Connecting the Other Half: Exploring Options for the 50% of the Population Unconnected to the Internet

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Abstract

As of the end of 2019, 46.4% of the world's population does not have regular access to the Internet. Bringing the more than 3.5 billion individuals still unconnected online is the primary goal for multiple international organizations, including the ITU and the UN Broadband Commission. Two important barriers that restrict connectivity are the lack of infrastructure and affordability. To address these barriers, several novel concepts that involve spaceborne and airborne platforms have been proposed to provide connectivity at a lower cost (improve affordability) to a wider reach of people (extend infrastructure). We develop a techno-economic methodology to assess the potential impact of space and aerial concepts in expanding connectivity to uncovered and under-served regions. In particular, constellations of geostationary orbit (GEO) satellites, large constellations of medium Earth orbit (MEO) and low Earth orbit (LEO) satellites, and high- and low-altitude aerial platforms are studied. Results show that under the current scenario, the impact of space and aerial systems in terms of expanding connectivity would be rather modest; the current cost of satellite technology (~$200 per Mbps/month) are affordable for less than 1% of the uncovered and under-served population in the countries of interest. In a future scenario in 8-10 years, space systems have the highest potential to bring uncovered and under-served populations online, being a viable technology for 24% of the population in these countries.

Keywords: global connectivity, internet, space architecture, digital divide, communication satellites

1. Introduction

1.1. Context

Telecommunication services have significantly impacted technological progress, economic growth, and social dynamics in the last century (International Telecommunication Union (ITU), 2018). In recent years, the widespread adoption of the Internet has resulted in a *new economy* (Godin, 2004), where the focus has shifted from manufacturing towards technology-based companies, and where innovation in the form of new products and services has supported economic and wage growth (Broadband Commission for Sustainable Development, ITU, UNESCO, 2018).

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However, not everyone is benefiting equally from this *new economy*. To date, 46.4% of the global population is still offline (International Telecommunication Union (ITU), 2019), and even though most of them live in areas covered by 3G and 4G connectivity, approximately 11% of the population live in areas with no coverage at all. The majority of areas with no broadband connectivity are located in the least developed countries in Africa, South America, and Southeast Asia. Two main reasons for the absence of connectivity are the lack of infrastructure and affordability issues (Sprague et al., 2014). In particular, due to the sparse distribution of the population and their relatively low incomes, traditional communications systems, such as copper and fiber optic lines, are not well-suited for extending connectivity into these regions since they are expensive to deploy and have limited coverage. Thus, new concepts such as satellite constellations, networks of interconnected balloons or unmanned aerial vehicles (UAV), and tethered blimps have been proposed in the last few years (Space Exploration Holdings, 2016; Telesat Canada, 2016; WorldVu Satellites Limited, 2016; Bleicher, 2018; Sundaresan et al., 2018).

1.2. Motivation

A recent study by Katz & Callorda (2018) showed that fixed and mobile broadband have had a significant impact on the global economy. An increase of 1% in fixed-broadband connectivity yields an increase of 0.08% in GDP, whereas a similar increase in mobile-broadband penetration results in an increase of 0.15% in GDP.

However, by the end of 2019, only 53.6% of the world's population was connected to the Internet (International Telecommunication Union (ITU), 2019); bringing online the other half is a stated priority of various international organizations, such as the ITU *Resolution 200 - Connect 2020 Agenda for Global Telecommunication/ICT Development* (Union, 2014) and the UN Broadband commission (Commission, 2018). The main goals of these two groups are to find scalable and replicable solutions to connect large rural offline populations at minimal costs and to find effective strategies for narrowing the usage gap across all regions.

Several studies have been conducted to determine the main factors which influence the number of people connected to the Internet in a given country (Sprague et al., 2014; Facebook Inc., 2015; GSMA, 2016). These studies identified techno-economic factors such as the degree of infrastructure roll-out (i.e., communications infrastructure, road infrastructure, power infrastructure) and affordability (i.e., device cost, service cost, electricity cost) as the two most important factors to be solved through technological innovations, while policy factors such as relevance (i.e., access to content in their primary language, perceived value of Internet use) and readiness (i.e., information technology skills, know-how, basic literacy) also play an essential role.

Affordability and infrastructure roll-out are closely related. Telecommunications operators do not deploy infrastructure in areas where business opportunities are not viable, and low-income individuals have few incentives to subscribe to broadband services. Deploying new infrastructure becomes increasingly complicated when the geographical distribution of those unconnected and their income levels is taken into account. 45.7% of the world's population lives in rural areas, and it is estimated that the poverty rate in these regions is three times higher than in urban areas (Ravallion et al., 2007). Therefore, bridging the connectivity gap will require technologies that allow for sparse populations to be connected in cost-efficient manners. New low-cost and wide-coverage solutions are an active area of research in both academia and industry, and several concepts have been proposed, developed, and tested within the last few years. Most of these new concepts differ from traditional broadband connectivity solutions (i.e., terrestrial systems like fiber, cell towers, or mm-wave links) in that they make use of space and aerial platforms to provide connectivity.

The main goal of this paper is to understand and identify space and aerial systems that can be used to expand broadband globally, and to quantify the impact (in terms of coverage capabilities and cost) of these newly-proposed concepts. This will require the analysis of both technical and economic factors, as well as comparing these systems to current terrestrial systems. Of the 46.4% of the population that is offline, we focus on the subset that has no connectivity at all or only 2G connectivity (i.e., under-served). This represents ~60% of the Earth's inhabited surface and contains 12.9% of the population. Specifically, the results presented herein focus on answering the following question: What is the potential impact of space and aerial systems in terms of connecting additional populations? The answer to this question can be leveraged by policy-makers to decide on what areas and technologies should policies to expand connectivity to uncovered and under-served regions focus.

1.3. Scope and contributions

Our work focuses on a techno-economic analysis of different space and aerial technologies as a means to expand global connectivity. The technical analyses herein presented use detailed performance models to accurately assess the potential capacity for each of the technologies, together with cost models available in the literature. The economic analyses focuses on assessing the affordability of each of the technologies in 37 different countries. This assessment is purely based on CapEx and OpEx costs, since the technological advancements that allow for higher capacities (and thus lower costs per bps) have been the main drivers for the price reductions in the last decade.

It is important to highlight that this economic analysis does not consider the effects of the market (lack of competition, dominance of incumbent players, regulatory framework, etc.) and policy measures might have in the price, as this would require detailed knowledge of the telecommunications market, regulation, and political situation in each of the 37 countries analyzed, which is out of the scope of the paper. Instead, we investigate what technologies are the most promising, with hopes that these findings aid policy-makers when designing policies.

Within this context, the main contributions of this paper are as follows:

- An analysis of the main barriers to connectivity, especially focusing on infrastructure and affordability issues.
- The development of a techno-economic methodology to assess space and aerial concepts as solutions to expand connectivity to uncovered and under-served regions.
- The assessment and quantification of the potential impact (in terms of people that could afford and people that would be brought online) in the next 10 years of space, aerial, and terrestrial technologies in bringing uncovered and under-served populations online through a comparative analysis in 37 countries.

2. Literature Review

2.1. The connectivity problem

Despite the remarkable advancements made in terms of connectivity within the last ten years (driven mainly by the widespread adoption of cellular communications), almost half of the world's population still lacks connectivity. Termed as the *digital divide*, this is considered as one of the most pressing issues that needs to be resolved by the international community in order to guarantee equal access to opportunity. Although there are many different definitions of the digital divide, the common desired impact is to achieve benefits from deploying information and communications technologies (Hilbert, 2011).

To raise awareness of the importance of expanding broadband connectivity and boost the issue's prominence within the international policy agenda, the ITU and The United Nations Educational, Scientific and Cultural Organisation (UNESCO) set up the *Broadband Commission for Digital Development* in 2010, whose main tasks include advocating at the international level for the expansion of broadband, defining target connectivity values to be met, and conducting progress monitoring, evaluation, and reporting activities. The latest targets defined in 2018 (Broadband Commission for Sustainable Development, ITU, UNESCO, 2018) that this paper will focus on are as follows:

1. By 2025, entry-level broadband services should be made affordable in developing countries, at less than 2% of monthly gross national income (GNI) per capita.
2. By 2025 broadband-Internet user penetration should reach 75% worldwide, 65% in developing countries, and 35% in least developed countries

Out of the 4.1 billion connected users, 1.1 billion are **fixed** broadband users, whereas 3.5 billion are **mobile** broadband users (UN Broadband Commission, 2017). Among those not connected to the Internet (i.e., 46.4% of the population), ~70% live in areas where mobile broadband connectivity (3G/4G technology) is available. Figure 1 shows the distribution of offline users by region and country[1]. The area of each wedge is proportional to the absolute number of people unconnected, whereas colors indicate the percentage of the population with broadband coverage on each country. The image highlights that the usage gap (i.e., those living in areas covered by mobile broadband networks but are not connected) is several times larger than the coverage gap (i.e., those living outside of areas covered by mobile broadband networks), which suggests that there are other factors other than the lack of network infrastructure preventing people from becoming online.

2.2. Space and aerial systems to expand connectivity

With the first wave of LEO megaconstellations in the '90s, significant effort was made to determine both the technical and economic feasibility of space systems and their constellation designs. Shaw (1998) developed GINA, a

[1] This plot was inspired by the one in `https://www.bloomberg.com/news/features/2019-06-07/the-next-big-phones-could-bring-a-billion-people-online` (Accessed on September 2019)

[3] `https://www.itu.int/en/ITU-D/Statistics/Pages/stat/default.aspx`

[3] `http://www.mobileconnectivityindex.com/`

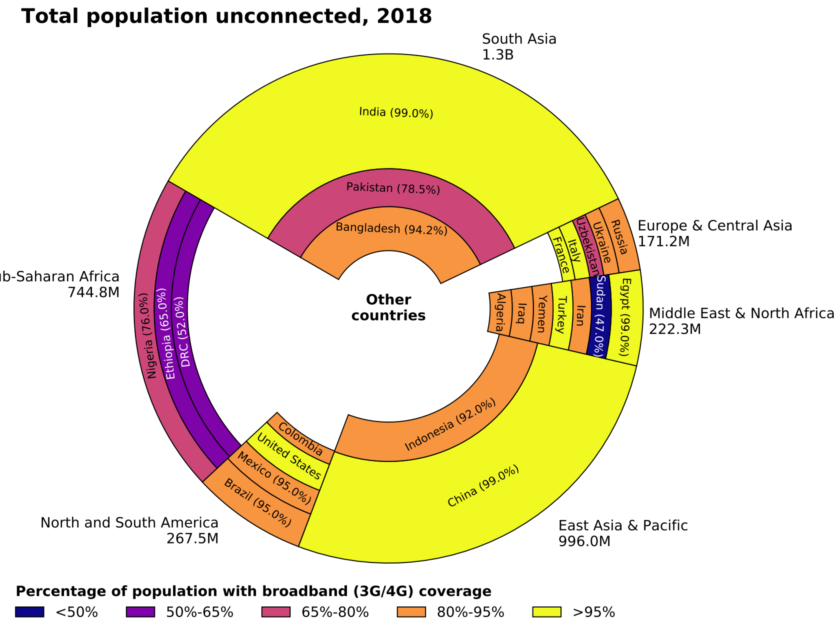


Figure 1: Distribution of offline users vs. percentage of broadband coverage at the end of 2018. The area of each of the wedges is proportional to the population unconnected[1]. Data sources: ITU[2](population unconnected) and GSMA Connectivity index[3](% of broadband coverage).

generalized framework for evaluating information networks, and used it to assess the designs proposed by Cyberstarr, Spaceway, and Celestri. Jilla (2002) extended GINA and integrated it with a multi-disciplinary design optimization (MDO) framework, which he used to conduct tradespace exploration of LEO, MEO, GEO satellite systems. Kelic (1998) and Gumbert (1996) proposed the "*cost per T1 link-per-minute*" as a metric to assess the financial viability of broadband satellite systems, and used it to study five GEO and LEO systems. Alternatively, Chiha et al. (2020) used the total cost of ownership for five years to calculate the average cost per user in two GEO satellite scenarios. Finally, de Weck et al. (2002) proposed a methodology for tradespace analysis of LEO personal communication systems, that combined technical, economic, and policy aspects with which he analyzed how staged deployments can be used to reduce risks associated with the uncertainty on demand (De Weck et al., 2004). Regarding newly proposed systems, del Portillo et al. (2019) compared from a technical standpoint the constellation designs of SpaceX, OneWeb, and Telesat.

Aerial systems, both high altitude platform (HAP) stations and low altitude platform (LAP) stations, have long been considered as a candidate solution to extend the reach of communication networks since they can cover larger areas compared to terrestrial systems.

On the one hand, a HAP is seen as a middle ground between terrestrial and space systems, which exploit the advantages of both: providing large coverage areas (100 - 10,000 km^2), requiring a small number of base stations, having low interference due to buildings and terrain obstructions, low latency, rapid, incremental, and localized deployments, ease of maintenance, and potential for reconfiguration (Djuknic et al., 1997). Research in the use of HAPs

Table 1: Summary of technologies to expand connectivity

		Reference	Models end-to-end system	Identifies architectural decisions	Conducts tradespace exploration	Evaluates economic feasibility
Satellite networks		Shaw (1998)	Yes	Yes	Partially	Yes
		Jilla (2002)	Yes	Yes	Yes	Yes
		de Weck et al. (2002)	Yes	Yes	Yes	No
		Gumbert (1996)	Yes	No	No	Yes
		Kelic (1998)	Yes	No	No	Yes
		De Weck et al. (2004)	Yes	Yes	Yes	Yes
		del Portillo et al. (2019)	Yes	Yes	No	No
		Chiha et al. (2020)	Yes	No	No	Yes
Aerial networks	High altitude platforms	Djuknic et al. (1997)	Yes	Yes	No	No
		Karapantazis & Pavlidou (2005a)	Partially	Yes	No	No
		Grace et al. (2001)	Yes	Partially	No	No
		Pace et al. (2004)	Partially	Partially	No	No
		Tozer & Grace (2001)	Partially	Yes	No	No
		Milas et al. (2003)	No	Partially	No	No
		Miura & Oodo (2001)	Yes	No	No	No
	Low altitude platforms	Al-Hourani et al. (2014a)	No	Yes	No	No
		Amorim et al. (2017)	Partially	Yes	No	No
		Al-Hourani et al. (2014b)	Partially	Partially	No	No
		Al-Hourani et al. (2015)	Partially	Partially	No	No

as a platform for communication services boomed in the 2000s after ITU's WRC-97, where the spectrum allocation for HAPs services was adopted by over 50 countries. The role of HAPs within the global connectivity landscape and their interactions with existing infrastructure (terrestrial and satellite) was the focus of Mohammed et al. (2011); Araniti et al. (2005); Karapantazis & Pavlidou (2005b); other parts of the literature analyzed the coverage problem (i.e., the number of HAPs required to provide coverage to a particular region) for selected countries (Tozer & Grace, 2001; Milas et al., 2003; Miura & Oodo, 2001).

On the other hand, even though the principal use cases for LAPs have been to facilitate rapid recovery of damaged terrestrial wireless infrastructure due to natural disasters (Qiantori et al., 2012; Alnajjar et al., 2014), to augment wireless networks to cover foreseen massive crowd movements (Valcarce et al., 2013; Federal Communications Commission, 2011), and for temporary military deployments (Sullivan, 2005), in recent years several commercial companies have proposed using LAPs to provide long-term communication infrastructure in rural and low-population density areas (Bleicher, 2018). With the increasing popularity of low-altitude UAVs, some cellphone companies have studied the use of "swarms" of UAVs to form low-altitude networks that extend the existing terrestrial networks (Sundaresan et al., 2018; Gupta et al., 2016).

Table 1 shows a summary of previous research in both space and aerial networks to expand global connectivity. As can be seen, most of the works considered end-to-end models of the system, and some identified the most important architectural decisions. However, there is a lack of analysis involving tradespace exploration while taking into account the economic feasibility of the different systems. This is mainly due to the lack of reliable economic models for these systems, which are in an incipient stage of development.

The 12.9% of the population that has no connectivity (i.e., uncovered) or only 2G connectivity (i.e., under-served) are spread out across more than 50% of the inhabited land area on Earth, making it extremely challenging to provide

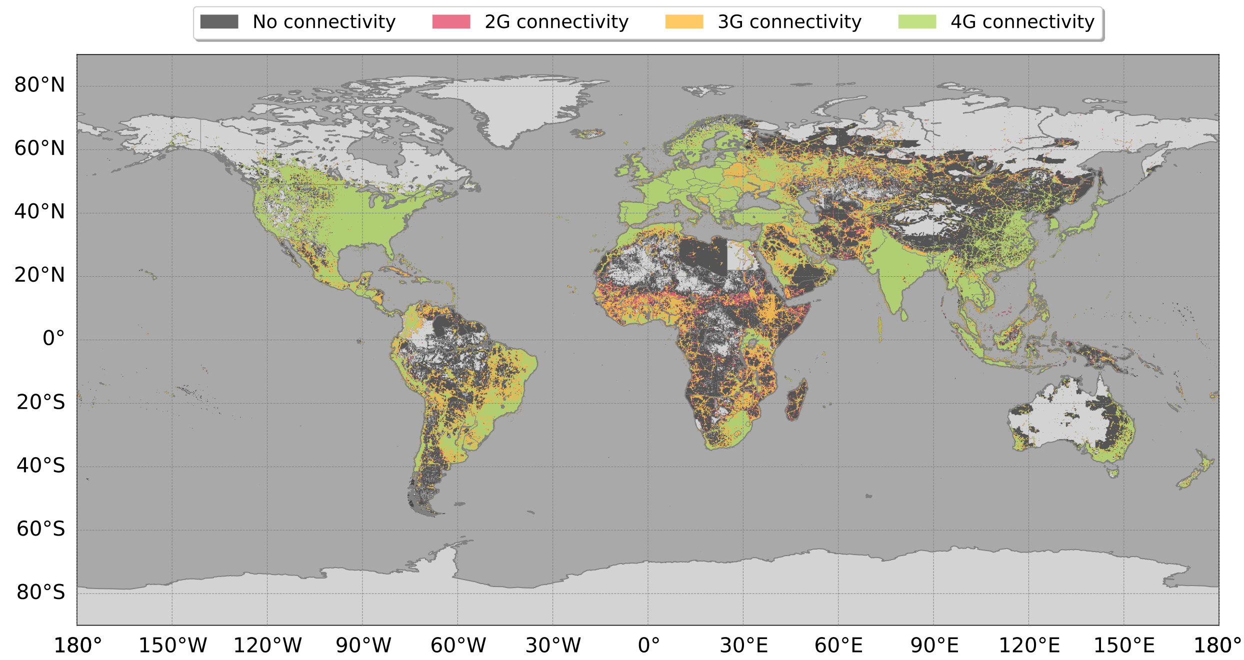


Figure 2: World map of most best mobile technology available at a worldwide level over populated areas. Colored areas represent inhabited regions, whereas gray areas represent uninhabited regions. Best viewed in color online.

connectivity to them using terrestrial infrastructure. To this end, space and aerial concepts lend themselves better to providing connectivity to those uncovered. This paper proposes a five-step techno-economic methodology which can be applied to both space and aerial concepts, to evaluate the viability of each concept in bringing connectivity to uncovered and under-served settlements and regions.

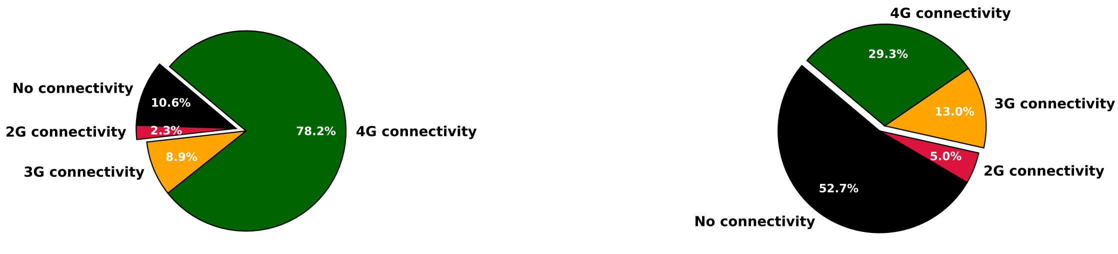
3. Data on barriers to connectivity

This section presents and discusses data highlighting the barriers to connectivity. Numerous studies (Sprague et al., 2014; Facebook Inc., 2015; Schmida et al., 2017; Lucini, 2016) have concluded that barriers to adoption can be classified into four groups: lack of infrastructure, affordability, readiness, and relevance. These barriers rarely exist in isolation, and overcoming them would require both technical- and policy-oriented actions to be carried out collaboratively by all the stakeholders involved (industry, governments, non-governmental organizations (NGOs), and non-profits).

3.1. Lack of infrastructure

A study by Myovella et al. (2020) showed that the effect of broadband internet on economic growth is minimal for sub-Saharan Africa compared to more developed countries due to underdeveloped infrastructure. Although infrastructure is usually associated with coverage, other obstacles prevent the rollout of new infrastructure, such as the lack of electricity, lack of road access, and underdeveloped (or outdated) backhaul and backbone networks. These obstacles are particularly prevalent in remote areas because of the challenging terrain, large capital expenditures, higher operating costs, and lower average revenue per user (ARPU).

To determine the mobile coverage over inhabited areas, data from the GPWV4 was combined with the cellular tower database from OpenCellId[4]. Figure 2 shows the *best* mobile technology available over inhabited regions of the world. We see how most of the world's inhabited area is covered by mobile broadband technology (i.e., 3G or 4G), which leads us to consider other barriers to connectivity beyond the lack of infrastructure. This realization is one of the more important takeaways from this section.



(a) Population

(b) Inhabited area

Figure 3: Fraction of a) population and b) inhabited area by best mobile technology available.

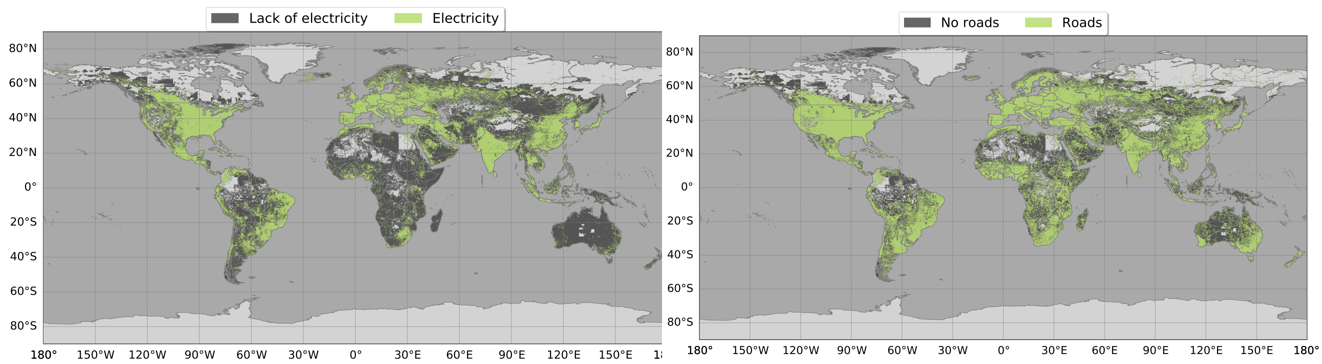
The relationship between 3G and 4G technology coverage and population density is better understood when looking at Figure 3a and Figure 3b, which show the percentage of the population covered by each technology and the percentage of inhabited areas covered by each technology respectively. Although 78.2% of the population (5.7 billion people) live in an area where there is 4G technology available, the area they occupy is only 27.1% of the total inhabited area. In contrast, those who live in areas with no mobile coverage only represent 10.6% of the population (750 million people), and yet it would be necessary to cover 56.3% of the inhabited land area to provide service to them. Therefore, the challenge presented by such sparsely distributed populations is evident.

Electricity is an essential requirement for connectivity, from both the deployment and user perspectives, since base stations need to be powered and users require electricity to charge their handset terminals or customer premises equipment.

Figure 4a shows a map indicating availability (or lack thereof) of electrical infrastructure, estimated using NOAA's Global DMSP-OLS Nighttime Lights Time Series (National Geophysical Data Center, 2013) and VIIRS Cloud Mask - Nighttime Lights (Elvidge et al., 2017) datasets. It can be observed that the lack of electricity is most pronounced in sub-Saharan Africa, where, according to WorldBank data, more than half of the population, do not have regular access to electrical power. Where electrical infrastructure is in place, the cost of access can still be a barrier to connectivity.

[4]Available at `www.opencellid.org`

The lack of road access is another common challenge which prevents infrastructure deployment. In inaccessible regions, material transportation needs to be done by hand, or by aerial means, which increases costs and deployment timeframes significantly. Figure 4b charts the regions on Earth with existing road infrastructure. This image was produced using the Open Street Maps (Haklay & Weber, 2008) dataset, which contains worldwide geographical road information. When compared to Figure 4a, it can be seen that the lack of road infrastructure is less prevalent than the lack of electricity, but still a challenge in regions of sub-Saharan Africa and South America.



(a) Presence of electricity infrastructure at a worldwide level over populated areas.

(b) Presence of road infrastructure at the worldwide level over populated areas.

Figure 4: Other infrastructure obstacles preventing the rollout of new infrastructure: a) lack of electricity, b) lack of road access. Colored areas represent inhabited regions, whereas gray areas represent uninhabited regions. Best viewed in color online.

3.2. *Affordability*

Affordability is defined as the cost of connectivity relative to income. The severity of this barrier is driven by the users' disposable incomes and the costs of cellphone devices and data package services. Historically, the device costs have been a significant barrier to access for lower-income groups, but the proliferation of low-cost terminals within the last few years has progressively reduced this barrier. The prices of the data services, on the other hand, remain the main barrier to access in most of sub-Saharan Africa.

As stated in the *Broadband Commission* targets, a connectivity service is considered affordable if its price is below 2% of monthly GNI per capita (Broadband Commission for Sustainable Development, ITU, UNESCO, 2018). Therefore, it is critical to take into account the income distribution across and within countries when estimating the potential impact of new connectivity technologies. Figure 5 shows the distribution of unconnected populations by country, with colors mapping to levels of GNI per capita. As can be observed, most of unconnected populations live in countries with GNI per capita less than $5,000; in sub-Saharan Africa and South Asia in particular, GNIs per capita are below $2,000, which, based on the ITU threshold implies a maximum price of $3.30 per month for connectivity services to be considered affordable.

[4] `https://databank.worldbank.org/`

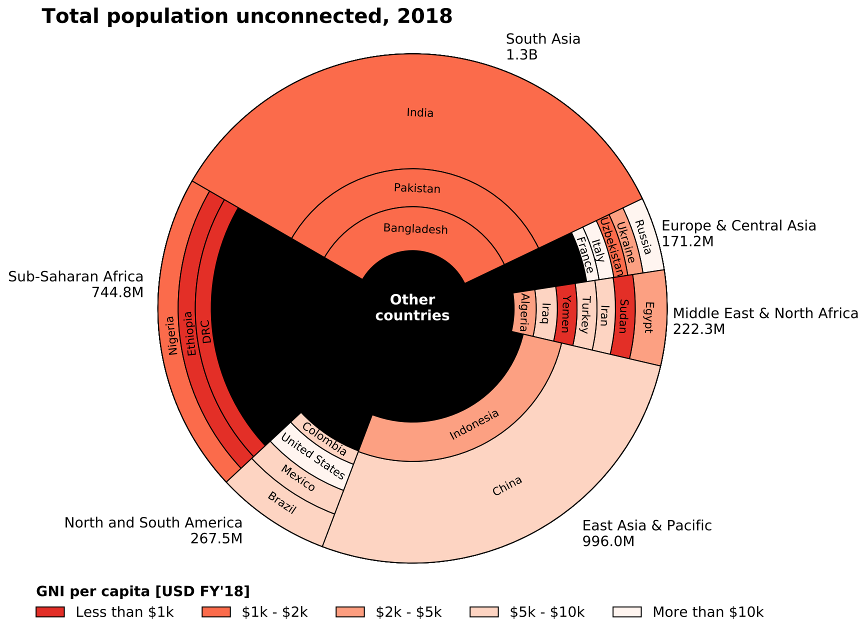


Figure 5: Distribution of offline users vs. GNI per capita. The area of each wedge is proportional to the population unconnected[2]. Data sources: ITU (population unconnected) and WorldBank (GNI per capita).

To estimate prices of basic mobile data plans in different countries, information on 6,000 data plans was extracted from three specialized websites: Prepaid Data SIM Card Wiki[5], Cable.co.uk[6], and the Alliance for Affordable Internet (A4AI) index[7]. All data sources were fused into a single table that estimates the monthly price of a basic plan for 189 countries. Figure 6a shows the price of a 1GB/month data plan as the percentage of the average income, taking into account the geospatial income distribution within each country. The large differentials between rural and urban populations are evident; in most countries in South America, where the average data plan prices are well below the 2% threshold, the price of a basic monthly data plan is above the affordability index is still unaffordable for populations in large regions of the country.

Fixed connectivity user penetration is much lower than of mobile connectivity, with, according to ITU estimates, only 1.1 billion people (~14% of the world's population) currently having access to a fixed-broadband subscription (UN Broadband Commission, 2017). Figure 6b shows the price of fixed-broadband monthly plans as a percentage of the monthly GNI per capita for each country using data extracted from Cable's "Worldwide Broadband Pricing" dataset[8].

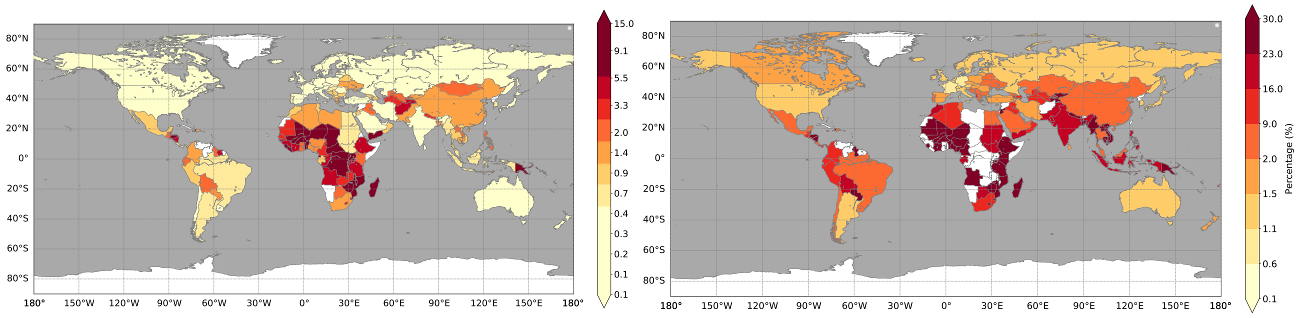
Lighter-colored countries are those where a fixed-broadband plan costs less than the ITU's 2% threshold, and dark-colored countries being where the price is above the threshold. Here the difference is starker; fixed-broadband is

[5] https://prepaid-data-sim-card.fandom.com/

[6] http://cable.co.uk

[7] https://a4ai.org/extra/mobile_broadband_pricing_usd-2019Q2

[8] See https://www.cable.co.uk/broadband/pricing/worldwide-comparison/ for raw data and a description of the methodology used to compute the values.



(a) Price of a 1GB/month mobile data plan as a percentage of the monthly income.

(b) Average price of a fixed-broadband monthly plan, as a percentage of the monthly GNI per capita.

Figure 6: Cost of mobile and fixed data plans. Countries where no data was available are depicted in white. Best viewed in color online.

only affordable in highly-developed countries and largely unaffordable in most of Southeast Asia and Africa, where costs can represent more than 20% of the average monthly income. In countries like Ethiopia, Tanzania, Mozambique, and Niger, costs can be as high as more than twice the monthly average income.

3.3. Relevance and readiness

Relevance barriers are those that arise from a perceived lack of usefulness (of the Internet) or because of accessibility issues. The most significant barrier in this category is the lack of content and services in local languages, which profoundly affects accessibility (Roycroft & Anantho, 2003). Even though more than 7,000 languages are currently spoken in the world, only 10 languages (representing the first language of ~3 billion people) account for 89% of the Internet content (Facebook Inc., 2015).

In contrast, readiness issues are related to the lack of digital abilities; for example, a lack of knowledge on how to operate a computer or a mobile device, or a lack of awareness on what the Internet is and how it may be used. In this regard, illiteracy is a major barrier, given that there are an estimated 1 billion people that currently cannot read or write. Furthermore, previous studies have shown that a large part of those unconnected to the Internet do not see any value or benefit from using the Internet, have security concerns (especially in South America) (GSMA, 2019), or are not even aware of the Internet. Even though some people in poor or rural areas can afford the Internet, without accessibility, perceptions on ease of use and usefulness are not clear (Zhang, 2013).

In most cases, relevance and readiness issues are best addressed from a policy perspective rather than through technological means. Prospective solutions include developing new business models which would make the Internet more relevant to local communities, creating adoption incentives, conducting advocacy, building capabilities through training, and acting as intermediaries between stakeholders of the connectivity ecosystem. With no universal solution, each region or country will have to identify the strategies best-suited to address their particular challenges; however, given that the focus of this paper is on technical solutions (i.e., novel concepts to expand connectivity) to address infrastructural and affordability concerns, policy-based solutions will not be further discussed.

4. Methods

This section focuses on the methodology adopted for the study of developing detailed technical and financial models for each of these space and aerial communication concepts to complement existing infrastructure, conducting techno-economic analyses for each of the concepts proposed, and comparing the impact of these concepts in terms of expanding connectivity to uncovered and under-served regions. The main difference with respect to other methods in the literature is that it provides a systematic procedure to analyze and compare dissimilar concepts that operate at different spatial and temporal scales.

The methodology comprises five steps, namely: 1) defining the scope, 2) developing the technical and economic models, 3) evaluating for technical performance, 4) evaluating financial impacts, and 5) analyzing the potential impact within a competitive market. A tabular overview of the methodology is depicted in Figure 7, where each of the five steps is represented by a column. For each step, the first row contains a summary of the tasks associated with each of the steps, and the second and third rows contain the inputs required and outputs produced by these tasks, respectively. A more detailed explanation of each step is given in the remainder of this section.

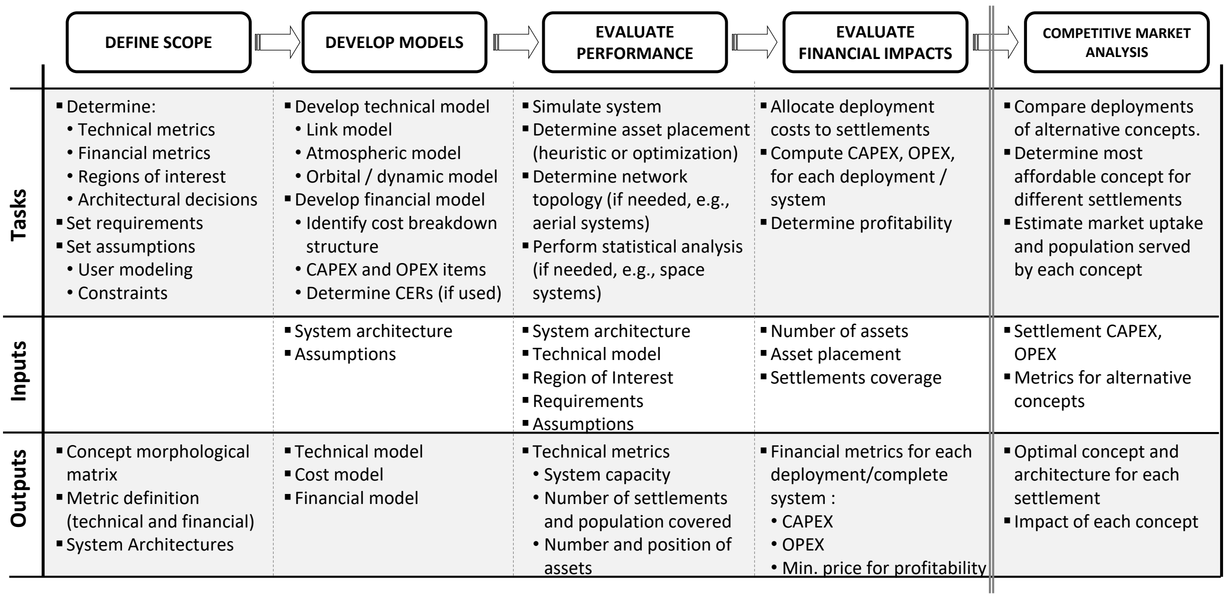


Figure 7: Overview of the techno-economic methodology used to evaluate the impact of new concepts proposed to expand global connectivity through space, aerial, and terrestrial networks.

4.1. Definition of the scope

The scope definition step consists of the following tasks: determining the regions of interest, defining the technical and financial metrics, establishing the architectural decisions under consideration, as well as characterizing the service and user requirements.

Since the focus of this paper is on space and aerial architectures as means of providing backhaul to wireless access networks (i.e., cellphone or WiFi-based networks) in uncovered and under-served regions, and it is assumed that space and aerial architectures will not be competitive to terrestrial infrastructure in those regions where there is currently broadband connectivity, the regions of interest are limited to places where there is currently no connectivity at all (i.e., uncovered) or only 2G connectivity (i.e., under-served), which represent ~60% of the Earth's inhabited surface and contain 12.9% of the population. It is important to emphasize that this paper does not seek to evaluate the impact of space and aerial concepts in closing the usage gap (i.e., addressing populations within areas where broadband is available but are not connected to the Internet), as it is assumed that affordability, relevance, and readiness issues are the main barriers in those instances, and that leveraging existing networks would be more cost-effective in expanding connectivity than introducing new space and aerial concepts.

The two main technical metrics of interest are the total sellable capacity (i.e., the capacity that could be realistically sold to users) and the number and locations of assets required. On the financial side, the focus is on estimating the capital expenditure (CapEx) and operational expenditure (OpEx) for each of the architectures (or deployments), together with the minimum selling price per Mbps/month that would achieve an internal rate of return (IRR) of 15%.

The architectural decisions to be considered include the types and altitudes of the space and aerial platforms, the network topology, and the operational frequencies of the payloads, given that these are the main drivers of performance and costs for the systems. For both space and aerial concepts, several architectural decisions, each with a set of options, are taken into account, as depicted in the morphological matrices in Tables 2 and 3, respectively. Tradespace exploration using a Bayesian Optimization-based method is used to analyze hundreds of architectures for each of the concepts and select a subset of the best architectures (those in the Pareto front) for further comparative market analysis in Section 4.2 and for which Section 5.1 contains a summary of the results.

Finally, in terms of service requirements, it is assumed that a minimum service availability of 99% is required for all the concepts and that an entry-level broadband service providing 1 GB/month per user for those living in uncovered regions (as per OECD (2012) and ITU's Information and Communication Technologies (ICT) price basket methodology ITU (2017)) and 3 GB/month per user for those in under-served regions (both of them having a conservative compound annual growth rate of 9% (Ericsson, 2019)) would be provided.

4.2. Technical and economic models

This step consists of developing the technical and economic models specific to each of the concepts considered, which are used to assess different architectures' performance and financial viability belonging to each of the concepts under study. The rest of the section summarizes the models and the main assumptions behind them, and a full description is available in Chapters 5, and 6 of del Portillo (2020).

4.2.1. Satellite networks technical model

For satellite networks, the performance is determined using a two-step process similar to the one described by del Portillo et al. (2019). First, the optimal locations and number of feeder gateways are computed using a genetic algorithm. Second, the resulting locations are combined with atmospheric models, link budget models, and orbital dynamic models to determine statistically the total system sellable capacity through Monte Carlo analysis.

Table 2: Morphological matrix for space systems

Decision name	Decision options					
Orbital Altitude	GEO	MEO	LEO			
Number of planes	1	5	10	15	20	50	
Number of satellites / plane	3	5	10	20	30	50	70
Orbital inclination	0	30	45	60	90		
Number of payload beams	7	19	37	74	370	740	
Freq. User ↔ Satellite	Ku	Ka	V/Q				
Freq. Satellite ↔ Gateway	Ka	V/Q	E	Optical			
Freq. Crosslinks	E	Optical	None				

In particular, the following decisions were considered when defining space networks, as shown in the morphological matrix in 2.

- **Orbital altitude and inclination**: possible orbital altitudes include GEO (35,768 km), MEO (8,000 km), and LEO (1,200 km). The orbital inclination can take one of the values in {0°, 30°, 45°, 60°, 90°}, with the except that for GEO networks, only equatorial orbits (inclination = 0°) are allowed and for LEO networks, only non-equatorial orbits are allowed.

- **Number of planes and number of satellites per plane**: these decisions determine the overall constellation structure and the total number of satellites. The number of planes considered can take any value in {1, 5, 10, 15, 20, 50}, whereas the number of satellites per plane is {3, 5, 10, 20, 30, 50, 70}. For equatorial configurations (inc=0°), the number of planes is always 1; for non-equatorial configurations, it is always greater than 1. Moreover, for MEO constellations, the maximum number of planes is 20 and the number of satellites per plane is any integer between 5 to 30; finally, only GEO architectures can have 3 satellites per plane, since constellations in other orbits cannot possibly achieve global coverage with such a small number of planes. In addition, GEO and MEO satellites have a minimum elevation angle of 10 degrees, whereas for LEO constellations the elevation angle is as low as required to guarantee full-coverage and at least 40 deg.

- **Number of beams per satellite**: the number of beams per satellite can take any value in {7, 19, 37, 74, 370, 740}[9]. However, the following constraints apply: for LEO networks, the number of beams must be fewer than or equal to 74 beams (due to the assumed power limitations of the spacecraft), whereas GEO networks must have

[9]It is assumed that each beam has up to 1 GHz of usable bandwidth

at least 37 beams (i.e., architectures comprised of"small-GEO" satellites are not considered). Finally, MEO networks with a large number of planes (10, 20, 50) must have fewer than 100 beams per satellite.

- **Operational frequencies**: these frequencies determine the bandwidth available (according to the ITU frequency allocation guidelines) and the achievable data rates. For the user links, frequencies {Ku, Ka, V/Q} are considered; for the feeder links: {Ka, V/Q, E, optical}, and for the crosslinks: {None, E, optical}.
- **User access**: All the architectures are assumed to require a customer premise equipment (CPE) to connect to users, as direct-to-user strategies are unaffordable for uncovered and under-served populations.

The method to compute the sellable capacity is simulation-based and combines a discrete-time simulation of a day of operations of the constellation (which includes propagating the satellite orbit and evaluating the population in line-of-sight of each satellite and the geospatial distribution of demand over time) with Monte-Carlo simulation (to model the effect of atmospheric attenuation for each frequency band as prescribed by the guidelines provided in recommendation ITU-P R.618-12 (ITU, 2015) to evaluate the effects of gaseous, cloud and fog attenuation, tropospheric scintillation and rain impairments), and is similar to the one described in del Portillo et al. (2019). The most relevant assumption of this method include:

- User demand is concentrated on land areas and is proportional to the population under reach by a satellite.
- Customers with multiple satellites within LoS select one randomly to communicate with.
- Satellites produce enough power to communicate at maximum EIRP whenever required.
- Ground stations can be located over any land area. There are no political, landing rights, or geographical constraints to their placement.
- Crosslinks across satellites can be used to route excess demand to other satellites.

4.2.2. Aerial networks technical model

For aerial networks, the model evaluates the sellable capacity by computing the number and locations of the aerial assets, and the payload dimensions required to satisfy the demand. The number and locations of the assets are determined using graph theory, whereas the performance of the payload is assessed using atmospheric and link budget models, together with a network topology model which uses a Gaussian random walk heuristic to determine the number of redundant platforms required to achieve continuous coverage and the target availability of 99%.

The following decisions were considered when studying aerial networks, as shown in the morphological matrix in 3:

- **Altitude**: The aerial platforms considered can either be HAPs with an altitude greater than 20km, or LAPs. In the latter case, a distinction is made between platforms flying at 200m or lower and platforms between 200m and 1km.

Table 3: Morphological matrix for aerial systems.

Decision name	Decision options				
Platform altitude	<200 m LAP	<1km LAP	HAP		
Platform station-keeping	Active	Passive			
Network topology	None	Bus	Ring	Star	Mesh
User access	Direct (handset)		CPE		
Number payload beams	1	7	19	37	
Freq. user ↔ platform	S	Ku	Ka	V/Q	
Freq. platform ↔ gateway	Ka	V/Q	E		
Freq. crosslinks	None	Ka	E	Optical	

- **Station-keeping ability**: Platforms can have passive or active station-keeping capabilities. Active platforms (e.g., planes, propelled blimps, tethered platforms) can hover over certain regions, whereas passive platforms are subject to wind-drift or have very limited station-keeping abilities (e.g., balloons).

- **Network topology**: The network topology determines the number of crosslink terminals and the ground segment requirements. Five topology options are considered, with various numbers of crosslink terminals per platform: in *bus* and *ring* topologies, aerial platforms have two crosslink terminals; whereas in the *star* and *mesh* topologies, there are three crosslink terminals. The fifth topology is the *no-crosslinks* topology, where aerial platforms do not have crosslink terminals and must be within line of sight of a gateway antenna to operate.

- **Number of beams in the payload**: The number of beams in the payload determines the number of times frequency bandwidth can be reused. The valid values for this decision are {1, 7, 19, 37}.

- **Frequencies of operation**: The frequencies of operation for the user links ({S, Ku, Ka, Q}), feeder links ({Ka, V, E}), and crosslinks ({Ka, E, optical, None}) determine the bandwidth available and the data rates achievable.

- **User access**: Both *direct* user access and access through a CPE terminal are considered. In the direct method, a user is connected directly to the aerial platform using their handheld device, whereas in the CPE method, additional equipment (e.g., a community-shared access point) is required.

The performance model evaluates the number and locations of the aerial assets, the number of additional platforms required to ensure continuous coverage, and the payload dimensions to satisfy the demand (at each frequency band). The number and locations of the assets is determined by transforming the problem into a clique edge covering problem in graph theory; whereas the performance of the payload is assessed using the atmospheric and link budget models similar to those described for satellite networks in the previous section, together with a network topology model which uses a Gaussian random walk heuristic to determine the number of additional platforms required to achieve continuous coverage and the target availability of 99%. In addition to those described above, the other main assumptions of this model are as follows:

- For platforms without station keeping capabilities (e.g., untethered balloons) that can be swept away by the wind, redundant platforms are necessary to achieve 95% availability.
- The maximum radius of coverage of a LAP is 40 km, and for HAPs, it is 80 km. However, the coverage of a LAP or HAP is highly dependent on the terrain elevation, and therefore, the SRTM digital elevation map (USGS, 2004) together with a line-of-sight model is used to determine real coverage.
- HAPs have an endurance of 135 days and a lifetime of 4 years.

4.2.3. Satellite networks economic model

The economic model assesses the total cost of a given satellite network, and to that end, it first sizes the spacecraft, then it estimates their cost, and finally, computes the total cost of ownership by adding the cost of the five broad categories, namely: spacecraft, launch, ground segment, program-level costs, and operational expenses.

The satellite-sizing model is based on the subsystems models described in Larson & Wertz (1992). The algorithm's main inputs are the payload parameters (mass, average data rate, average and peak power), which are estimated using a regression model built using data from 65 communication satellite payloads launched in the last 15 years.

Then, two different parametric cost models are used to estimate the satellite cost: SSCM and USCM-10. SSCM, the *Small Satellites Cost Model*, was developed by the Aerospace Corporation to predict the development costs of modern, small satellites (under 1,000 kg.) (Mahr et al., 2016). USCM-10, the *Unmanned Spacecraft Cost Model*, was developed by the Air Force to estimate the costs associated with earth-orbiting, unmanned space vehicle programs (Nguyen et al., 1994). These models estimate the spacecraft cost using cost estimating relationships (CERs), which, given the mass (or other parameters) of a subsystem, provide estimates for its costs. Such models are better suited for trade studies during the conceptual design stage, as this phase is characterized by the lack of precise information to inform detailed cost estimates.

USCM-10 provides estimates for both non-recurring costs (e.g., research and development costs, prototype unit costs, program costs) and recurring costs (e.g., manufacturing costs per unit), whereas SSCM provides combined estimates for non-recurring plus first unit costs (it is assumed that the non-recurring costs are 60% of this value and the first unit costs 40%). For satellites weighing over one tonne, the estimates from USCM-10 are used; otherwise, the SSCM model is employed.

Finally, it is worth noting that the launch cost is computed as the cost per launch vehicle multiplied by the number of launches required, and the ground segment cost is computed using the recommendations from the *DoD Facilities Pricing Guide* (Department of Defense, 2018).

4.2.4. Aerial networks economic model

Detailed parametric cost models for aerial networks are lacking in the literature due to the early stage of development of aerial platforms. Instead, simplified CER models based on platform weights and performance are used.

For heavier-than-air platforms (UAVs), the average of the US Army's performance-based CER and weight-based CER models are used to characterize the CapEx costs of heavier-than-air (HTA) platforms (Cherwonik & Wehrley, 2003). The performance-based CER is shown in Eq. 1:

$$\mathrm{UAV}_1 = 118.75 \cdot (\mathrm{endurance} \cdot m_{\mathrm{payload}})^{0.587} \cdot e^{-1.951} \qquad [FY'03\$k] \tag{1}$$

where UAV_1 is the theoretical first-unit cost (in FY'03 $k) of air vehicle hardware, normalized for learning (95% slope) and rate (95% slope), *endurance* is the UAV's endurance in flight-hours, and m_{payload} is the weight of the total payload in pounds.

The weight-based CER model is shown in Eq. 2:

$$\mathrm{UAV}_1 = 12.55 \cdot (\mathrm{MGTOW})^{0.749} \cdot e^{-0.371} \qquad [FY'03\$K] \tag{2}$$

where UAV_1 is the theoretical first-unit cost (in FY'03 $k) of UAV air vehicle hardware, normalized for learning (95% slope) and rate (95% slope), and MGTOW is the maximum take-off weight in pounds.

For lighter than air platforms (balloons), the CapEx costs are computed considering the costs of the payload, electronics, solar panels, and the volume of helium required to provide lift, as detailed in Table 4. With these values, the total cost per balloon is determined to be $49,500 (not yet considering the cost of helium required). This number is in line with estimates for high-pressure balloons used in current projects.

Table 4: Parameters of the cost model for lighter than air platforms.

Item	**Price**	
Balloon shell	$12,000	per balloon unit
Electronics and batteries	$10,000	per balloon unit
Solar panels	$6,000	per balloon unit
Structure	$1,500	per balloon unit
RF equipment	$7,000	per balloon unit
Feeder antenna	$7,500	per balloon unit
User antenna	$7,500	per balloon unit
Crosslink antenna	$6,000	per antenna unit
helium	$7.50	per m^3

4.3. Evaluate performance

The primary performance output metric is the total system sellable capacity, whereas the economic metrics of interest are the system cost, the architecture's financial feasibility, and the minimum price per Mbps/month required to meet a stipulated minimum internal rate of return. Evaluating the different concepts' performance and financial viability is done by running each concept's technical and economic models (as described in the previous Section) and conducting tradespace exploration using a Bayesian Optimization-based method. As opposed to more traditional methods that primarily rely on expert opinion and detailed analysis of a few point designs (known as "expert design"), tradespace exploration advocates for the evaluation of a multitude of designs corresponding to different concepts (Ross & Hastings, 2005).

Bayesian optimization (BO) is a set of optimization techniques used to find the extrema of black-box functions that are expensive to evaluate repeatedly (Brochu et al., 2010). In these instances, Bayesian optimization is very effective in minimizing the number of function evaluations required to locate the extrema. However, BO performs best when the function domain and image are continuous, which is not the case in our combinatorial system architecture problem (SAP) due to categorical decision variables. We adapt the typical BO formulation to solve an SAP by using different models (e.g., random forest, tree Parzen estimator), different kernels (e.g., Matérn, Kendall, Mallows), and different distance functions (e.g., Hamming distance, Damerau-Levenshtein distance) (del Portillo, 2020).

4.4. Evaluate financial impacts

The financial model evaluates the feasibility of a satellite constellation or an aerial deployment by using a discounted cash flow analysis, (which takes into account the revenue, CapEx, and OpEx) to compute the internal rate of return (IRR). In addition, the model determines the minimum average price per Mbps/month that a company would need to charge its users to achieve an IRR of at least 15%, at which point we consider a deployment feasible. Note that the IRR is only used as a proxy to evaluate the economic feasibility of a particular deployment, as the main assumption of the paper is that no corporation will undertake a business project if the IRR does not exceed a given threshold (independently of the magnitude of the NPV of such project), and that this metric should be combined with other financial (NPV, ROI, DCF) and non-financial metrics (a project being part of a bigger strategic plan, impeding competition) when making the decision of undertaking or not a project.

Finally, it is worth mentioning that due to the global-coverage nature of space networks, the financial analyses took into account their impact on a global scale (i.e., assuming they can capture market all over the world). For aerial systems, however, the analysis targeted a set of countries for which high granularity demographic and income data were available (see Table 5) since these types of networks can be deployed to target specific regions where their economic viabilities are guaranteed.

4.4.1. Satellite networks financial model

The financial model evaluates the constellation's economic feasibility using a discounted cash flow analysis, which takes into account the revenue, CapEx, and OpEx items. The goal of the model is to determine the minimum average price per Mbps/month that a company would need to charge its users to achieve an IRR of at least 15%. Cash flow projections are computed assuming a 20-year horizon; besides, the following assumptions were made:

Revenue generation

- Satellites are first launched in year 2, and service operations begin in year 3.

- Capacity is sold progressively, starting at 20% in the first year of operations, and stepping up to 40%, 50%, and 65% in years 2, 3, 4 respectively. From year 5 onward, 70% of the system's total system throughput is sold. The variable ρ is used to represent the percentage of capacity sold.
- The average price per Mbps/month is a variable chosen such that the IRR within a 20-year horizon equals 15%.
- The average price per Mbps/month decreases at a rate of 5% annually.
- Finally the annual revenue is computed as:

$$\text{Revenue} = \text{System capacity} \times \rho \times \text{price Mbps} \tag{3}$$

Capital Expenditure

- The items that constitute CapEx are: satellite manufacturing costs, launch costs, insurance costs, ground segment costs, and R&D costs.
- The satellite manufacturing costs, launch costs, ground segment costs, and R&D costs are given by the cost models described in the previous two sections.
- The insurance costs are assumed to be 8% of the launch value (launch costs + total costs of the satellites on-board), following the recommendations of Larson & Wertz (1992).
- Constellation replenishment costs are distributed uniformly across all years of operations.

Operational Expenditure

- The items that constitute OpEx are: ground segment sustainment costs, backhaul costs, and other operational expenses (including salaries, marketing, etc).
- The ground segment sustainment costs are given by the ground segment cost model.
- Given the flexibility of satellite operators to locate gateways in close proximity of major internet exchange points, the backbone transit costs are assumed to be $5 per Mbps/month, with an annual decrease rate of 5% (Telegeography, 2019).
- Other operational expenses (including salaries, sales, marketing, leases, power, etc.) are assumed to be 35% of revenue once the constellation starts offering service, and up to 10% of the CapEx in the years prior operations begin.

Once the revenue, CapEx and OpEx items have been taken into account, the cash flow for each year is simply given by:

$$\text{CF} = \text{Revenue} - \text{CapEx} - \text{OpEx} \tag{4}$$

Finally, the IRR (the discount rate that makes the difference between current investments and the future NPV equal to zero), is the solution to Equation 5,

$$0 = \sum_{t=0}^{20} \frac{\mathrm{CF}_t}{(1 + \mathrm{IRR})^t}, \tag{5}$$

where CF_t is the cash flow in year t.

4.4.2. Aerial networks financial model

The financial model estimates the free cash flow for each of the deployment, as well as the net present value and the IRR. If the IRR is higher than 15%, a deployment is considered profitable. For the model, the CapEx costs are computed using the cost models described previously, whereas the OpEx costs are estimated as follows:

- For heavier-than-air (HTA) concepts such as balloons and blimps, the OpEx is primarily driven by the re-fill costs of helium required for successive launches, which is given as $\$7.5/m^3$, according to estimates from the USGD National Minerals center[10], and the costs to recover a balloon, procure a new shell costs, in addition to day-to-day maintenance. These expenses amount to 30% of the CapEx.
- For HTA platforms, the OpEx is estimated to be 10% of the CapEx .

In addition, the following assumptions are made:

- The backbone transit cost is estimated to be $20 per Mbps/month with a compound annual growth rate (CAGR) of -5% Telegeography (2019).
- The ARPU is set as 2% of the estimated monthly income, averaged across of all the settlements covered.
- The number of subscribers is assumed to increase progressively up to 60%, and the data-consumption per user is 1GB with an compound annual growth rate of 9%.

4.5. Competitive market analysis

The last step of the techno-economic methodology determines which of the technologies studied is the most affordable for each region of interest. Besides space and aerial concepts, terrestrial networks are also included in the comparative analysis as baseline systems. Since terrestrial networks for backhauling are well established and leave little potential for disruptive innovations to take place, tradespace exploration is not conducted for these types of networks. Instead, the models for fiber and wireless backhaul networks are based on the current technologies' performance and costs.

[10] Available at `https://www.usgs.gov/centers/nmic/helium-statistics-and-information`

In addition to the estimates for sellable capacity and the minimum selling price that would achieve profitability, this step requires two more pieces of data: the locations of the uncovered and unconnected settlements, and the population and income estimates for each of these settlements, which allows us to assess the relative impact of each of the concepts (in terms of population covered that can afford the service and in terms of the number of new users brought online) if they were to operate within a competitive market with other backhaul options available.

Table 5: Countries considered in the comparative analysis of technologies.

ISO2	**Country**	**ISO2**	**Country**	**ISO2**	**Country**
AF	Afghanistan	ID	Indonesia	PG	Papua New Guinea
AR	Argentina	IN	India	PH	Philippines
BD	Bangladesh	KE	Kenya	PK	Pakistan
BF	Burkina Faso	LK	Sri Lanka	RW	Rwanda
BR	Brazil	LS	Lesotho	SD	Sudan
CD	Congo (DRC)	MM	Myanmar	TH	Thailand
CI	Cote d'Ivore	MW	Malawi	TR	Turkey
CM	Cameroon	MX	Mexico	TZ	Tanzania
DZ	Algeria	MY	Malaysia	UA	Ukraine
EG	Egypt	MZ	Mozambique	UG	Uganda
ET	Ethiopia	NG	Nigeria	ZA	South Africa
GH	Ghana	PE	Peru	ZM	Zambia
HT	Haiti				

In particular, the comparison of technologies is carried out for the 37 countries in Africa, Southeast Asia, and South America that were shown in Table 5 using the following two-step procedure:

1. For each settlement, the different technologies (terrestrial (both fiber and mm-Wave backhaul), aerial, and space) are ranked by monthly price per user. To compute the price per user, it is assumed that for uncovered settlements each user is to be provided with a data tonnage of 1 GB/month, whereas for under-served settlements 3GB/month are required. Moreover, a conservative 9% CAGR in demand is assumed (VNI, 2019), which results in a data rate allocation of 30 kbps and 100 kbps for uncovered and under-served users, respectively[11]. Then, the price per Mbps/month of each technology is divided by the number of subscribers 1 Mbps would support (using

[11]The computation starts with estimating the per user data tonnage allowance per month, which considers the mix of traffic for different services required by a "representative" user. After applying a set of correcting factors, the data tonnage is transformed into an average throughput per user required to guarantee a given quality of service during the busy hour (i.e., the sliding 60-minute period during which occurs the maximum total traffic load in a given 24-hour period). In particular, the average (busy-hour) throughput per user $R_b^{(bh)}$ is given by:

$$R_b^{(bh)} = \underbrace{\frac{D_t}{30}}_{\substack{\text{data-volume}\\ \text{per day}}} \cdot \overbrace{\frac{B}{24}}^{\substack{\text{busy hour}\\ \text{ratio}}} \cdot \underbrace{\frac{1}{60 \cdot 60}}_{\substack{\text{conversion}\\ \text{to bps}}} \cdot \overbrace{\frac{(1+\alpha)}{\eta}}^{\substack{\text{QoS and}\\ \text{utilization ratio}}} \tag{6}$$

where D_t is the monthly data tonnage (in bits), B is the busy-hour ration (equal to 2.5-3 for backhauling systems), α is a security factor to guarantee a minimum QoS during unexpected peaks (assumed to be equal to 10%), and η is the utilization factor (assumed equal to 0.85).

the data rate allocations). Furthermore, the cost of the customer premise equipment (CPE) is also included (if required) in the price per user (distributed evenly across subscribers).

Finally, the price per user for each technology is compared to the 2% of the average monthly income of each settlement (as per the ITU recommended threshold), to determine which technologies are affordable in each settlement.

2. Settlements in each country are ordered in descending order of income, and the most affordable technology is assigned to the settlements sequentially (so that wealthy settlements are assigned first). When doing so, the limited capacity of aerial and space systems is taken into account,

The following three scenarios with different time horizons are considered in the analysis:

- **Current scenario**: Current costs are used as a reference for the analysis. Only fiber, mm-Wave, and space technologies are considered, as there are currently no viable aerial communication networks.

- **Next-generation scenario (2-5 years)**: The cost (and thus price) reductions that might be achieved in the next 2-5 years are considered. In the space industry it is estimated that monthly cost per Mbps could drop to the \$70-\$100 range. For aerial systems, it is assumed that the best performing lighter-than-air HAP network is used, as this was identified as the most cost-effective solution.

- **Future scenario (8-10 years)**: Advanced concepts for space and aerial networks are considered. Previous analysis show MEO networks to be the most cost-effective space architectures, allowing for prices to be set at ~\$30 per Mbps/month. For aerial networks, a passive station-keeping, Ka-band system with no crosslinks, a single beam, and direct-to-user links is considered, allowing for prices to be set at ~\$50 per Mbps/month.

5. Results

5.1. Summary of best space and aerial architectures

This section presents an overview of the results of the best space and aerial architectures to provide coverage to uncovered and under-served populations. Detailed discussion and results are available in del Portillo (2020).

5.1.1. Space architectures

Our analysis concluded that constellations with satellites in GEO and MEO are the most affordable and viable space architectures to extend connectivity to uncovered and under-served regions.

For GEO networks, the dominant architectures have a small number of satellites (3-10) carrying highly-capable payloads (~ 1 Tbps of throughput), and use higher frequency bands (Q/V or E-band) for user and feeder links. For MEO satellites, a larger number (~20) of moderate-capacity spacecraft is preferred. Finally, some LEO designs can also be competitive, with our model predicting that the best designs would feature a relatively small number of satellites (200-450) with simple payloads, positioned at inclined orbits. Mega-constellations with thousands of satellites were deemed as ineffective to serve uncovered and under-served regions due to the high CapEx costs and the diminishing satellite-utilization (i.e., the percentage of time that a satellite is actively transmitting) as more satellites are launched.

5.1.2. Aerial architectures

Given the low ARPU and small coverage area of aerial systems (when compared to space systems), the dominant aerial architectures are those that can achieve such coverage at very low costs. Among the different concepts studied, balloon-based HAPs with limited station-keeping capabilities were superior to UAV-based platforms, which were deemed sub-optimal because their CapEx costs (over 1 million dollars per unit) are a large hurdle, and the deployments will rarely work out to be affordable by the uncovered and under-served populations.

Overall, in order to provide affordable coverage to uncovered and under-served regions, high-capability systems are not required; rather, low-cost, moderate-throughput concepts are best-suited for these goals. Thus, balloon-borne direct-to-handset architectures without crosslinks and using the S- or Ka-band (the same frequencies as those authorized for 4G and 5G networks) for the user links are preferred.

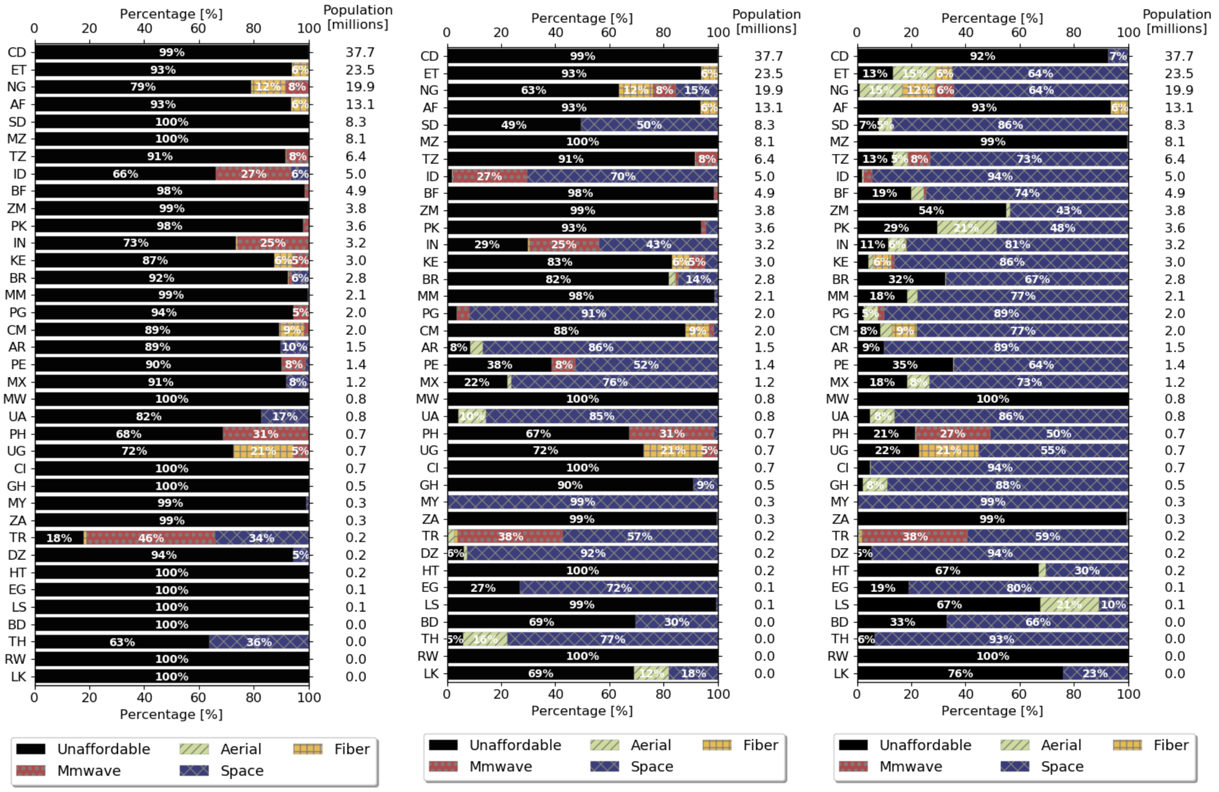
5.2. Percentage of population that can afford connectivity services by technology

This section presents the results of the most affordable technology for each settlement. For each of the space and aerial technologies analyzed, only the best architectures (as described above) were considered (i.e., a GEO constellation of 5 very high throughput satellites, and a network of balloon HAPs). Figure 8 shows the distribution of the most affordable technology as a percentage of the total population in each country for the current, next-generation, and future scenarios. These values are computed by grouping settlements by the most affordable technology, adding up their populations, then dividing that by the total uncovered and under-served population in each country.

For the current scenario, Figure 8 shows that for a significant percentage of the population, mm-Wave and fiber would be affordable (more than 20% of the population in several countries). Also, it can be observed that mm-Wave is generally preferred over fiber (as one would expect, given the lower costs).

Looking at the next-generation scenario in Figure 8b, it is evident that satellite-backhauled networks would be able to provide affordable connectivity to almost all the population of the medium-income countries such as Argentina, Myanmar, Turkey, or Thailand. However, low-income countries would still pose a challenge as none of the technologies considered will be affordable to a large portion of their uncovered and under-served population.

Finally, for the future scenario (Figure 8c), the results show that space technologies are the most promising, since the future-generation spacecraft (which we predict will be able to lower the final price per Mbps/month into \$30-\$50 range) would become the most affordable backhaul technology in the majority of the countries studied (in multiple countries, more than 80% of the uncovered and under-served will be able to afford the service). However, providing connectivity to those uncovered and under-served in the lowest income countries like Malawi, Mozambique, and the Democratic Republic of Congo will still remain a difficult task, as no-technologies will be affordable.



(a) Current (b) Next generation (2-5 years) (c) Future (8-10 years)

Figure 8: Percentage of uncovered and under-served population that can afford connectivity services for all countries considered, broken down by most affordable technology, under the a) current, b) next-generation, and c) future scenarios. Countries are ordered by the total uncovered and under-served population in descending order.

Based on these results and understanding that successful measures will depend on the specifics of the market situation in each country, we anticipate that two broad groups of policies should be taken to extend connectivity to uncovered and under-served regions. On one hand, for mid-income countries where space and aerial technologies will be affordable in the 8-10 years time-frame for a significant percentage of the uncovered and under-served population, governments should focus on incentivizing competition and removing barriers of access through the simplification of the process for acquisition or approval of spectrum rights. On the other hand, for low-income countries where reductions in price driven by technological progress will not be enough to ensure a viable business case, policy in the form of state-run services (e.g., Bolivia's Space Agency Tupac-Katari program), private-public partnerships (e.g., the on-going projects in Colombia and Brazil), subsidies (e.g., RDOF in the USA), lower taxes, or mandatory-coverage regulation will be necessary.

Figure 9 shows the most affordable technology by percentage of the population, this time aggregated across all countries, under the three scenarios considered. It can be observed that at current prices, only 8% of those uncovered and under-served (approximately 13 million people in the 37 countries of interest) can afford connectivity and that the most effective technology would be mm-Wave deployments. The introduction of a new generation of satellites in the next 2-5 years could bring that number up to slightly higher than 19%, but it is worth noting that space networks will barely cannibalize any market share from other technologies such as mm-Wave or fiber, at least not when considering only uncovered and under-served populations. Finally, if space connectivity prices continue to drop, as is expected to happen in the next 8-10 years, the number of people that could afford connectivity through space networks will drastically increase to approximately 45% of the uncovered and under-served population in the 37 countries studied.

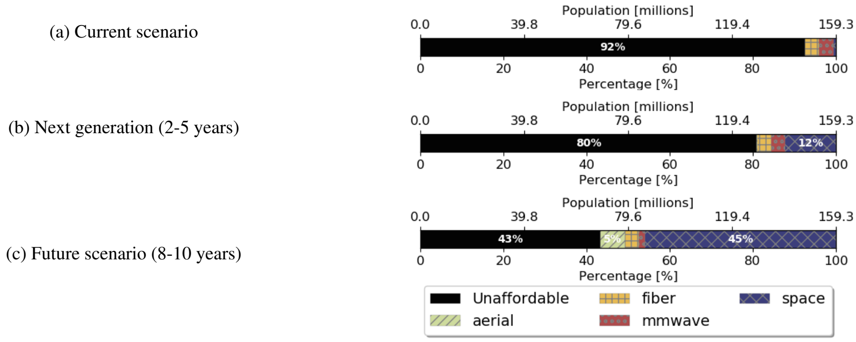


Figure 9: Overall percentage of uncovered and under-served population that **can afford** connectivity services for the 37 countries considered, broken down by most affordable technology, under the a) current, b) next-generation, and c) future scenarios.

5.3. *Users brought online per technology*

In the previous section, the population that could afford each of the technologies was analyzed. However, the analysis ignored non-price factors such as the market uptake rate or capacity saturation limits of space and aerial concepts. Figure 10 shows the percentage of the population that is estimated to be brought online under the three scenarios considered. Several key differences can be observed between these results and those regarding affordability from the previous section (Figure 9):

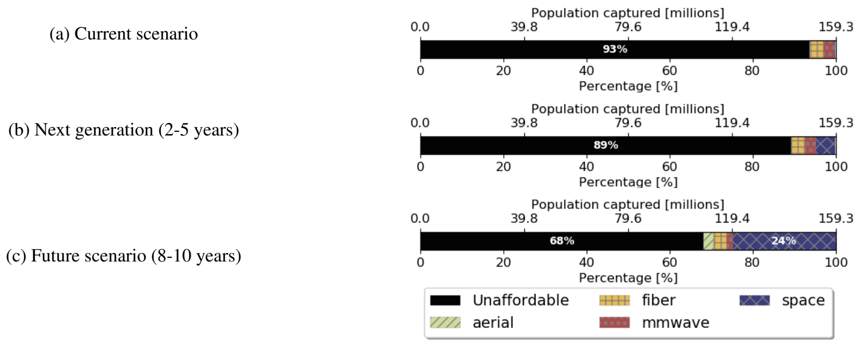


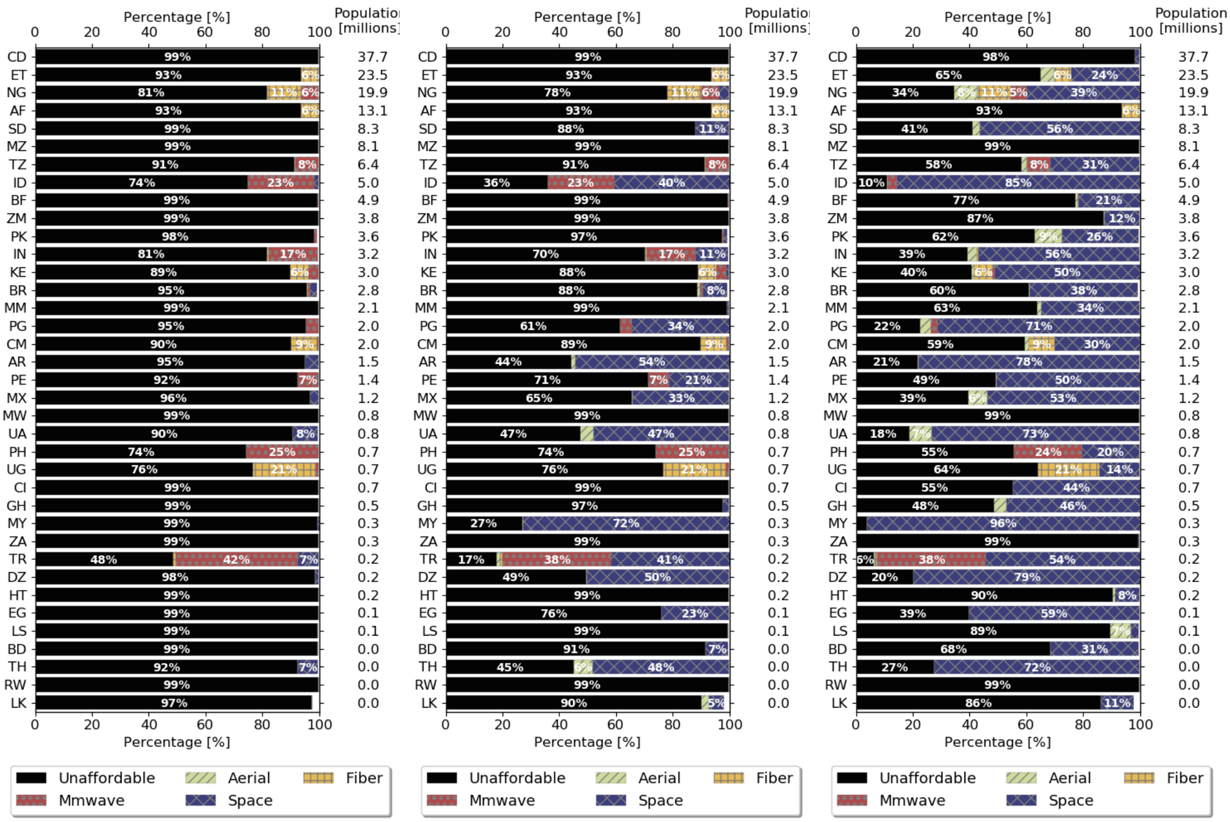
Figure 10: Overall percentage of uncovered and under-served population that **will become users** of connectivity services for the 37 countries considered, broken down by most affordable technology, under the a) current, b) next-generation, and c) future scenarios.

- For the current scenario, the difference between the population that can afford connectivity services and the number of users brought online is very small. This can be explained by the observation that most of the affordable deployments are fiber and mm-Wave deployments, which are effective to cover large settlements, not capacity limited, and capable of offering low prices per user which ensures high market uptake.
- For the next-generation scenario, it was estimated that up to 19% of those uncovered and under-served could afford connectivity services (Figure 9b); however, given the capacity constraints and the market adoption model considered, only half of them are estimated to actually become Internet users, bringing the aggregated potential impact of all the technologies considered in this paper down to just over 11% of the total population of these countries.
- For the future scenario, the greatest differences can be observed. Given the ever-lower satellite connectivity prices and the ubiquity of service, it was estimated that over 56% of the population on the countries studied could afford connectivity. However, after taking into account the market uptake estimates and limited satellite capacity, this value decreases to 32%.

Figure 11 shows detailed estimates for the amount of users that would be brought online at the country-level. Comparing this image to Figure 8, several characteristic behaviors can be observed.

- Countries with relatively small uncovered and under-served populations and relatively high incomes, such as Indonesia, Turkey, Ukraine, Argentina, Algiers, and Thailand, present the smallest differences between the population that can afford connectivity services and users brought online. This is because the high incomes result in higher market uptake and the smaller populations do not saturate the satellite capacity.

- Sub-Saharan countries with large uncovered and under-served populations, such as Nigeria, Ethiopia, and Tanzania, suffer the largest losses in terms of users actually brought online. The reasons for this are a combination of low GNI per capita (which translates into low market uptake) and saturation of the satellite capacity (especially in Ethiopia and Nigeria).



(a) Current

(b) Next generation(2-5 years)

(c) Future (8-10 years)

Figure 11: Uncovered and under-served users brought online for each country broken down by most affordable technology, under the a) current, b) next-generation, and c) future scenarios. Countries are ordered by the total uncovered and under-served population, in descending order.

Figure 12 shows the uncovered and under-served population that can afford satellite connectivity vs. price per Mbps/month for the 37 countries studied. Given that current prices for the satellite backhaul and broadband markets are ~$200 per Mbps/month, it is estimated that up to 6 million uncovered and under-served people within the 37 countries of interest (~5% of the total uncovered and under-served population of those countries) could afford satellite backhauled connectivity. Moreover, if prices go down in the next 2-5 years to $80-$120 per Mbps/month, the number of people that would be able to afford satellite connectivity would increase to 17 million. Finally, the future generation will enable prices to go even further down to $30-$40 per Mbps/month, making satellite connectivity affordable for 60 million in the 37 countries. This graph shows the high elasticity of demand and how satellite technology advancements are bringing down prices to the point where it becomes a viable option for a large percentage of those uncovered and under-served.

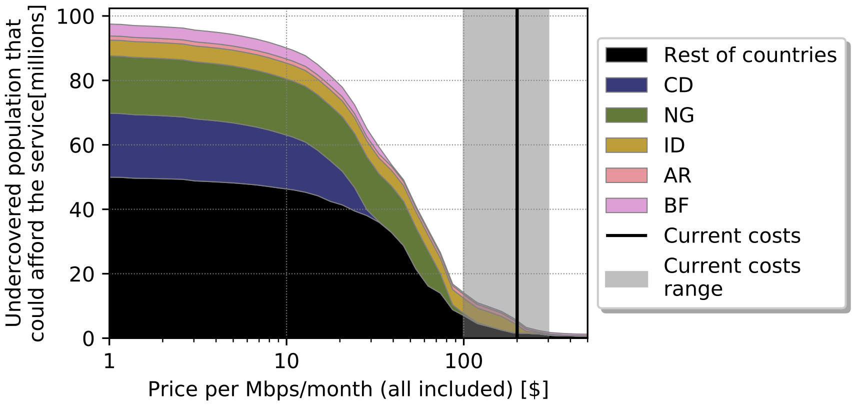


Figure 12: Uncovered and under-served population that can afford satellite connectivity vs. price per Mbps/month. Results only consider the 37 countries analyzed (see Table 5). The price per Mbps/month includes the service fee, rental of equipment, and taxes. The vertical axis represents the uncovered population that could afford the service at the given price per Mbps/month, assuming that a basic 1GB/month service is to be provided. (as described in Section 4.1)

The barriers to connectivity for those uncovered and under-served are mostly economic barriers, not technology barriers. Monthly reductions in cost per Mbps alone would greatly increase the population connected within the next 10 years. Because it is projected that space systems will contribute the greatest to increasing connectivity, these cost reductions would require no added infrastructure. Additionally, given their wide area coverage, space systems can offer services to not only unconnected and under-served customers, but also those already covered. The analysis in this paper does not take into account these paybacks, therefore we only represent the business case for the market of these 37 countries. The demand from already-covered regions can be used to cover the initial fixed costs of new constellations, effectively subsidizing service costs for uncovered and under-served regions given that the marginal cost of providing service once the satellites are in orbit is extremely low.

6. Conclusions

This paper assessed the potential impact of space, aerial, and terrestrial technologies in bringing uncovered and under-served populations online through a comparative analysis in 37 countries. We develop a techno-economic methodology to assess the potential impact of space and aerial concepts in expanding connectivity to uncovered and under-served regions. The methodology provides a systematic procedure to evaluate, analyze, and compare concepts that operate at different spatial and temporal scales (e.g., a GEO satellite with a 15-year lifetime vs. a network of stratospheric LTA balloons with an endurance of a few months), a problem not addressed before within the literature. With regard to the comparative analysis, the results showed that space systems represented the concept with the highest future potential to bring uncovered and under-served populations online.

Under the current scenario, the impact of space and aerial systems in terms of expanding connectivity would be rather modest; the current cost of satellite technology (~ \$200 per Mbps/month) is affordable for less than 1% of the uncovered and under-served population in the countries of interest. In contrast, it is estimated that fiber optic and mm-Wave deployments could bring online 7% of the uncovered and under-served population. Looking at the next 2-5 years, after large LEO constellations and very high-throughput satellites (VHTS) GEO and MEO satellites are launched, the impact of space and aerial systems might still be limited; aerial concepts would remain too expensive, and space systems would only have an impact in moderate-income countries in South America and Southeast Asia, where around 8 million people (~5% of the uncovered and under-served population in the countries studied) would connect to the Internet by satellite backhauled services. Finally, in the future scenario (8-10 years), where satellite connectivity prices are expected to drop to the \$30-\$50 per Mbps/month range, satellite networks would be a viable technology for up to 38.4 million people (24%) in the 37 studied countries.

Overcoming barriers to connectivity will required of both technical and political actions. With decreasing service costs over time along with the possibility for a government or firm to underwrite the costs of services, cheaper access would increase demand by increasing relevance and readiness. Based on the results, two groups of policy measures to extend connectivity to uncovered and under-served regions were identified. On one hand, for mid-income countries where space and aerial technologies will become affordable in the 8-10 years time-frame, governments should focus on incentivizing competition and removing barriers of access through the simplification of regulation. On the other hand, for low-income countries where reductions in price driven by technological progress will not be enough to ensure a viable business case, policy in the form of state-run services, private-public partnerships, subsidies, lower taxes, or mandatory-coverage regulation will be necessary.

The analysis in this paper has focused on studying the impact of space and aerial concepts in reducing the *coverage gap* (i.e., providing connectivity in areas where it is currently not available). However, the majority of the offline population (72%) resides in places where broadband *is* currently available (the *usage gap*), and thus it can be concluded that readiness, relevance, and (perhaps most importantly) affordability barriers are preventing a significant portion of the population from becoming active Internet users. Beyond looking to socio-political measures, a study to understand how space and aerial concepts might benefit these communities could prove to be an important area for future research. Our analysis has shown that satellites, while limited in capacity, can achieve lower monthly costs per Mbps than terrestrial systems in low- and medium-density regions if new infrastructure has to be built. However, it is unclear if this result would hold in regions where existing infrastructure is already in place, and if so, what potential impact these architectures might have in high-density areas.

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