The current state and the future of Space Internet - the Space Generation Perspective

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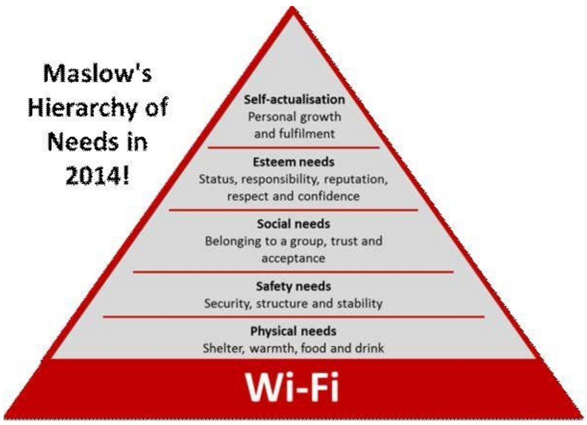
Abstract

During the Space Generation Congress 2015, held in Jerusalem, Israel, students and young professionals representing 14 countries participated in the *Space Communication - Space Internet* working group. The group investigated the possibilities, risks, and opportunities of using satellites, drones, and high altitude balloons to provide widespread access to the internet. The group focused on one of the barriers for worldwide connectivity - the lack of economic viability of providing internet access using land infrastructure, and the possible solutions that will address this problem. As a result of these findings, the working group participants proposed several recommendations. These recommendations take into account the numerous challenges that come with developing air and space-based internet access; whether it be via balloons, drones, satellites or a combination of these. These challenges range from acquiring regulatory approval to technical and practical limitations, such as the potential for damage to property and issues related to orbital debris. Due to our group's consensus that worldwide internet availability would ultimately be beneficial, given both humanitarian and economic concerns for poor and wealthy nations alike, we propose four "game changing" ideas that have the potential to positively impact the space economy. We first suggest that market studies be conducted to illustrate demand for the service. With sufficient demand, a phased approach to the solution should then be instituted. We further propose that national governments serve as anchor tenants and expedite regulatory processes. Finally, to ensure commercial sustainability, Internet Service Providers (ISPs) should be considered as potential distribution partners for the system. Our paper deals with the current status and the future of space-based internet services and details our recommendations.

Keywords: space internet, space communications, internet providers, Space Generation Advisory Council, Space Generation Congress

1. Introduction

In the last decade, the internet has become an integral part of daily life in the developed world. The internet is used for a plethora of different purposes in many aspects of life. It connects people, aids in navigation and orientation, allows access to updated information about various subjects, and serves as an efficient way to receive services from businesses and the government. Many people in first world countries refer to the internet as a basic commodity like electricity or running water, with its sudden rise to this level mirrored in popular culture, such as the meme shown in Figure 1. This, however, can apply only to 39% of the world's population which, according to [1], have internet access. As many as four billion people are left without access to the internet, and without the ability to enjoy its benefits.



Fi1. A common viral meme showing WiFi as the basic need in life. Source: [2]

Providing internet access to these four billion people is a major opportunity to improve their lives, and in recent years, several companies have attempted to provide internet services. In wealthy countries and high density areas around the world, this is fulfilled using fiber optic cables that enable high speed internet connection, but this “traditional” approach is neither feasible nor economical in countries where the population is spread sparsely. In the past few years, several companies eyed the opportunity to offer “sky-fi” (internet access from the sky or space). Such companies offer potential technological ideas to supply global access to the internet. These possible solutions provide challenges to the current laws and regulations that exist among nations. Little regulation has been introduced to cater for these new technologies.

The UN-backed Space Generation Advisory Council organized its annual Space Generation Congress (SGC) in 2015 for students and young professionals between age of 18 and 35. At SGC 2015 in Jerusalem, the communications working group investigated the possibilities and risks of using satellites, drones, and high altitude balloons to provide widespread access to the internet. This paper serves to present those findings. We begin by reviewing the possible technologies and current companies that seek to provide “sky-fi”. We then describe our working process and its results. Finally, we conclude by providing our main insights and recommendations.

2. Historical overview

The primary technology for providing internet access today is based on fiber optical communication. Cables are spread worldwide to connect continents and countries and to provide high-bandwidth access to the internet. Figure 2 shows the extent of deep-sea cables connecting the world today. The two main exceptions are local Wi-Fi networks, cellular connections and satellite communications. In all three cases, the internet is supplied in a small region by a local broadcasting router, gateway or antenna, which is eventually connected to the global network with the aforementioned cables.

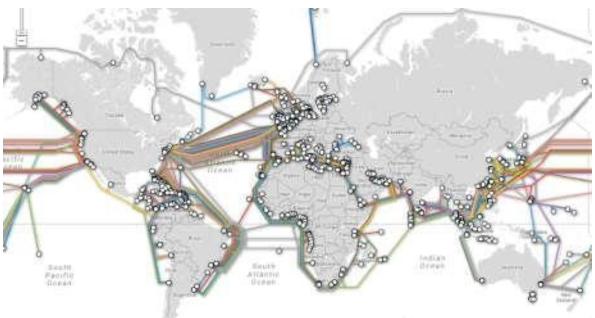


Fig. 2: Submarine cables connecting continents and countries. Source: [3]

This architecture is not feasible in many countries and the requirement to build new infrastructure is one of the barriers to internet access [4].

Such a barrier is further compounded by the sheer expense of connecting populations widely distributed over large areas. Connecting remote villages with landlines would increase the costs of internet access to consumers to the point of not being economically viable. Moreover, in some countries the national infrastructure is underdeveloped, lacking the bandwidth to fulfill the demand. Furthermore, in some cases the adjacent infrastructure - such as electricity - is absent, or of poor quality, representing a severe barrier to providing any internet service.

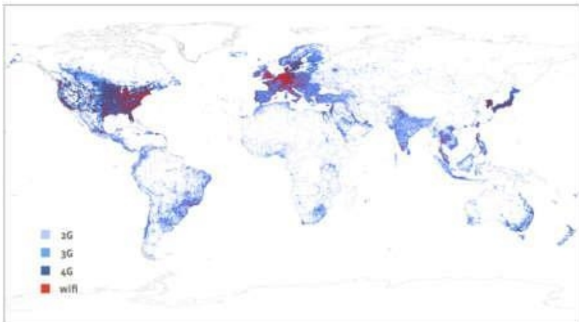


Fig. 3: Current world-wide internet access. Source: [5]

The idea of providing global internet coverage to the disconnected population has been discussed in academia and by commercial companies. For example, in 2013 an idea was published [6] to provide sustainable and affordable internet access using microsatellites for the Brazilian Amazon region. Recently, many companies have begun to experiment with their own ideas on how to introduce global internet coverage including Google’s Project Loon, Facebook, SpaceX and OneWeb. We focus on possible sky-fi alternatives to provide internet access using these approaches.

The most popular technology for space communication is radio frequency (RF) communication. This technology has been the “workhorse” of satellite communications since Sputnik 1, and all current satellites use RF communication to transmit and receive data. RF technology has existed for nearly 100 years, is very reliable, and is also cheap, owing to the numerous companies offering such products for sale. It is not uncommon to see RF dishes outside private homes used to receive television transmission signals.

RF beams can be wide, which means that an accurate pointing algorithm is not always needed to create a link between two terminals. This will also depend on the system used; for example if the link is provided by a Geostationary satellite or if the link is provided by a moving LEO satellite. A moving terminal, onboard a ship or an airplane must still use tracking antennas. Power density at the target is low; however, and this limits the data throughput. Additionally, the radio frequencies are in the order of tens of Giga-Hertz, limiting the modulation speed of the carrier wave and the bandwidth achieved.

The new emerging technology for space communication is laser communication (lasercomm). Laser beams are very narrow and have a carrier wave of the order of Tera-Hertz, which means that the power density on the target is much higher and the data can be modulated very quickly, in the same manner it is done in fiber. The narrow beam is a great advantage of lasercomm. However, a substantial obstacle to overcome is pointing accuracy. A very accurate pointing mechanism should be developed in order to hit the receiver "antenna".

Visibility issues also negatively affect lasercomm. Clouds and rain can block laser beams, so terrestrial applications might suffer some limitations. Lasers should therefore only be used to connect platforms that fly above clouds. In fact, lasercomm is already incorporated in several future projects for inter-satellite communication such as the European Data Relay System (EDRS), which is shown in Figure 4. The system ideally should consist of several communication satellites that will transmit data to Earth using an RF signal, but relay the data from satellite to satellite using lasers, which will save power, time, and provide significant bandwidth.

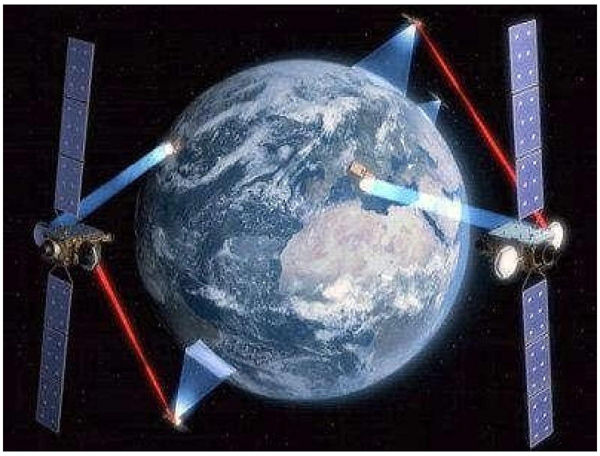


Fig. 4: EDRS - artist concept. The inter-satellite comms. is based on lasers. Image from ESA.

3. Balloons

Google's project "Loon" is designed to provide worldwide internet coverage using a fleet of stratospheric balloons [7]. Each balloon will float in the stratosphere and provide internet access to the population in a large area below it. The balloons are mobile, and will drift with the stratospheric winds across the globe. Figure 5 illustrates the provision of bandwidth via this method. Stratospheric winds are well-studied, and their velocities and directions, which alter with altitude, are well known. It is possible to control the location of the balloon simply by varying its altitude. A control center would be able to monitor the locations of all balloons, ensuring that damaged balloons are replaced, and that no area is left without coverage. In June 2013, the first test of the balloons took place in New Zealand. Thirty balloons were launched, which provided internet access to testers. Currently, tests are conducted in open areas, with the aim of providing uninterrupted connectivity for distinct regions, before operating on a global scale. Google has recently announced that it intends to launch 300 balloons in collaboration with three of Indonesia's mobile providers in 2016 [8].

Fig. 5: Illustration of the solution concept of project "Loon". Source: [7].

4. Drones

The drones proposed by Facebook would be powered electrically, and use solar panels to stay in the air for long periods. Figure 6 displays this concept, which removes the need for landing, refueling or the logistics needed to provide fuel to all the aircrafts.

Drones can fly close enough to the ground to maximize signal strength but high enough so that wind and obstacles will not compromise the endurance of the mission.

Fig.6. Facebook's drone. Source: [5]

In addition, [5] mentions the fact that drones can be precisely controlled and are re-usable in the sense that they can land to be upgraded or fixed, if needed (unlike satellites).

This solution is fine for high population density areas but would become expensive for low population density areas, since a drone has a small footprint and many drones would be needed to cover large areas; without enough customers it would be expensive. As a complementary solution for this problem, [5] proposes using satellites for low-density areas. The satellites would naturally have lower signal strength and smaller bandwidth but still provide the required coverage, as illustrated in Figure 7.

Recently Facebook partnered with Eutelsat to lease the Ka transponder of AMOS-6 to connect disconnected African regions to the internet [9]. AMOS-6, however, was in the failed launchpad test in September 2016.

As a complement to the hardware, Zuckerberg [5] launched internet.org - an initiative to create an internet portal that will be more efficient and require less data, allowing connectivity even under narrow bandwidth conditions.

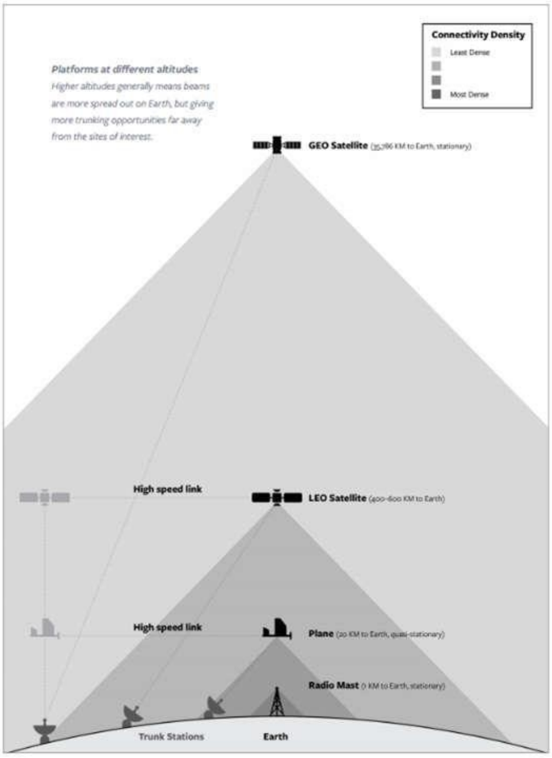


Fig. 7: A comparison of the area covered and the signal strength for different platforms. Source: [5]

5. Satellites

Both SpaceX and OneWeb are working towards a solution that is based on satellites, with some difference in the details.

Using geostationary satellites to provide truly global internet access is problematic due to some technical and physical challenges. Latency is significant, there will be no coverage in the polar areas. At 36,000 km altitude, it takes the information about 200 milliseconds to be transmitted from the user to the server, which can accumulate to almost 500 milliseconds of delay between the request and the response. This issue is a physical limitation, which cannot be solved technologically; thus, both companies decided to use low Earth orbit satellites. These satellites offer much lower latency and stronger signal. However, they are moving with respect to the ground, and one specific satellite will only be visible for an observer for a limited time before it sets behind the horizon. To provide continuous coverage, a constellation of satellites is needed. The number of satellites needed is varying depending on the system design - 700 according to OneWeb and 4000 according to SpaceX [10].

Launching constellations this big is expensive and raises some issues to address - such as interference (see [11] for example), controlling the constellation, avoiding debris and avoiding becoming space junk, as well as maintaining the constellation and replace/replenish satellites.

6. New types of network approach

6.1 Discrete Morse theory

Modern communication satellites operate essentially by having an originating signal, dubbed the source, transmitted to the satellite. This signal can then be transmitted to another ground source in a different location, hereby dubbed the receiver. The receiver may send a response, which will be sent to the satellite, and eventually back to the source. In this manner, the source and the receiver can communicate with each other.

Admittedly, this basic idea behind satellite communications surprisingly simple, yet major difficulties arise when this idea is put into practice. Satellites are unable to transmit signals unless they can clearly view their target on the ground [12]. Anything that blocks this clear view can adversely affect satellite communications, and this can include the weather at some frequencies. Rain, snow, cloud cover, and temperature can all affect the signal. The weather creates even greater problems as the frequency increases, which is inevitable in the future as more and more satellites are sent into orbit and frequency band allocation climbs to even higher frequencies [13][14]. Thus, if the source sends a signal to a satellite, the source inevitably will eventually encounter network latency, whereby the signal must wait a time until it can be sent to the receiver. This latency issue can be compounded if the satellite is responsible for sending multiple signals at a given time, each experiencing a delay. It would be ideal to be able to know when and where to send data to have it transverse the most economical and clear path.

The other major problem with modern internet networks is the amount of data being sent through them, and this is increasing steadily every day. Much of this data is not needed, and is not required to be retained for the network to run correctly. Even in security situations, it would be better to store only the necessary information needed, and filter out the rest to keep the information manageable. How is this possible? After all, humans are far too slow to process the growing amount of information in a manner that would be effective for this sort of work. How do we tell what is significant and what is not? The answer to all of these issues seems to lie in the study of higher order mathematics, notably applied topology. Together these methods have the potential to help solve many of our current network issues, and perhaps hold the key to designing new and more efficient communications systems.

Geometrical analysis usually begins by first defining a metric. Since the velocity of a satellite in orbit depends only on the altitude, defining a metric does not pose a major issue to satellites in geostationary orbits, as they appear fixed ground positions on earth. Communication satellites; however, are not all launched in geostationary orbits, so they will move with respect to the ground, as well as each other, which motivates a topological perspective.

All addressing schemes are topological in nature, and yet no topological distinguishability exists between nodes in the space network. This begs the question as to what is the most efficient method to send data between them. In topology, the notion of distance is replaced by the concept of nearness. It is a generalized method for describing the geometric properties and relations of a space that are preserved following a continuous transformation. This generalized concept provides the starting point for some remarkable results concerning our understanding of spaces.

If an individual transverses a terrain with hills and valleys, he/she would notice that the terrain has three types of critical points. The first are the summits of the hills, the local maxima. The second are the valleys, the local minima. The third are the areas in which there is an increase in elevation in one direction, and a decrease in the other. These are the saddle points. Suppose we had a smooth function with non-degenerate critical points f that exists on the terrain. If our function f exists on a smooth manifold M, which is a topological space that resembles Euclidean space locally (our terrain), Morse theory allows us to determine the global topology of M via the critical points of f. Information gathered about the critical points can be used to construct a cell complex having the same homotopy type of M, as well as allowing for the construction of a chain complex to compute M's homology [15]. This allows us to understand and analyze the topology of the manifold.

Knowing the homotopy type could enable us to transform the topology of a particular space into a topologically equivalent space, which may be simpler to study. Homology, rather, is algebraic structure that essentially provides information on the topology of a space, such as the number of distinct pieces that form the space [16]. Since it is much easier to define algebraic constants than to compute them [17]; however, we rarely have computability. When we look at the satellite structure throughout space; however, we do not see a hilly terrain. Taking a snapshot of the position of space satellites at any one point and time, we see a set of data points in some space, rather a point cloud. Upon a point cloud, we can define a simplicial complex, but we are left with the issue of trying to analyze the topology of the simplicial complex. In this area, discretized version of Morse theory offers some much needed assistance.

Discrete Morse theory is a combinatorial adaptation of Morse theory that works on simplicial complexes (noting the theory works on the more general CW-complex as well) [15,18]. Discrete Morse theory performs two actions on a complex that are important for our purposes. It simplifies data on the Morse-Smale complex, which we build on our point cloud data. It also picks out features and structure from the data, which could be hidden from view.

Fig.8. Eiffel Tower, Courtesy of the Wikimedia Foundation

To explain, we will borrowing an idea for an example from Schmuel Weinberger [19] by examining a painting of the Eiffel Tower by Seurat (see Figure 8).

Seurat's painting is composed of small flecks of paint, not smooth brushstrokes. We can think of his painting as similar to a point cloud dataset in that each fleck of paint is a data element in the painting. Now in the case of visual data, the human eye is very good at picking out visual patterns. For humans, it is clear that these flecks are organized to create the image of France's Eiffel Tower. In this case, we are able to extract the overall structure from essentially paint fleck data. The other paint flecks that are not needed to identify the overall image of the Eiffel Tower could be essentially filtered out from the painting without removing the major topologically significant structure. Discrete Morse theory has the potential to accomplish a similar effect on point cloud data, which is often too complicated for humans to directly extract structure and features from the data. Knowledge of topological structure of space satellites could lead to the creation of a new addressing scheme for networks.

6.2 Topological data analysis

It is important to note that discrete Morse theory is one of many other topological theories that have the ability to help create new and improved networks. Persistent homology is another concept that could aid in the study of such spaces. When constructing a simplex, how do we determine which points to connect to form a simplex? If we choose an arbitrary distance d, we run the risk of either connecting too little or connecting too much, which can have a major effect on the topology. Alternatively, we can vary d over our entire data set. As d varies, new homology classes can be born or die. This idea is related to Morse theory in that every critical point of a Morse function indicates the birth or death of a homology class [18]. Features that are detected over a wider range of distances (they persist) are more likely to represent the underlying topological features of the data.

This area, generally known as topological data analysis, has the potential to be applied to both the structure of the space network, and the data traveling through it. To date, these methods have been very successful. Time will tell if the same holds true as topology is applied to the study of space communications.

6.3 Quantum satellite networks

The quantum communication is based on the laws of quantum mechanics, and utilizes different quantum-based algorithms and protocols [20]. Comparing with classical algorithms, which are used in classical computation, the advantages of quantum algorithms are the speed, the factorization and encryption. The base unit of the quantum computing is the quantum bit (qubit), which can be represented by different polarization states of a photon. The state of a classical bit can be represented by only one of the 0 and 1 values, but the qubit can be an in arbitrary superposition of 0 and 1.

The quantum-based satellite communications offers revolutionary solutions for the near future including secure, encrypted communication. Due to the nature of the quantum mechanics, passive attack is not possible, the only types of attack is the active one. If an active eavesdropper approaches, a noise will appear in the communication channel, which makes possible for the communication parties to learn about the presence of an eavesdropper.

There are two groups of the currently used quantum key distribution (QKD) solutions [21]. The first generation protocols use singe-photon sources, while coherent laser is used and the wave properties of light is exploited in the second-generation protocols. This first approach is named as Discrete Variable QKD (DV-QKD), the second one is named as Continuous Variable QKD (CV-QKD).

For satellite-based quantum communication, we distinguished three types of communication links: satellite–satellite, satellite–ground, ground–satellite. A complex, satellite-based network could enable a global quantum key exchange service [22]. Due to the nature of quantum-based protocols, the noise of the channels need to be estimated since the errors introduced by an eavesdropper could be masked by the natural noise of the channel. Currently, several research groups are investigating the potential benefits of the quantum-based satellite communication. In Aug 2016, China's (and the world's) first quantum communication satellite was launched [23].

7. Results of our working group

The working group started with a discussion about the issues involved with this topic and an overview of the mandatory background reading. The team agreed to try a simulation of several companies pitching different sky-fi technologies to a government, so that the main challenges and opportunities of each technology would emerge. The team split into four sub-working-groups, with three representing industry: satellites, balloons, drones, and one representing government interests. Each sub-working-group performed a Strengths, Weaknesses, Opportunities and Threats (SWOT) analysis, which was then presented to the full group. The nature of each of the technologies was apparent without need for the simulation and so the merits of each in several scenarios (i.e., disaster, regional areas, sparsely populated areas, and so on) were discussed instead. In this way, common challenges and opportunities were brought to light and then debated.

The results of the working group have been detailed according to the sub-groups that were formed.

7.1. Balloons

Balloons are a cheap option. There is potential for balloons to cover a wide area at a lower cost than drones and to be available with a shorter lead-time than satellites. Balloons can be deployed in a variety of locations, although they do require fortuitous wind conditions to fly over the desired location. Less infrastructure would be required than for drones, without the need for airports and maintenance facilities. Wind can be a limiting factor on the way that balloons can fly at certain latitudes, although Google Loon is forging ahead with plans to fly across some countries and latitudes, using fleet control algorithms.

7.2. Drones

These have high bandwidth due to altitude. They are also highly maintainable and have possibility for upgrade. Perhaps one of the greatest potential uses of drone technology is for post-disaster internet, where drones can be launched quickly and then directed to fly over affected areas on short notice.

The lower altitude also results in low coverage, and it is the most expensive option by unit coverage, because of ongoing operational costs. Operational efficiencies (e.g., artificial intelligence) are still some time away.

7.3. Satellites (LEO)

These is the truly global option. They can cover the whole of planet Earth all the time, depending on the type of constellation in place. Satellites have benefits in terms of smaller delay times, as the satellite-to-satellite and satellite-to- ground data transfer paths are straight and have few nodes. The paths are also topologically distinguishable, making it easier to predict locations and then calculate efficient data paths.

The bandwidth would be smaller, due to the distance of the spacecraft from the user. The capital costs of this system would be the highest of the options, due to launch and spacecraft construction costs.

7.4. Government

The first thing that we discovered about governments is that their needs and wants might not always be compatible with global internet coverage. The choice of service from a particular internet enabler could depend on topography, population distribution or latitude - as just a few examples of constraints that a government could consider.

Areas where a government could assist internet access providers without necessarily injecting money into the venture would be to assist with country-oriented constraints. This refers to regulations and international obligations that could make business investment unattractive if not addressed, such as applications for satellite frequency bandwidth. There are also restrictive regulations that make balloon and drone flights difficult, if not illegal, over certain regions of the planet. A final government role could be as an anchor tenant, where an agreement is made early to purchase wifi or to subsidise with tax concessions.

Governments would have a further role in limiting danger to consumers and citizens. This includes minimising risk of damage to property and injury to people through any mode of sky-fi delivery. Governments might also have an interest in the security in the system and danger of hacking and invasion of privacy.

7.5. Common opportunity

A further finding concerns the potential for different modes to be used by one or more companies to scale global connectivity. This would move over time from the cheaper and more readily available options such as drones and balloons, to the satellite option, which would not only allow for iterative improvement of sky-fi systems, but also allow for satellites to be placed in orbit iteratively and enable coverage fillers in case of satellite failure.

8. Recommendations and conclusions

The working group proposes a number of recommendations. These recommendations take into account the numerous challenges that come with developing Sky-Fi whether it be via balloons, drones or satellites. The challenges range from regulatory to technical and practical limitations, such as the potential for damage to property and orbital debris issues. Below are the key recommendations that were established as part of the working group:

(1) Conduct market studies to illustrate demand.

A number of companies are trying to push forward with their plans for wider and cheaper internet coverage for the less connected parts of the world. One significant issue identified was whether or not these remote or disconnected regions can even afford internet. There are more pressing issues such as lack of clean water and electricity, and malnutrition. The question here is how such a system can cater for these markets when such basic needs are not being met. The first step towards understanding this problem would be to carry out market studies to identify what the potential take up rate and willingness to pay levels would be, were such systems to be in place. Without understanding the market need there is high risk of failure for such endeavours.

(2) Institute a phased approach. Instead of building a full system with all the development carried out in one big chunk, it is recommended that any proposed system be scaled up slowly with consideration for both the changing market conditions and any issues relating to the system in question, such as regulatory filing and property damage issues. Scaling up helps reduce impact of failure by ensuring the system is delivered in incremental steps, where each step has taken into account lessons learned from previous versions - similar to the iterative design process of programming. For example, the system could focus on one specific region before expanding to cover other areas.

(3) Let governments serve as anchor tenants and expedite regulatory processes. This will help ensure resolution of any legal hurdles, while the government assists in the development of the system, especially in rural areas where distribution partners are hard to come by. Having local and regional governments assist and be part of the process can ensure smoother transition to commercial operations. Risks surrounding regulatory filings, market access, and other fundamental barriers to entry can be mitigated with the help of the target markets' governments.

(4) Provide future connectivity to Internet Service Providers to ensure commercial sustainability. Once government service has been established and the reliability of the system has been confirmed, the service can be deployed to commercial internet service providers to diversify and improve revenue streams, while catering for a wider population through increased service subscriptions.

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