintended global effects on network coverage. Ultimately, while LEO networks can enhance resilience in emergency scenarios, their role should be framed as part of a broader, multi-layered approach to Internet infrastructure security. Future work should explore dynamic spectrum use, satellite network design, and economic models for sustained emergency coverage.

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A Background

As Low Earth Orbit (LEO) satellite networks become increasingly integrated into global communications, their role in emergency connectivity and national resilience planning has gained significant attention. Beyond their use in remote areas, LEO networks have demonstrated their ability to provide critical connectivity during infrastructure failures, supporting disaster response, military operations, and large-scale outages. Given this emerging role, national governments and international organizations are exploring ways to systematically incorporate LEO networks as a failover mechanism for terrestrial infrastructure. However, deploying and regulating these networks presents unique challenges, including licensing, spectrum allocation, and capacity constraints imposed by shared satellite infrastructure. This section examines the policies surrounding LEO network deployment, focusing on their use as a failover solution and the regulatory frameworks that govern their operation. We close the section wit a brief overview of related work.

A.1 LEO Networks Policies

LEO networks as failover. Starlink already has a high-profile track record of supporting critical operations when all other network infrastructure fails, including supporting first responders in Florida [61] and North Carolina [67], protesters in Iran [50, 76], and military and civilian operations in Ukraine [17, 46]. In all these scenarios, the deployment of satellite networks was reactive. There are also proactive proposals for dealing with outages using satellite networks [28, 33]. For example, Starlink, recently, started offering a low-cost "backup plan" where inactive users pay a low monthly fee to use Starlink when the user's primary source connectivity fails [33]. More importantly, Starlink and other LEO networks are being considered for nation-wide or even multi-national efforts to improve resilience in cases of terrestrial infrastructure failure. For example, HEIST is a NATO project to improve resilience of submarine cables through satellite-based communication [5, 28]. Other examples include Pakistan and Israel where Starlink is considered to be a failover network in case of wide-spread outages [64]. In this paper, we focus on scenarios where satellite infrastructure is considered proactively and systematically as failover at the national level. Our focus is motivated by the negotiation power that national governments have with satellite operators. Moreover, such plans will have far reaching effects when it comes to the funding of satellite networking infrastructures and the expectations of citizens regarding the resilience of their infrastructure.

LEO network regulation. A communication satellite has to comply with many regulations to limit its interference with other space-borne and terrestrial communication systems. Each nation regulates its own spectrum, licensing spectrum access to satellite operators [29]. The licensing process includes filing with the International Telecommunication Union (ITU), which tracks technical and operational parameters of communication satellites, including their transmit power, transmit beam contours, receiver sensitivity, and orbital parameters [30]. In contrast to cellular operators, satellite operators do not license exclusive access to bands and instead share these bands [18, 30]. Therefore, the capacity of failover LEO networks depends not only on decisions made by operators but also on government regulations on how RF spectrum is used, especially in emergency scenarios.

A.2 Satellite Networks Technical Primer

A LEO satellite network, or a constellation, comprises thousands of satellites orbiting the Earth at altitudes in the range of 200-1600 km [16]. Satellites are placed in a number of shells, each consisting of multiple orbits (or orbital planes) at specific altitudes. Orbital planes in a shell are equally spaced and are characterized by their altitude (the height above sea level), and their inclination angle (the angle at which they intersect the equator). An inclination angle of 90^o refers to a polar orbit. However, most of the current constellations have smaller inclination angles to provide greater coverage to densely populated areas [70].

Network customers use their terminals to access the satellite network through radio-based Ground-Satellite Links (GSLs). The network accesses the Internet through gateways that communicate with satellites through radio-based GSLs. A ground station only communicates with satellites that are visible above a certain *elevation angle* above the horizon, limiting the time traveled by the wave in the Earth's atmosphere to ensure the quality of the link. There are two modes of communication that rely on satellites. First, the "bent pipe" scheme, where traffic goes through a single satellite hop before going back through a ground station. Second, data can travel through multiple satellite hops. Satellites communicate with each other through laser-based Inter-Satellite Links (ISLs). Figure 1 illustrates the components of the network.

RF Resource Management. There are two main resources in a satellite network: RF bandwidth used for communication between satellites and ground stations (i.e., user terminals and gateways) and ISL bandwidth used for inter-satellite communication. To maximize RF bandwidth utilization, it is divided in time, space, and frequency. In particular, the coverage area of a satellite is divided into cells and the bandwidth is divided into channels. Each satellite uses highly directional beams to communicate with terminals in a specific subset of cells within its coverage area, with each beam using a particular channel. The radius of a cell is typically within a few tens of kilometers, while the total coverage area of a satellite has a diameter measured in hundreds of kilometers. The smaller the cells, the more efficiently RF capacity can be utilized. However, smaller cells require more satellites to provide full coverage and the technology to illuminate small cells with very narrow beams. In our analysis, countries with smaller areas would greatly benefit from using smaller cells to improve RF efficiency. On the other hand, countries with large areas are typically bottlenecked by the number of satellites that cover them. Satellites operators further improve RF efficiency by employing multiple directional antennas to enable frequency

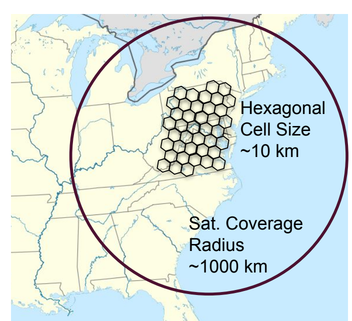


Fig. 8. The area of a cell is a small fraction of the total coverage area.

reuse (i.e., a satellite can transmit multiple beams on the same frequency). Figure 2 visualize beam allocation and Figure 8 visualizes the scale of cells compared to the total coverage area. ITU and local regulations limit the power per beam and the contours of the coverage area of each beam [18, 30].

A network operator must decide how many beams to allocate per cell to maximize RF bandwidth utilization while providing service to all its customers. Beam allocation is constrained by potential interference between beams. In particular, two beams that use the same channel have to be physically separated or use a different polarization. When a satellite reuses a frequency, the beams using the same frequency must be angularly separated.[1] The beam allocation problem is known to be NP-hard [58]. Note that communication between satellites and user terminals typically employs a different frequency band than communication between satellites and gateways (e.g., OneWeb and Starlink). Moreover, gateways have a sophisticated setup (e.g., larger antennas and better receivers) to enable communication with multiple satellites while maximizing utilization of the RF spectrum. The utilization of ISLs is dictated by the traffic engineering policy employed by the network operator.

A.3 Related Work

Characterization of the performance of LEO satellite networks has received a lot of attention with real measurements [31, 40, 52, 53, 75, 78] and simulations [13, 34, 35, 39, 55, 56, 58]. A common theme between these studies is their focus on per-user performance, ranging from available bandwidth [20, 55, 56, 58], RTT variability [13, 35], route properties [31, 35]. Instead, we study the aggregate capacity available in a given country. Although some studies examine the global capacity of different LEO network constellations, their focus is on the performance per customer and the global coverage of the network for fixed demand [20, 55, 56, 58]. However, in cases of infrastructure failure, demand is subject to the needs of the populous and is primarily impacted by how governments distribute terminals that will be used by failover traffic. Moreover, we pay special attention to the policy implications for using LEO networks as failovers as it pertains to potential coordination between governments and network operators. Finally, our methodology is particularly unique in providing a clear framework for the capacity offered by satellite networks. It uses real submarine cable failures as a reference point for understanding the capabilities of LEO satellite networks. Additionally, we examine this framework in six different case studies.

B Modeling LEO Failover Capacity

We assess the viability of LEO networks as a failover network in cases of national connectivity infrastructure failures. We select real-world submarine cable failures as a reference to contextualize our analysis, providing an estimate of the demand that satellite networks could be expected to fulfill in similar scenarios. We assume that in such scenarios, governments will deploy LEO user terminals and aggregate their bandwidth to offset capacity lost due to infrastructure failure. We analyze the failover capacity achieved by different terminal deployments under various RF spectrum allocation and traffic engineering policies.

[1] We enforce angular separation by preventing two beams reusing the same frequency by the same satellite to illuminate neighboring cells.

Our analysis characterizes the impact of multiple deployment strategies. We refer to this problem as the terminal distribution problem and introduce several alternatives that yield different levels of performance (§ B.1). Furthermore, performance depends on how satellite network operators allocate their resources (i.e., RF, ISL, and gateway capacity). No existing publicly available simulator captures all these aspects of a satellite network. Thus, we build a new simulator that analyzes the capacity of LEO networks under different terminal distribution and resource allocation policies while scaling to tens of thousands of satellites and hundreds of thousands of user terminals (§ B.2). Our objective is to identify the key factors that determine the capacity of the satellite network to derive lessons learned and policies that can be followed for emergency planning and response. To this end, we implement and study multiple RF resource allocation and traffic engineering policies (§ B.3).

B.1 The Terminal Distribution Problem

A unique problem faced by governments planning to leverage LEO satellites as failover is how to distribute their user terminals to serve their needs and maximize the aggregate network capacity. As discussed earlier, satellites allocate their capacity in beams that cover cells whose diameter is in the range of tens of kilometers. If a cell has too many terminals, the cell's RF capacity will get congested, limiting overall network capacity. Thus, we separate the terminal distribution problem into two components: 1) cross-cell distribution, deciding the aggregate number of terminals to be allocated to individual cells, and 2) local terminal distribution, deciding how terminals should be deployed within an individual cell. The intuition behind the two different scales of terminal distribution is the difference between the service capacity of individual terminals and the service capacity of satellites.

Cross-cell terminal distribution attempts to maximize the utilization of the RF capacity of satellites by spreading terminals between cells. On the other hand, local cell distribution attempts to meet the requirements of individual users or communities (e.g., individual buildings). Local terminal distribution accounts for user demand and the availability of infrastructure to deliver network capacity from terminals to individual users (e.g., WiFi or 5G). The local terminal distribution problem resembles cellular network planning [54, 63, 79], where backhauling is done through satellites instead of other forms of terrestrial networks. In this paper, we are concerned with the aggregate capacity of the satellite network, not the fine-grained planning of failover network design. Thus, we focus on the cross-cell terminal distribution problem.

The cross-cell terminal distribution problem exhibits a fundamental tradeoff between network utilization and deployment practicality. Clearly, the number of user terminals in a cell plays a major role in determining the achieved capacity in that cell. However, the aggregate capacity provided to a single cell in the LEO network is capped by the RF bandwidth licensed to the network. On the one hand, a government needs to deploy resources where they are needed, with more terminals deployed at locations with high population densities. On the other hand, the more terminals deployed to a particular location, the less the available RF bandwidth to individual terminals.

Algorithm 1 The GCB Terminal Distribution Algorithm

```
procedure GreedyTD(cell_populations, num_terminals, cap=0)
    sorted_cells ← Sort cells by population density in descending order
    cell_terminals ← Empty dictionary
    terminals_left ← num_terminals
    for each cell in sorted_cells do
        if cell_population[cell] ≥ cap then
            cell_terminals[cell] ← min(200, terminals_left)
            terminals_left ← terminals_left − cell_terminals[cell]
        end if
    end for
                    ▷ If any terminals are left, assign them uniformly amongst cells with more than pop_limit population
    return cell_terminals
end procedure
```

We assume that a government assigns each cell a priority level, reflecting needs, say based on population density, infrastructure criticality, or national security considerations. The assignment of terminals solely on the basis of priority sacrifices the aggregate capacity of the network by creating contention for spectrum capacity in high-priority regions. Spreading terminals evenly over different cells can lead to terminals being assigned to uninhabited cells, making it impractical to leverage the added capacity. We design a configurable heuristic that enables a government to perform terminal distribution along that spectrum.

The proposed algorithm is Greedy, Capped, and Batched, referred to herein as GCB. GCB is greedy, prioritizing cells with higher priority. The cap sets a lower limit on the priority of cells that can receive terminals, ensuring that terminals are allocated only to cells that meet a predefined criterion (i.e., high-priority cells). GCB assigns terminals to cells in large batches where a batch of terminals is enough to saturate the RF capacity in a given cell. The combination of greedy and batched allocation ensures that higher priority cells maximize their RF utilization. GCB can also be uncapped, distributing terminals to all cells while prioritizing higher-priority cells. Uncapped GCB maximizes network capacity by avoiding wasting RF resources but can potentially assign terminals to sparsely populated cells. A cap set to a high priority value limits the number of cells that receive terminals, potentially limiting the overall network capacity. Without loss of generality, we assume population density as our proxy for priority. For example, a cap of 10,000 ensures that only cells with a population of 10,000 or more are assigned terminals. We refer to such an approach as **GCB (cap x)**, where x is applied cap. The exact steps are shown in Algorithm 1. Although GCB significantly improves performance, governments may still need to customize the algorithm, targeting their unique requirements and population distributions.

B.2 CosmoSim

We built CosmoSim, a simulator to model aggregate network capacity under a wide range of terminal distribution, RF allocation, and traffic engineering policies, while scaling to tens of thousands of satellites and hundreds of thousands of user terminals. Existing simulators typically focus on per-connection performance. Instead, our simulator is concerned with the aggregate capacity on the network. To that end, we formulate our

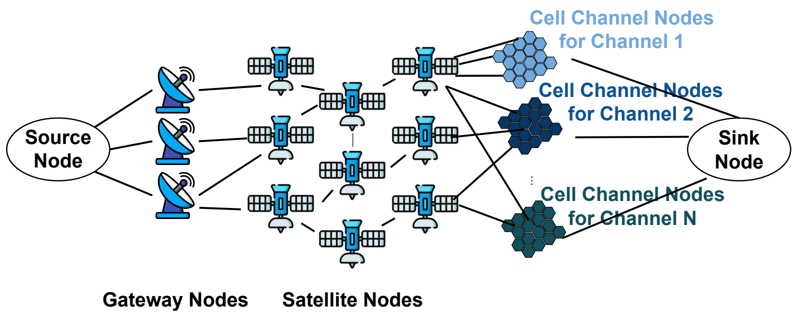


Fig. 9. Construction of CosmoSim graph. Cell channel nodes represent the same set of cells, where each cell is covered by a different set of channels.

simulation as a maximum-flow problem. In particular, our analysis aims to compute the maximum possible flow between source nodes (gateways) to destination nodes (user terminals) subject to different policies. Policies determine the connectivity of the graph, the valid routes that flows can use, and the available capacity at individual edges. Our simulator is lightweight, programmable, and modularized, enabling the community to not only further study the aggregate capacity of satellite networks but also experiment with different resource allocation policies and network loads and configurations.

We model a LEO satellite network as a graph with five types of nodes: gateway nodes, satellite nodes, user terminals, a source node, and a sink node. RF allocation restricts each cell to a fixed number of channels. To improve the flexibility of representing RF allocation policies, we represent each cell as a set of channel nodes, with each channel node corresponding to an individual channel used at a given cell. The source and sink nodes represent the source and destination of all traffic traversing the network from gateways to cells. CosmoSim can also capture incumbent traffic on the network. To that end, we add the cells from the areas that comprise the incumbent traffic (e.g., cells from all the countries served by the operator, not just the specific country we study). Each satellite can connect to other satellites with a number of edges limited by the number of ISLs it supports. Edges between satellites and ground stations (i.e., gateways and terminals) are based on satellite visibility from a given gateway or a cell and the RF allocation policy. The weight assigned to an edge represents the capacity of the link represented by the edges. Figure 9 illustrates the graph.

A naive implementation of the model presented in Figure 9 would imply processing graphs with hundreds of thousands of nodes for each network configuration. Such an approach would require running the simulator for several hours for every configuration (e.g., number of terminals and policies employed). To address this issue, we implement several optimization steps to reduce the number of nodes in the graph and reuse precomputed data to accelerate simulations.

To reduce the number of nodes in the graph, a first step is to forego representing each terminal as an individual node in the graph. Since RF allocation is performed on a per-cell basis, we can represent the number of terminals in a cell as a label of the node of that cell in the graph. Terminals within a cell are evenly distributed across its active channel nodes (i.e., channel nodes connected to a satellite). The label helps determine the

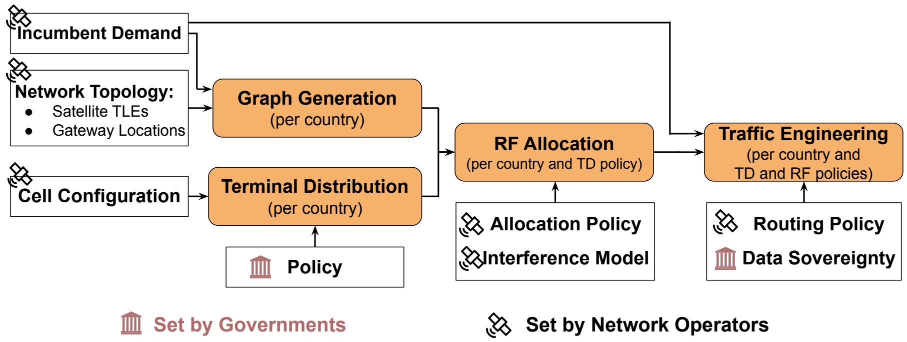


Fig. 10. The four main stages of CosmoSim in orange. First two stages can run in parallel. White boxes represent programmable components and configurations.

maximum possible throughput achieved at the cell based on the number of terminals at the cell and the capacity of an individual terminal. Specifically, the capacity of a channel used at a particular cell is constrained by the minimum of the capacity of the terminals using that channel and the channel's maximum capacity. This optimization helps to reduce the number of nodes in the graph by 100×, reducing processing time to under an hour. In this paper, we analyze nearly 1000 different scenarios each requiring a complete simulator run. In the naive case, this takes more than 4-5 hours per data point. While our optimization to reduce the number of nodes brings this time down to less than an hour per data point, the reusability of the initial phases of CosmoSim for later phases, particularly the graph generation phase, further helps to reduce the total time for all the different simulations. For instance, the graph generation phase that can take up to 30 minutes is reused 60-80 times resulting in multiple hours of savings.

CosmoSim divides its operations into four sequential phases, where the output of each phase is reusable under different configurations of the following phases in the pipeline. In particular, it has the following phases (Figure 10):

Graph Generation takes in as input satellite configuration (i.e., a two-line element set), gateway locations, and the cell configuration in a country to generate all nodes in the graph. ISL edges are defined based on the assumed topology of the satellite network. On the other hand, GSL edges are defined solely by visibility constraints. Specifically, a channel node of a cell or a gateway is connected to a satellite if that satellite is visible from the cell or gateway. Clearly, this stage creates many invalid edges which will be eliminated by subsequent processing phases. It is important to note that the graph generation step, being the most computationally intensive, is performed only once per country.

Terminal Distribution (TD) implements the cross-cell terminal distribution algorithm. In particular, it assigns labels to individual cells, reflecting the number of terminals assigned to that cell. This phase is performed once per country, per TD policy.

RF Allocation prunes the graph by eliminating GSL edges based on the RF allocation policy and wireless interference constraints. Moreover, this phase distributes the terminals allocated to a cell evenly between the channel nodes of that cell that have not been pruned. By this stage, we know precisely the demand placed on each satellite based on the cells it covers. Thus, to further reduce the size of the graph, we remove all channel nodes and replace them with the aggregate demand value at individual satellites. The aggregate demand value is used as the weight of the edge connecting a satellite node to the sink node.

Traffic Engineering determines the possible routes that traffic can take while traversing through the network graph. Taking as input the network graph, the TE policy updates the weights assigned to different edges in the graph. In the cases where we are also considering the incumbent traffic, the TE policy defines the demands from the incumbent cells in the form of the weight of the edges from the satellites serving the incumbent cells to the sink. This final graph is used to estimate the capacity using max-flow. Specifically, we use the `max_flow_min_cost` function from NetworkX [6] that performs max-flow while reducing the the number of hops between terminals and gateways (i.e., the of a path cost).

B.3 CosmoSim Resource Allocation Policies

Extensibility is an objective of CosmoSim. Thus, we simplify the process of implementing different terminal distribution, RF allocation, and traffic engineering policies. Moreover, we bootstrap the CosmoSim policy library by implementing and studying the following policies.

Terminal Distribution Policies. We consider the GCB policy under different values of the priority cap. Moreover, we compare it with the distribution of terminals based primarily on population density, representing scenarios where the government attempts to optimize primarily for local service coverage, ignoring overall network capacity.

RF Allocation. Our objective is to better understand the fundamental bottlenecks for LEO network capacity. Thus, we employ a greedy algorithm for beam allocation, similar to an algorithm that was shown to provide good performance [82], compared to other more sophisticated algorithms [43]. The simplicity of the greedy approach is particularly beneficial for our use case because it allows us to easily understand allocations created by the algorithm. More complex algorithms (e.g., multi-staged algorithms [10, 43]) would have been more complicated to analyze.

Specifically, our greedy beam allocation strategy prioritizes allocating beams to cells based on their priority. In addition, we prioritize the usage of satellites equipped with ISLs to ensure connectivity and reduce congestion at nearby ground stations. Of all satellites equipped with ISLs, we prioritize the least utilized satellites. Finally, we ensure that the allocated beams obey interference rules. In particular, we capture intra-satellite beam interference, ensuring a separation angle between beams when a satellite reuses the same frequency for the two beams. Thus, after allocating a beam to a cell, we prune the GSL edges that can interfere with it. Moreover, a cell is removed from the list once its demand is satisfied. We iteratively repeat the above process until all demand is satisfied or we all beams are exhausted.

We consider two variations of this greedy algorithm, differing based on the way they prioritize cells. The first prevents cell starvation, ensuring that each cell with at least one terminal is allocated at least one beam. Specifically, it ensures max-min fairness between cells by invoking the above algorithm repeatedly in the following way. The algorithm creates separate lists for all cells with demand of one or more beams, two or more beams, three or more beams, etc. Each list is sorted based on the population density of the cells. The above algorithm is invoked repeatedly for each of the lists until all demand is satisfied or all beams are exhausted. This algorithm is our best estimate of operator behavior which will avoid starving any of their clients while attempting to prioritize cells based on their estimated population density. However, it can severely underutilize the RF capacity by allocating beams to cells with not enough terminals to fully utilize the beam capacity. The second variation of the algorithm greedily prioritizes cells strictly based on the number of terminals at each cell. This proportional allocation maximizes overall network capacity by ensuring that the allocated beams can be fully utilized.

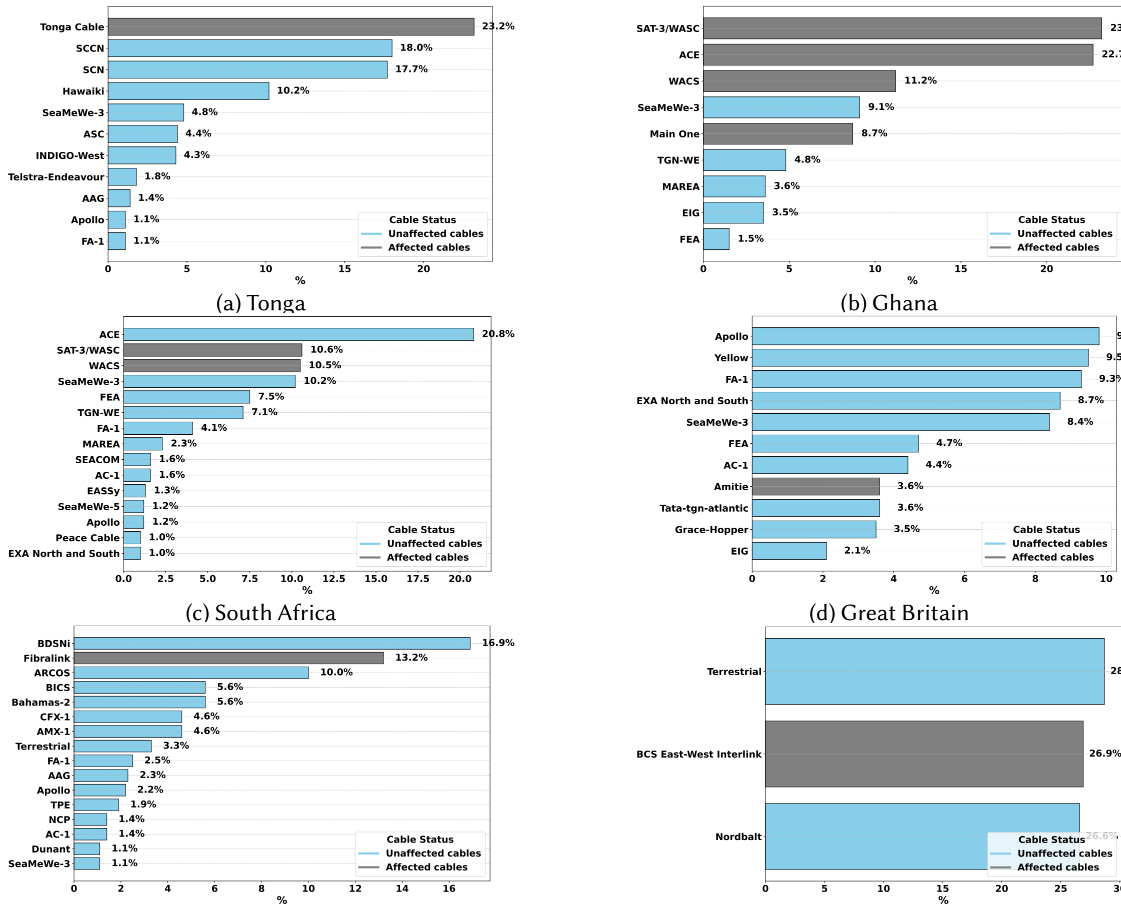
We do not aim to exhaustively identify the best RF allocation heuristic for failover satellite networks among the many recent proposals [43, 57, 58, 82]. Instead, we compare RF allocation policies that are aware of terminal distribution decisions (i.e., greedy proportional allocation) and those who are oblivious to it (i.e., attempting to achieve max-min fairness between cells).

Traffic Engineering Policies. We consider two traffic engineering policies: Max-flow and hot potato. Max-flow represents the best possible scenario where the network operator spreads the failover traffic across its whole network, avoiding congested links and balancing loads between all gateways. Hot potato represents the worst case where a network operator attempts to minimize the footprint of failover traffic on its network by routing traffic only through the gateways nearest to user terminals. The two policies allow us to study the magnitude of the impact of network operator decisions on achieved performance.

C Selected countries and cable cuts impact

To understand the impact of submarine cable failures on a country or region's international connectivity, we estimate the relative importance of each cable from that region's perspective. Prior work shows that the frequency with which a cable appears in traceroute paths serves as a proxy for the traffic volume it carries [21, 66]. Building on this insight, we analyze RIPE Atlas traceroute data from probes in the affected countries, collected one week to one month before known submarine cable failure events. We map these paths to the submarine cable infrastructure [14, 62], identify mappable routes, and distinguish domestic from international links. For each case, we compute the fraction of submarine-bound traceroutes mapped to each cable and use this ratio as a proxy for its relative importance. We complement this with capacity data from Telegeography [9], allowing us to estimate the potential gap for satellite networks to fill as backup infrastructure.

We apply this approach to six case studies that represent diverse conditions for LEO satellite coverage. These include differences in: (1) available land area for satellite cells, (2) proximity to ground gateways, (3) satellite density (affected by latitude), and (4) population distribution, which limits practical coverage. By analyzing scenarios with varying combinations of these factors, we explore the feasibility of satellite backup under realistic constraints. We present the geographic distribution of our six case studies in figure 11. and provides a detailed analysis of the relative importance of submarine cables for Tonga, Ghana, and South Africa.



(a) Tonga
(b) Ghana
(c) South Africa
(d) Great Britain
(e) Haiti
(f) Lithuania

Fig. 12. Submarine Cable Relative Importance for all the case studies.

For each case, we identify relevant cable failures, estimate the cable's role in regional traffic, and calculate capacity loss. We use these values to gauge the adequacy of satellite alternatives.

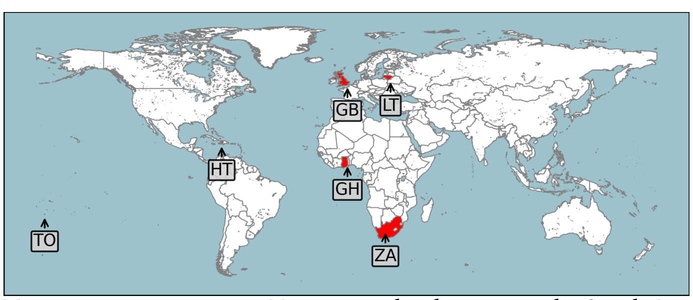


Fig. 11. Geographic Distribution of Case Studies

Tonga — January 2022. Tonga, an island nation in the South Pacific, is highly vulnerable to natural disasters and relies entirely on a single submarine link—the Tonga Cable—for international connectivity. With a maximum capacity of 320 Gbps [9], this cable connects Nuku'alofa to Fiji and the global Internet. On January 15, 2022, a volcanic eruption at Hunga Tonga-Hunga Ha'apai triggered a tsunami that severed the cable 37 km offshore, resulting in a near-total communications blackout [51]. A similar failure in 2019 left the country offline for over 10 days. We analyzed one month of RIPE Atlas traceroutes from probes in Tonga and found that 92% relied on submarine cables, with the Tonga Cable ranked as the most critical path—underscoring the nation's complete dependence on a single international link [15]. While submarine infrastructure development has been minimal in recent years [81], Tonga has improved resilience since the 2022 outage by partnering with multiple satellite providers—including SpaceX's Starlink, Kacific, and SES—to provide alternative connectivity [27, 44, 68].

South Africa — August 2023. South Africa, the continent's second-largest economy, hosts landing stations for ten international submarine cables, including SAT-3/WASC, SAFE, SEACOM, EASSy, and METISS. One month of RIPE Atlas traceroutes shows that 87% of outbound paths rely on submarine links, underscoring their central role in the country's global connectivity. On August 6, 2023, an underwater landslide in the Congo Canyon disrupted two key west-coast cables—SAT-3/WASC and WACS—causing widespread service degradation across southern Africa [47]. RIPE Atlas probe 1003709, located in South Africa, recorded a marked increase in latency, jitter, and packet loss during the outage, shown in Figure 13.

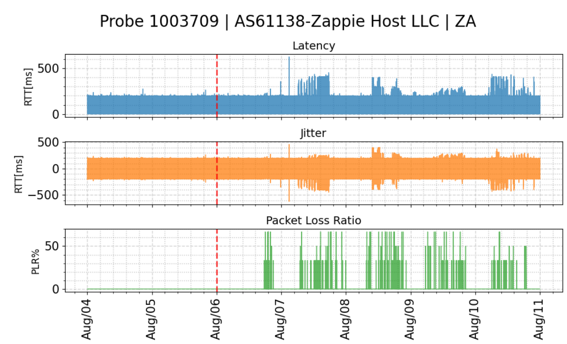


Fig. 13. Impact on latency, jitter, and packet loss during the August submarine cable failure in South Africa as observed by a RIPE probe.

Both cables rank among the top three in our criticality analysis. Together, they provide 10,700 Gbps of lit capacity, with a potential maximum of 31,700 Gbps if fully upgraded [9], making them essential for regional and international transit.

RIPE Atlas probe 1003709, located in South Africa, recorded a marked increase in latency, jitter, and packet loss during the outage, shown in Figure 13.

Ghana – March 2024. Ghana, a key player in West Africa's Internet connectivity, relies heavily on submarine cables for global access. Its Gulf of Guinea coastline hosts six major cables, including wacs, MainOne, sat-3/wasc, ace, Glo-1, and 2Africa. On March 14, 2024, a suspected underwater rockslide off Côte d'Ivoire disrupted Ghana's connectivity by taking four major cables offline: ace, sat-3/wasc, wacs, and MainOne [69]. Analyzing one month of traceroutes, we found that 90% relied on submarine cables, highlighting their critical role. sat-3/wasc ranked as the most essential, with ace, wacs, and MainOne also playing significant roles. These rankings reflect the high concentration of traffic on these routes, emphasizing the need to identify vulnerabilities and guide contingency planning. The four affected cables have a combined lit capacity of 57,170 Gbps, with a potential maximum of 83,700 Gbps if fully upgraded, according to TeleGeography.

Great Britain - August 2024. Great Britain's submarine cable system is a critical part of its national infrastructure, supporting both telecommunications and energy transmission [19]. Nearly 99% of Britain's data traffic depends on 56 active undersea cables [9, 48]. As a key global connectivity hub, the country relies on this extensive network to facilitate data exchange between Europe, North America, and other regions [8]. However, this dependence on international links introduces significant risks, as disruptions could have severe economic and security consequences. Recent concerns over potential sabotage have led to increased surveillance of undersea infrastructure, particularly in the North Sea and the English Channel, amid rising geopolitical tensions [80].

On August 1, 2024, Telegeography reported damage to the Amitie cable, which failed at segment 1.2 within the UK Exclusive Economic Zone (EEZ). However, no further details were provided regarding its impact. One possible reason for the limited disruption is Great Britain's extensive submarine cable infrastructure. Analyzing one month of traceroute data, we observed 75% of the routes traversed submarine cables. As shown in Figure 12d, Amitie ranks eighth among numerous submarine cables, indicating relatively low criticality in the network.

Despite this resilience, concerns are growing over the aging submarine cable infrastructure. According to Telegeography, 18 cables currently in service were activated before 2000, meaning they have been operational for over 25 years—well beyond the average submarine cable lifespan of 17 years [49]. Compared to other countries analyzed in case studies, even after excluding cables nearing decommissioning, the UK still has a substantial number of operational submarine cables. However, proactive measures are needed to support increasing capacity demands.

The impacted cable has fully conmissioned since July 2023 and has an estimated total capacity 400Tbps [60].

Haiti - September 2024. Haiti, an island nation in the Caribbean, is highly vulnerable to natural disasters such as hurricanes and earthquakes due to its geographic location. The country relies heavily on a small number of submarine cables, including Fibralink and Bahamas Domestic Submarine Network (BDSNi), to maintain its domestic and international connectivity. With limited infrastructure, these cables are critical for supporting Haiti's data and communication needs.

Since September 14, a damaged submarine cable near Kaliko Beach has led to significant internet connectivity problems for thousands of Digicel customers in Haiti. This disruption has severely affected families in the metropolitan area of Port-au-Prince, depriving them of reliable service and worsening the difficulties of living in a society of gang-related insecurity[24]. Digicel, Haiti's largest provider of mobile and internet services, pinpointed the severed cable Fibralink, situated roughly 34 miles north of Port-au-Prince, as the primary cause of the outage.

Analyzing one month of traceroute data, we observed 82% of the routes rely on submarine cables. Figure 12e illustrates the relative importance of submarine cables in Haiti, highlighting the country's heavy reliance on Fibralink for international traffic. With a design capacity of only 320 Gbps [1], Fibralink poses a significant bottleneck, as Haiti's lack of redundancy makes even minor disruptions highly consequential. The only other significant submarine cable, BDSNi, now offers nearly twice the capacity of Fibralink after a recent upgrade [25]. However, limited overall capacity and aging infrastructure continue to challenge Haiti's ability to meet growing connectivity demands, especially as digital services become increasingly vital for communication, commerce, and emergency response.

Lithuania – November 2024. Lithuania, a Baltic nation with a population of approximately 2.8 million, relies on a combination of terrestrial and submarine cables to sustain its international internet connectivity. The BCS East-West Interlink, a 530-kilometer (330-mile) submarine cable system, connects the Baltic Sea to the North Sea, serving as a critical link for Lithuania's internet traffic to Western Europe and beyond.

The disruption of the BCS East-West Interlink on November 17, 2024, resulted in a significant reduction of Lithuania's available bandwidth by approximately 30%, necessitating immediate rerouting efforts through alternative infrastructure [11]. While terrestrial routes provided temporary relief, the incident underscored the critical role of submarine cables in ensuring long-term connectivity resilience. Our analysis processed a total of one month traceroutes, with 65% traversing the submarine cables. As shown in figure 12f, terrestrial paths are ranked as the most frequently utilized routes, based on observed traffic patterns and inferred mappings. However, in scenarios where submarine cables are employed, the BCS East-West Interlink consistently ranks as a critical pathway, highlighting its indispensable role in enhancing Lithuania's network resilience and global connectivity.

BCS East-West Interlink cable has been in service since 1997, but no official data is available on its total capacity. However, reports indicate that during its failure, the cable carried approximately one-third of Lithuania's internet traffic. The most recent per-user bandwidth data, reported in 2016, estimated Lithuania's per-user bandwidth at 125.45kbps [22]. Since no updated information is available, we use this as a reference to estimate the country's internet capacity in 2024. With 2.41 million internet users in Lithuania as of January 2024 [37], the estimated total national capacity is approximately 302Gbps. Based on this, the BCS East-West Interlink cable is estimated to have a capacity of around 101Gbps.

D LEO Network Failover Capacity Analysis

We study the different factors and policies that impact the failover capacity provided by LEO satellite networks. Our findings (marked by $\mathscr{F}$) highlight critical bottlenecks in failover LEO networks. Based on our findings, we make policy recommendations to governments and operators (marked by $\mathscr{R}$). Our recommendations aim to facilitate the attainment of maximum network capacity. Further, they highlight areas that require further study. In particular, we answer the following questions:

- How does terminal distribution affect available capacity? (§D.2)
- Should governments and network operators coordinate their resource allocation efforts? (§D.3)
- Will LEO network growth increase the available capacity for failover traffic? (§D.4)
- What's the impact of sharing LEO network capacity with failover traffic? (§D.5)

Shell	Alt.	Incli.	Orbits	Satellites	ISLs	Status
S1	550	53^o	72	1584	0	Deployed
S2	540	53.2^o	72	1584	3	Deployed
S3	570	70^o	36	720	3	Deployed
S4	560	97.6^o	6	348	3	Deployed
S5*	530	43^o	28	2128	3	Deployed
S5*	530	43^o	28	1232	3	Approved
S6	525	43^o	28	3360	3	Approved
S7	535	33^o	28	3360	3	Approved
S8	340	53^o	48	5280	3	Pending
S9	345	46^o	48	5280	3	Pending
S10	350	38^o	48	5280	3	Pending
S11	360	96.9^o	30	3600	3	Pending
S12	604	148^o	12	144	3	Pending
S13	614	115.7^o	18	324	3	Pending

Table 2. Configuration of the current and planned Starlink constellation [23, 70–73]

D.1 Simulator Configuration

We use the configurations drawn from current and planned Starlink deployments, the only LEO satellite network with thousands of satellites and the most prominent failover network in many recent scenarios [17, 28, 33, 46, 61, 67].

Topology. Starlink has about 6,500 satellites deployed in space across five different shells [32]. Table 2 shows shells for the existing and planned Starlink constellation that we used for our analysis. The FCC has announced the approval of two more shells while deferring approval for another six [23]. For satellite orbital configuration, we use Celestrak [36] two-line element sets (TLEs) to derive the configurations but generate our own idealized version to facilitate the creation of ISL-based topology.

All satellites, except those in shell 1 have three full-duplex ISLs with two connecting to satellites in the same orbital plane and one to a satellite in a neighboring orbital plane. Figure 14 shows the motif we apply to create a mesh from three ISLs in contrast with +Grid connectivity. +Grid stipulates that every satellite has an ISL with a neighbor from both the adjacent orbital shells. We modify this so that in every orbital plane, satellites alternate between having a link with only one neighbor from the right or left orbital plane. While the exact motif for three-ISLs is unknown, we choose this one as it closely resembles +Grid providing all its stability benefits and it tiles uniformly for the entire constellation.

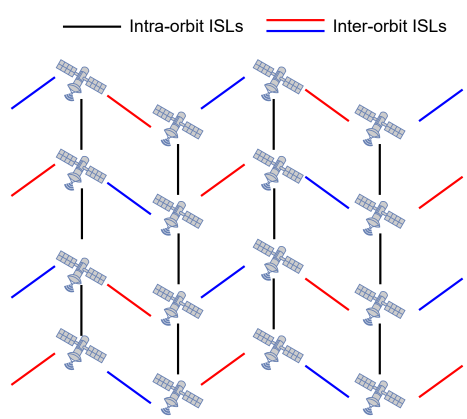


Fig. 14. Depicting connectivity in a satellite network with three ISLs. With the +Grid connectivity, both the red and blue inter-orbit ISLs are used, while for three ISLs, only the blue ones are used.

Data Rates (Gbps)	Config A	Config B	Config C
Ku GSL beams (Users)	1.28 [59]	0.956 [57]	2.5
Ka GSL beams (GWs)	2.6 [59]	2.6 [59]	5
ISLs	100	100	200

Table 3. Different wireless configurations used in this paper.

We obtain the location of Starlink gateways from
FCC filings (e.g., [3]). We use 198 gateways spread over 23 countries. For cell configuration, Starlink has been reported to divide its coverage region into hexagons, following a scheme similar to Uber's H3 hierarchical spatial indexing system [42, 45]. We assign the population density for each cell using the Kontur.io dataset [38].
Wireless Link Data Rates. The data rates achieved by wireless GSLs depend on many technological (e.g., modulation and coding schemes) and environmental factors (e.g., weather). Thus, instead of using a single value for the capacity of each type of GSL, we consider two different estimates made in prior work [20, 57, 59, 65]: Config A and Config B in Table 3. Moreover, we add an estimate of wireless capacities, assuming technological advancements in next-generation LEO satellites that double the capacity of all links (Config. C). Our objective is to compensate for the inaccuracy of our simulation-based approach by providing an envelope on network performance that captures most plausible network behaviors. Our estimate of ISL capacity is based publicly available technology specifications from Starlink [7].

We use Config A for most of our analysis, preferring the optimistic estimate of channel capacity when communicating with users. In particular, a single beam connecting a satellite to a cell for user communication has a capacity of 1.28 Gbps. Each satellite can communicate over eight such channels with a frequency reuse factor of four [20], resulting in a total per satellite capacity of 40.96 Gbps for communication with user terminals. On the other hand, each Ka band GSL beam connecting from the gateways to the satellites has data rate 2.6 Gbps. With eight active gateways per site, total gateway site capacity reaches 166.4 Gbps which is the capacity of all the source -gateway links in our graph.
Default policies. Unless otherwise stated, we use the following policies by default. For terminal distribution, we use GCB. For RF allocation, we use the greedy policy that allocates capacity purely based on the number of deployed terminals by the government, potentially leading to the starvation of other users while maximizing failover capacity. For traffic engineering, we use max-flow. Our selection of default policies favors the maximization of failover capacity. However, we investigate the impact of other policies as well.

D.2 How Should Terminals be Deployed for National Resilience?

Terminal distribution decisions must balance maximizing spectrum utilization, by spreading terminals between coverage cells, and ensuring that terminals are deployed where they are needed, potentially leading to resource contention between them. In this section, we focus on assessing the maximum achievable capacity, assuming that there is no other traffic on the network and that all cells can potentially be used by emergency responders, including completely uninhabited remote areas.

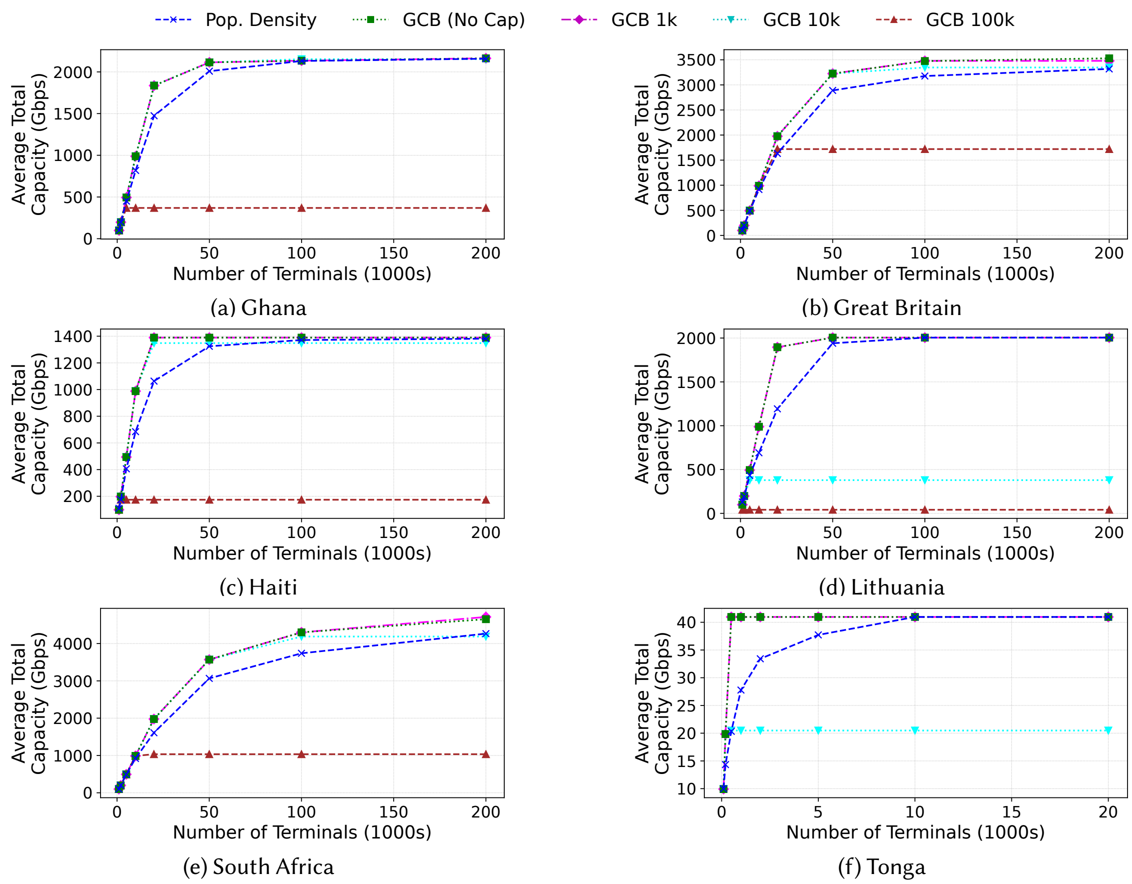


Fig. 15. Estimated capacity for various terminal distribution strategies indicates that distributing terminals based solely on population density can reduce network capacity by causing RF contention in densely populated areas and not allocating enough terminals to other areas with RF capacity.

Figure 15 reports the total capacity achieved in each of the case studies under different number of terminals and terminal distribution strategies. Clearly, increasing the number of terminals increases aggregate capacity. Moreover, the GCB algorithm improves failover capacity compared to distributing terminals based on population density, especially when the number of terminals is small relative to the number of cells. When the number of terminals is limited and they get allocated based on population density, *areas with very high population density end up getting most of the terminals, creating an RF bottleneck* ($\mathscr{F}$ 1). For example, in case of Lithuania, the capacity jumps by over 3 times when terminals are deployed more uniformly across cells used GCB instead of based on their population density. In such scenarios, more terminals are needed so that sparsely populated cells can receive enough terminals to consume the resources of beams allocated to them. *Therefore, terminal distribution needs to balance population density and RF availability* ($\mathscr{R}$ 1).

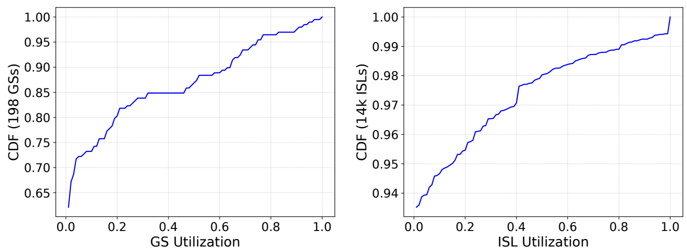
Capping the minimum population density of cells that receive terminals can limit available capacity. However, we find that, for populous countries, the impact is most significant when the limit is 100k. A limit of 100k can reduce the maximum achievable capacity of a country to 2.5-65% of the maximum achievable capacity. *The impact of focusing on densely populated area depends primarily on how a country's population is spread over its landmass.* ($\mathscr{F}$ 2). We consider the impact moderate if it can achieve 50% or more of maximum capacity (e.g., Britain and Tonga). We consider the impact significant otherwise. Although South Africa and Great Britain have comparable populations with 60.41 and 68.35 million, respectively, the impact of the cap is much more severe in the case of South Africa (72% reduction in capacity) compared to Britain (40% reduction). The reason is that Britain's population is more spread out over its landmass, leading to more cells with over 100k people compared to South Africa. Obviously, Tonga does not even have a single cell with that 100k people, making it infeasible to apply that limit. A 1k cap achieves the maximum possible throughput with a comparable number of terminals to a cap of zero.

Increasing the number of terminals yields diminishing returns in large deployments. For small deployments, adding terminals yields a linear increase in aggregate capacity because each added terminal makes use of some beam capacity. However, large deployments, starting with 10-20k terminals and beyond, yield diminishing returns when adding additional terminals. These diminishing returns are not an outcome of network congestion, but rather due to some cells receiving more terminals than the capacity of all the beams assigned to them. Thus, *deployments with a large number of user terminals exhaust the capacity of all satellites visible from the country.* ($\mathscr{F}$ 3)

While bandwidth can always be viewed as the only bottleneck, there are two key factors that play a role in limiting the bandwidth available for a given country: the land area of the country and the number of satellites covering the country. Countries with a small land area, like Tonga (4 cells) and Haiti (136 cells), can have all their cells receiving 8 beams, saturating the RF capacity of each cell when each cell is allocated 200 terminals. Any additional terminals, or satellites, will not increase the capacity of the satellite network. Therefore, *the remedy for smaller countries is either improve their RF efficiency using smaller cells and narrow beams or to allocate more RF bandwidth to satellite networks* ($\mathscr{R}$ 2). In contrast, the larger the land area of a country, the more satellites it will need so that each cell receives 8 beams. Thus, countries with large landmasses are bottlenecked on the number of deployed satellites. For example, South Africa, with 4545 cells barely receives one beam per cell. The bottleneck is exacerbated because South Africa cannot utilize any of the satellites in the first shell of Starlink, as "bent-pipe" satellites require the presence of nearby gateways, which South Africa does not have.[2]

An important concern when studying aggregate network capacity is congestion. To examine the impact of congestion, we focus on the case study of South Africa. In particular, South Africa achieves the highest aggregate capacity due to its large landmass. Moreover, South Africa does not have any gateways nearby, forcing it to rely primarily on ISLs, increasing the chances of ISL congestion. First, we examine the levels of GSL utilization (Figure 16a). We find that only 35% of gateways are utilized with just 15% of them exhausting more than 50% of their capacity. Our traffic engineering approach attempts to minimize the number of hops

[2]The nearest gateway to South Africa is in Ghana, requiring the use of ISLs to reach it.



(a) GS Utilization (b) ISL Utilization

Fig. 16. CDF of GSL and ISL utilization for South Africa when 200k terminals with the GCB policy with no cap.

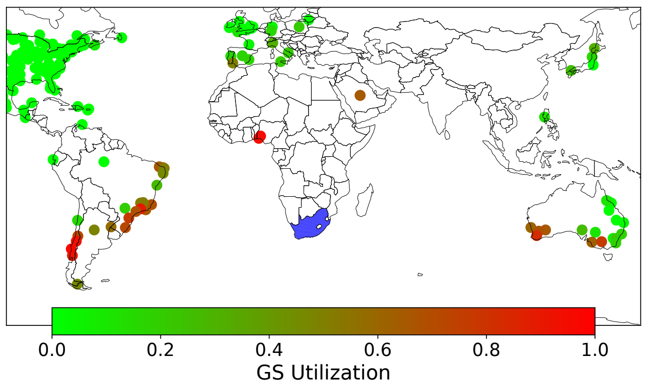


Fig. 17. Utilization for different gateways for South Africa when 200k terminals with the GCB policy with no cap.

used, even when max-flow is employed. Thus, gateways located closer to South Africa, like those in Ghana, Chile, and Australia, achieve higher utilization (Figure 17). Next, we examine ISL utilization (Figure 16b). Only 6% of ISLs are ever used in the South Africa case study, with less than 1% of ISLs achieving near 100% utilization. To better understand ISL utilization, we focus on utilized ISLs (919 out of 14k) and plot a 2D histogram as a function of ISL utilization and hop count from user terminals (Figure 18). As expected, most ISLs are barely utilized, including those close to user terminals. Highly utilized ISLs belong to two categories: 1) those close to user terminals, potentially carrying the traffic of its satellite's GSL as well as other traffic of nearby satellites, and 2) those close to gateways, carrying the aggregate traffic of the country. Countries with small landmasses exhibit even fewer ISLs and gateways with high utilization. Thus, *we conclude that congestion is a nonissue, if failover traffic is prioritized or provided exclusive access to the LEO network* ($\mathscr{F}$ 4).

D.3 Impact of Network Operator Policies

Impact of spectrum allocation decision. Recall that in normal scenarios beam allocation is done independently of the terminal distribution. In particular, the LEO network operator can require having at least one beam allocated to very sparsely populated cells, with remaining beams distributed based on population density or customer presence. Starlink targets rural communities and recreational travelers operating in remote areas. For example, Britain can have many Starlink users using its network in sparsely populated regions of Scotland. Moreover, its customers include airlines that fly their aircrafts over sparsely populated areas. Thus, *the number of beams allocated to failover traffic, and hence its capacity can be affected dramatically by the spectrum allocation policy* ($\mathscr{F}$ 5). Figure 3 shows the impact of coordinating beam allocation to maximize the capacity available to failover traffic, compared to spreading beams uniformly over a sparsely populated area of Britain. Lack of coordination can reduce the available capacity by 42% when using 100k terminals. The scarcity of the RF spectrum requires careful management of the resource. *We argue that countries should stipulate in their laws and spectrum licenses how spectrum should be used by satellite networks in cases of national emergency* ($\mathscr{R}$ 3). The spectrum should be allocated in the best way to meet the needs of the country. We believe that such an approach is feasible given the leverage that governments have with the contract sizes currently planned for such infrastructure [2, 12, 41]. *Combining $\mathscr{R}$ 1 and $\mathscr{R}$ 3 improves the capacity of the network at 200k terminals by 1.7-1.8× for countries with large landmasses. Alternatively, combining the two recommendations can help reduce the number of terminals needed to achieve high capacity. For example, combining $\mathscr{R}$ 1 and $\mathscr{R}$ 3 achieves 1.3× more capacity with 4× less terminals in the case of South Africa, compared to using max-min fair RF allocation and terminal distribution based solely on population density.*

Beams should be allocated to cells based on their utility from the perspective of the government facing infrastructure failure. In particular, a government assigns each cell a priority level, say based on population density, infrastructure criticality, or national security consideration. The problem can be formulated as finding a configuration of terminal distribution and beam distribution to cells to maximize overall bandwidth utilization while minimizing interference between beams. Exploring such algorithms is left for future work. The tight coupling of terminal distribution and spectrum allocation might be untenable in practice. A simpler alternative could be to clearly mark the terminals used for failover traffic (e.g., with their MAC address). The network operator then provisions beams exclusively for those terminals. Note that this is done only in cases of national emergency by dedicating the spectrum to emergency efforts.

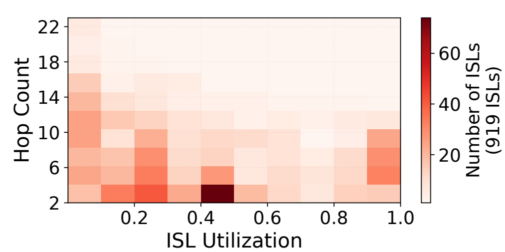
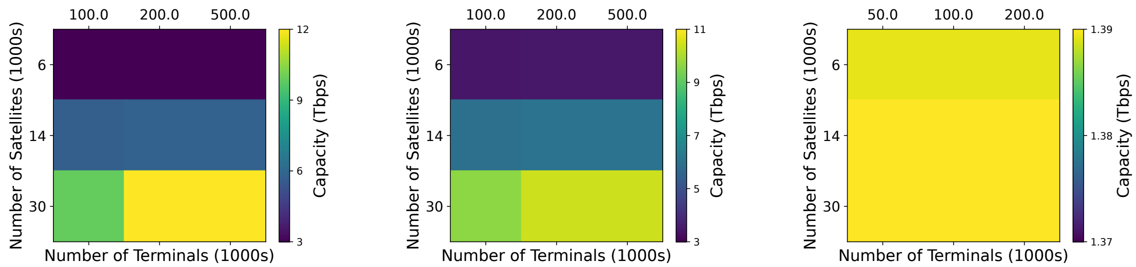


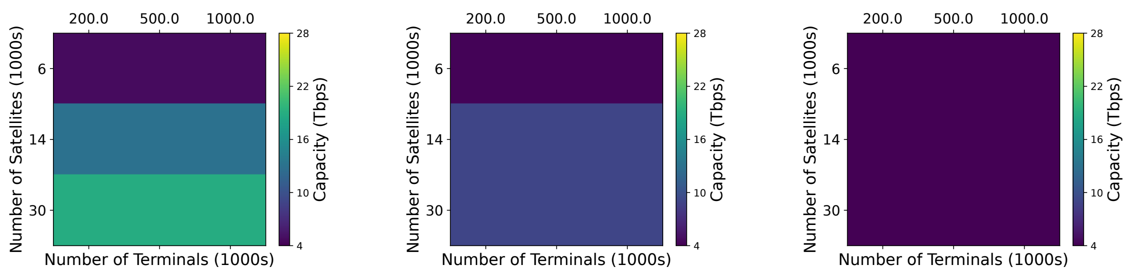
Fig. 18. ISL utilization and hop count for South Africa when 200k terminals are deployed using the GCB policy without caps.

Impact of traffic engineering policies. Figure 4 shows the normalized capacity achieved using max flow and hot potato policies. Hot potato limits the number of gateways that a country can use to one or two, based on the hop count between satellites serving the country and gateways. Countries with bottlenecks on the number of cells they can use, due to smaller land mass or population concentration in a small number of cells, are less affected by hot potato routing. On the other hand, Britain is significantly affected because it has significantly higher traffic generated from and near London that gets routed to the Villenave-d'Ornon gateway in France leading to congestion along those routes. Hot potato routing, which optimizes primarily for latency and network utilization, leads to abysmal results. Thus, it is important that traffic is spread across many gateways, prompting data sovereignty concerns.



(a) Ghana (b) Great Britain (c) Haiti

Fig. 19. Even with uniform terminal deployment and no caps, failover capacity plateaus due to spectrum exhaustion at or before 34k satellites as the LEO network size increases.



(a) 1k (b) 10k (c) 100k

Fig. 20. Impact of capped terminal distribution on South Africa's estimated capacity with an expanding LEO network, highlighting how usable capacity quickly plateaus due to RF bottlenecks in densely populated areas.

Impact of data sovereignty rules. The potential sensitivity of failover traffic can require it to go only through gateways deployed in friendly nations. We study the effect of a gateway mask that a country can use to list its approved gateways and then use the max-flow TE policy to direct traffic to those approved gateways. We focus on the case study of Ghana, the only case study where only one neighboring country, Nigeria, having Starlink gateways and all other gateways farther away. For all other case studies, either all gateways are far or several neighboring countries have gateways. Figure 5 shows normalized capacity when only Nigeria's gateways are used and when all other gateways, except for Nigeria's are used. Clearly, using very strict constraints, like with hot potato routing, significantly impacts achieved capacity. However, none of our case studies were bottlenecked on aggregate gateway capacity. Thus, *as long as the data sovereignty constraints are not too restrictive, they will have no impact on aggregate capacity* ($\mathscr{F}$ 6).

D.4 Impact of LEO network growth

As discussed earlier, Starlink and other LEO networks plan to dramatically grow their capacities over the next few years. In addition, the main bottleneck for countries with large land areas is the number of satellites that cover the country. Thus, we explore the impact of increasing the capacity of the LEO network. We use three configurations – (i) fully deployed Starlink shells S1 - S4 and partially deployed S5 (6,400 satellites), (ii) all the deployed and approved Starlink shells S1 - S7 (14k satellites), and (iii) all the deployed, approved, and proposed shells S1 - S13 (34k satellites). Additionally, we increase the number of terminals to determine if the increased capacity can be fully utilized by the nations. Terminals are distributed uniformly with a cap of zero on cell population.

Figures 7 and 19 present the capacity matrix achieved by nearly doubling the number of satellites on the y-axis and doubling the number of terminals on the x-axis. As expected, both Tonga and Haiti see minimal gains with increasing number of satellites, since all cells receive the maximum number of beams even with fewer satellites. Lithuania approaches 8 beams per cell with 14k satellites. Conversely, Ghana, Britain and South Africa nearly double their capacity each time the number of satellites is doubled. Furthermore, these nations require even more terminals to realize the maximum capacity when the entire constellation is deployed with 34k satellites. Crucially, we observe that *all the case studies plateau at or before 34k satellites, having fully exhausted their spectrum* ($\mathscr{F}$ 7). Adding more satellites would not increase the capacity for any of these nations, as they are bottlenecked by their available spectrum.

Adding a cap to the population density of cells that receive terminals further limits the value of increasing the size of the LEO satellite network. Figure 20 shows the impact of increasing the number of satellites and terminals on aggregate capacity when with different caps in the case of South Africa. The maximum capacity achievable in South Africa is 28 Tbps when the number of satellites is 34,000 and a cap of zero is applied to the minimum population density of serviced cells. In contrast, applying a cap of 100k reduces available capacity to 1 Tbps, regardless of the number of satellites in the constellation. A cap of 10k improves the maximum achievable capacity up to 9 Tbps. Thus, *even for larger countries, the easily-usable capacity nears its plateau with the main bottleneck being RF contention within densely populated areas* ($\mathscr{F}$ 8). This phenomenon could already be observed in some US cities, where Starlink is no longer accepting new customers due to its network being at capacity [74]. Overcoming this problem will require further innovation in the management of RF resources, including the use of narrower beams. Moreover, governments can license more RF capacity to satellite operators as demand grows.

Impact of wireless channel capacity. The above results were generated using Config A for wireless channel capacity (Table 3). We reproduced the results in Fig. 15 using Config B and C. We observe similar trends. However, Config B reduces network capacity by 12.5-28% (Figure 21). On the other hand, Config C assumed better data rates improves network capacity by 1.8-5.5× while requiring up to 2.5× more terminals to achieve the maximum possible capacity (Figure 22). However, even under such an extremely optmistic outlook for LEO networks, they can only support a fraction of submarine cable capacity (e.g., 32% of the capacity of a single cable in South Africa).

D.5 Impact of Sharing the Network

Our analysis thus far assumes that failover traffic is the only user of the network. Now we examine the impact of other users, referred to as "Incumbent Traffic." We assume that incumbent demand is uniform across all

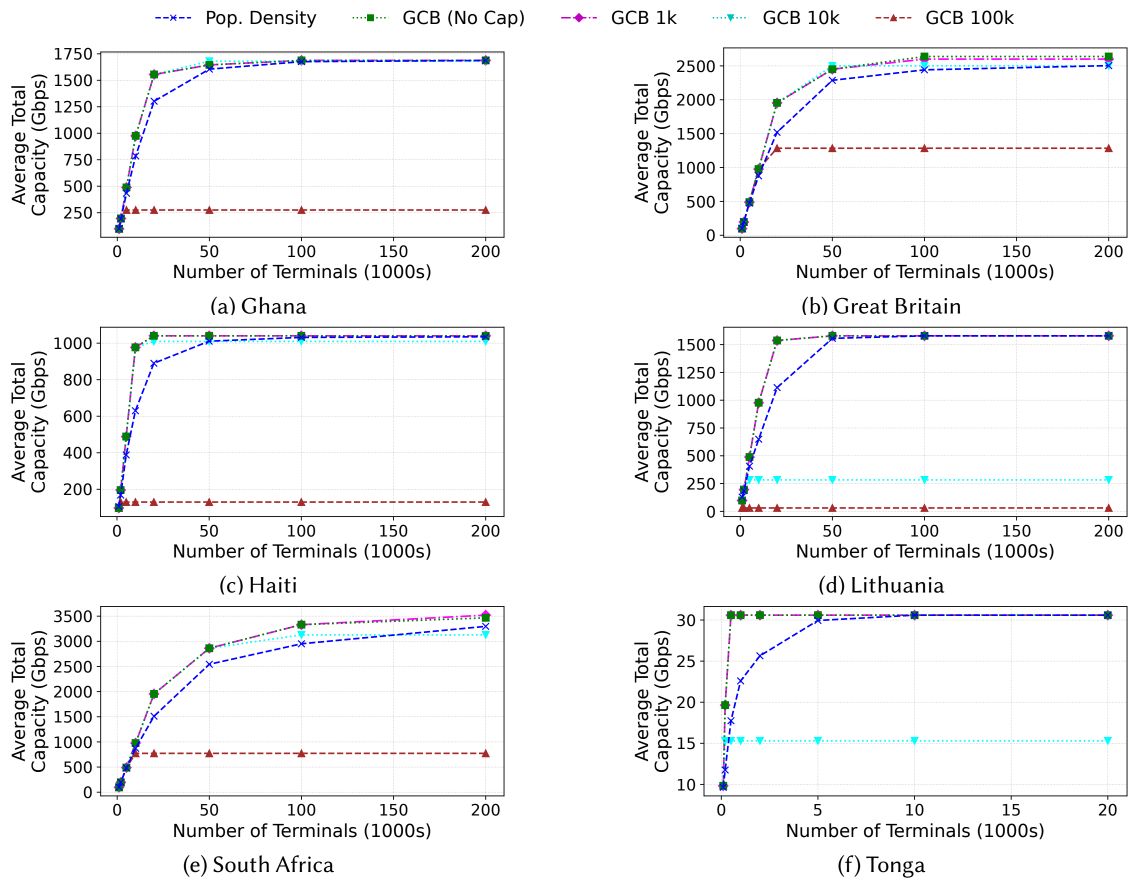
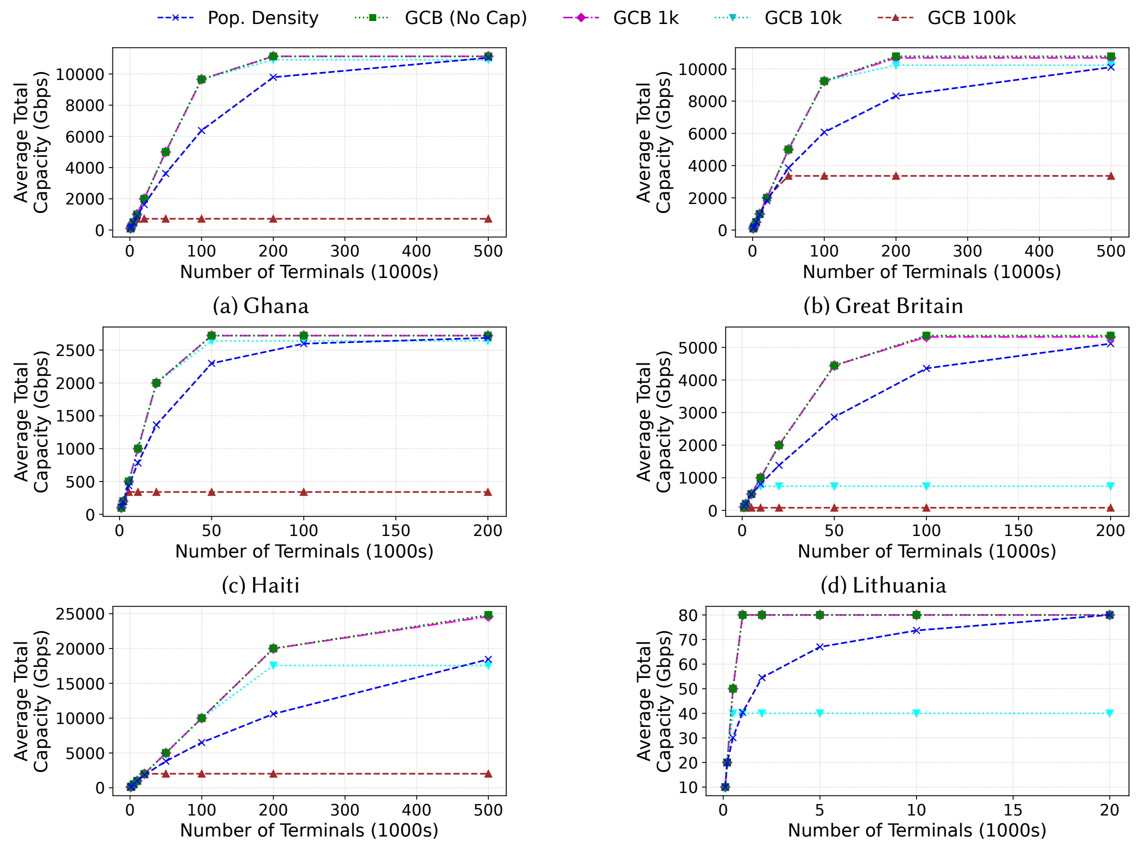


Fig. 21. Even with a different wireless model with reducing the Ku band data rate to 0.956 Gbps (config B in Table 3), the estimated capacity for various terminal distribution strategies follows similar trends.

satellites. We only consider demand originating from the countries where Starlink currently offers its service. This traffic matrix is more representative of Starlink operations today compared to the ones used in prior work [13, 35] that focused solely on traffic between the top 100 most populated cities.[3] We focus on terminal distribution strategies that maximize capacity for different caps on the population size of serviced terminals.

Relative priority between failover traffic and incumbent traffic can impact the performance and cost of the failover solution. Prioritizing failover traffic to extract maximum capacity can come at a premium while potentially impacting the performance of incumbents. Examining the impact of high-priority failover traffic on low-priority incumbent traffic in aggregate is not very informative given the geographical spread of incumbents and their relatively higher demand. Thus, we study the magnitude of the impact on incumbents as a function of its spatial spread. Figure 6 is a heatmap demonstrating normalized incumbent capacity per cell

[3] Note that most of the 100 most populated cities do not have gateways. Thus, pairwise traffic matrices between specific cities is not at all representative of Starlink operations.



(a) Ghana (b) Great Britain

(c) Haiti (d) Lithuania

(e) South Africa (f) Tonga

Fig. 22. Even with a different wireless model with increasing the Ku band data rate to 2.5 Gbps (config C in Table 3) and increasing the number of satellites to 14k, the estimated capacity for various terminal distribution strategies follows similar trends.

across Europe and Asia. The heatmap value is assigned per cell as the average of the percentage of incumbent traffic served by the satellites visible to the cell. We assume 8.4 Gbps incumbent demand for every satellite serving incumbent traffic. *The high failover demand of Britain has far-reaching impact on Starlink's global coverage* ($\mathscr{F}$ 9). This affects most of Europe with some of the neighboring areas only receiving 50% of normal capacity. Further, this impact is even felt in Iran and Mongolia that rely on the gateways in Europe.

Figure 23 shows the impact of Ghana's failover traffic on the nearby region. The four countries in close proximity of Ghana using Starlink, namely, Sierra Leone, Liberia, Benin, and Nigeria are affected due to Ghana's failover traffic. Benin and Nigeria have a larger impact due to GSL congestion caused by sharing more satellites with Ghana due to being more closer. South Africa has a similar impact on global coverage. However, other case studies have localized or no impact.

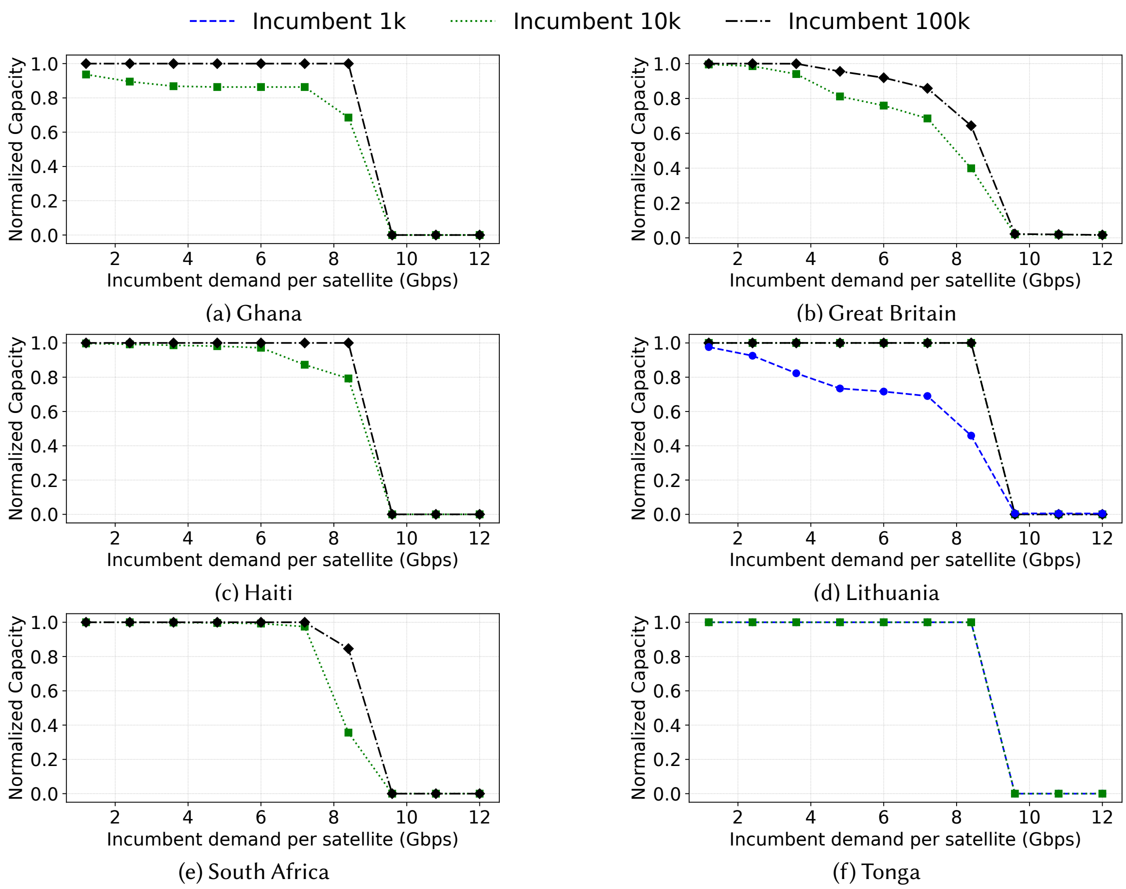


Fig. 24. Estimated capacity for different incumbent demands per satellite.

Conversely, *a LEO network with heavy incumbent traffic significantly impacts the failover capacity, to the extent of making it unusable* ($\mathscr{F}$ 10). Figure 24 shows the normalized failover capacities while competing with higher-priority incumbent traffic. There are three factors at play in this scenario: incumbent demand, failover demand, and LEO network access by neighboring countries. As incumbent demand grows, ISL capacity is exhausted, limiting the amount of capacity available to failover traffic. Countries with higher failover demand are more impacted by incumbent demand as they need more capacity. Finally, neighboring countries that access Starlink will not only congest ISL capacity but also GSL capacity, competing for satellite access with failover traffic. Thus, South Africa can achieve 3x higher failover capacity (absolute) than Lithuania at an incumbent demand of 10Gbps.

E Discussion and Limitations

Table 1 summarizes our findings for the six case studies. The two nations that can reasonably compensate for lost submarine cable capacity are Haiti and Lithuania, largely due to relatively low capacity of their existing infrastructure. In the four other scenarios, LEO networks can compensate for a very small portion of lost capacity. Moreover, achieving that maximum theoretical capacity assumes that terminals can be deployed in remote regions and that the network is dedicating its resources to the country in the case study. Some case studies require 200,000 terminals to achieve that maximum capacity. We note that the deployment size is not a concern. For example, Ukraine received over forty thousand terminals to help offset failures in its infrastructure during the war [77]. The distribution of terminals based on population density is a more realistic approach, as it provides capacity in regions where it can be used. However, it can yield worse results, especially when the number of terminals is limited. Attempting to distribute terminals more evenly between cells, even when capping the minimum population size of serviced cells, can significantly impact performance.

Limitations. This paper provides an optimistic approximation of the available capacity on a LEO network. In particular, we assume that all wireless and optical links operate at their maximum capacity. Moreover, we assume that any terminal deployed by a government in an emergency scenario will be fully utilized. These assumptions can be violated with poor weather conditions and wireless interference (due to other usage), limiting the capacity of wireless links. In addition, logistical challenges can limit the use of terminals. We choose to err on the side of optimism to provide an upper bound on the best achievable performance under the different conditions that we study. We show that despite this optimistic approach, the achieved capacity of satellite networks is typically a very small fraction of that achievable by terrestrial and submarine infrastructure.

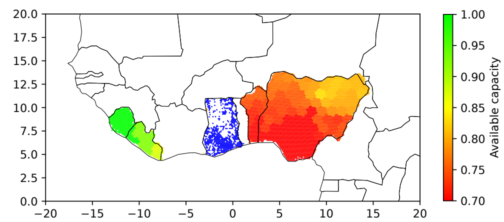


Fig. 23. Impact on deprioritized incumbent traffic during Ghana's failover using 10k threshold.

We focus our study on a small subset of resource allocation policies for traffic engineering, spectrum allocation, and terminal distribution. Our chosen policies reflect extreme approaches, with more nuanced policies likely to provide compromises between the extreme scenarios we select. For example, we compare max flow and hot potato traffic engineering, proving the best possible throughput with the first and extreme case of gateway congestion in the latter. Our goal is not to declare a winner between the policies, but rather to show how choices made by governments and network operators can impact network performance.