Broadband Connectivity in Rural and Remote Canada Present (2021) and Future (2030s)

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I. Introduction

The COVID 19 pandemic has brought many challenges for current communication technologies. In countries like Canada and US, a large amount of population live in rural and remote areas, it becomes harder for them to have the same life with those people in urban areas because of the difficulty in having broadband. This unequal of broadband accessibility between urban and R&R areas has broadened the digital divide [1] during the pandemic. As a result, several possible solutions for this phenomenon have been proposed, such as fiber optics, fixed wireless and satellite access internet. Satellite network plays a key rule in next generation communication technologies, it also provides a flexible alternative for fiber optics. Relocating fiber optics seems impossible because of the cost, a reasonable solution is abandon it. But for satellite access broadband, what users need is just two units (outdoor unit and indoor unit) and line of sight. In this report, we first investigate R&R connectivity in Canada and also other countries, discuss possible solutions. Then we survey the current satellite technologies. At last, futuristic technologies are discussed.

II. R&R Connectivity in Canada

A. Definitions

Rural and remote: According to [2], all the area that is non-population center is defined as rural area. The definition of rural areas by Statistics Canada is used for census, to be specific, the population density of rural area is below 400 person per square kilometer. Fig. 1 shows how rural area and population center are distributed.

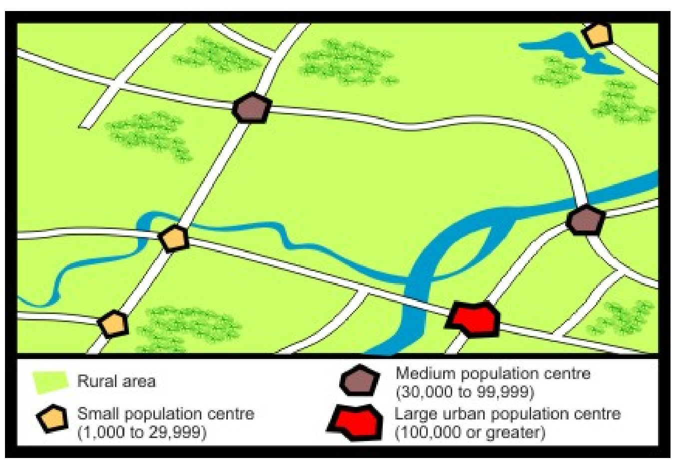

Figure 1: A demonstration of rural area and population center [3]

The definition of 'remote' is published by Canada government in 2009 in respond to H1N1 outbreak, which is borrowed from Health Canada [4] [5]. A geographical area where a first nation community is located is called remote if the nearest service with year-around road access is located at least 350 km away.

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Broadband connectivity: Term ”broadband” originated from physics and radio systems engineering [6], it was first used to describe data transmission with wide bandwidth over medias like coaxial cable, optical fiber or radio in the scenario of telecommunication. As the advent of internet, broadband was loosely used to indicate internet access faster than dialup access. Up till now, the speed of broadband has evolved from greater than 1.5 Mb/s to latest 50 Mbit/s downlink, 10 Mbit/s uplink (made by CRTC [7]).

B. R&R connectivity situation in Canada

According to the monitoring report conducted by CRTC in 2019 [8], the coverage of broadband (from now on, bradband means 50 Mbps downlink and 10 Mbps uplink unlimited data unless otherwise specified) national wide has shown growth, as shown in below table from the report

Availability of 50/10 Mbps with unlimited data	2018	2019
Canadian households	85.7%	87.4%
Rural households	40.8%	45.6%

Figure 2: Avilibility of broadband in Canada [8]

Unlimited broadband internet coverage is available to 45.6% of the population in rural areas, increased 4.8% from 40.8% in 2018. According to the report, this broadband internet covers 98.6% of the population in urban area, so the gap between them is still significant. From 2016 to 2019, internet services via FTTH (Fiber-to-the-home) had experienced dramatic increase, but they mostly happen in urban area, that didn't contribute to bringing connectivity to rural area. Besides, almost a quarter (26.7%) of rural population only rely on fixed wireless technology (LTE, WiMAX, etc.)

Territories in Canada experience much worse connectivity, in Yukon and Northwest Territories, only about sixty percent of households can have 25 Mbps and higher internet while in other provinces this figure is around 95%. The situation seems to be worse in Nunavut territory, people don't have access to 25 Mbps and higher internet. The situation seems to be worst for first nation communities, according to the figures, only 34.8% of the population in first nation reserves have broadband internet.

Regarding to internet service providers (ISP), we can see obvious difference of ISP number between provinces and territories. According to [9], only four cities in Nunavut has internet provider and it's all Bell, there are only one or two providers in each city of Yukon, they are Bell and Explorenet, near half of cities in Northwest Territory has internet service providers, Bell and SSi Micro. Areas in these territories are mostly rural area, while in southern provinces like Ontario, one city can have up to 33 internet providers. Dense population makes cost for infrastructure relatively cheap, and easier to profit.

C. Technologies used for R&R connectivity

In rural and remote areas, options for high speed internet are limited because of economic consideration, in this section we will talk about general options for internet access and their feasibility for R&R areas.

1) Dial-up internet access: Dial-up is an internet access technology from 1980s that uses PSTN (public switched telephone network) and modems to build connection to internet service providers, it has a limit speed of 56 kbit/s, but usually lower. Because it uses audible carrier (audible signal has frequency of acoustic signals, most telephone connections have frequencies between 300 Hz and 3300 Hz), bandwidth is limited, therefore data rate is also limited. Dial-up is obsolete technology, but according to [10], the Chawathil First Nation in B.C. province is still using dial-up to access internet, which is causing a lot of inconvenience to residents. However, it is their only choice and dial-up is reasonable based on existing infrastructure [11].

2) DSL : Digital subscriber line (DSL) is one of the broadband technologies in widest use. It transmits digital data over telephone lines, a DSL modem for a user connects with a DSLAM (digital subscriber line access multiplexer) with telephone line, one DSLAM usually connects many households in a community because it shouldn't be located too far away from users because of attenuation [12].

3) Optical fiber : Fiber-optic communication is the key enabler for broadband coverage, it has very high data rate because of the high bandwidth and allows transmission in a long distance but stays cost-efficient [13]. It has advantages over DSL for in long distance communication scenario due to low attenuation around 0.3 dB/km, state-of-the-art research for fiber-optic communication can have hundreds of Gbit per second per channel over hundreds of kilometers. Fiber optics seems to be promising for rural areas and Bell is already progressing in its project that connecting rural families and communities in Canada with fiber and WHI (wireless home internet). [14]

4) Satellite internet access : Broadband using satellite communication is becoming a more favorable choice nowadays. Common satellite internet service uses GEO (geostationary) satellite, working in K_u band (12-18 GHz), which usually suffers from high latency [15]. Newer generation of GEO satellite applies point beam to reuse spectrum resources and the opening up of K_a-band (26.5-40 GHz) improved the situation significantly. There are several on-going satellite constellations construction like Starlink, OneWeb and Kuiper of Amazon, they use LEO (low-earth-orbit) satellite, which can achieve lower latency and more promising to provide broadband for users. The Starlink is providing up to 150 Mb/s data rate and 20-40 ms latency, and this speed is estimated to double within a year [16]. A satellite communication link is usually composed of user terminal, satellite and Gateways. The dish antenna (or outdoor unit) of user end connects equipments like laptop and cell phones, antenna receives and transmits signal to satellite, satellites act as relay in the network and repeats the signal to ground Gateways without processing, then Gateways are connected to backbone internet, they transmit data to internet and user accesses internet eventually.

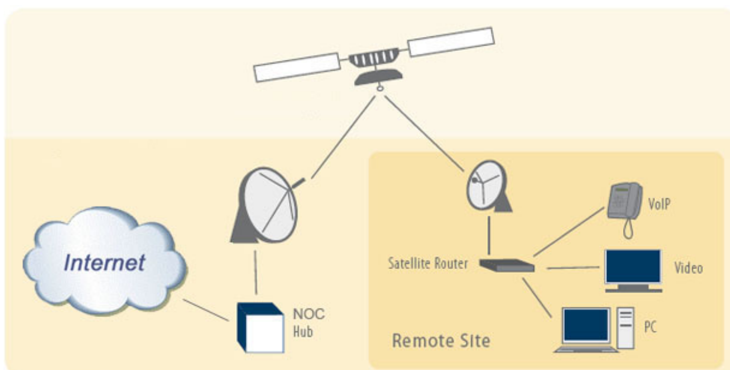

Figure 3: How satellite internet access works [17]

In the newer constellations like Starlink, satellites also work as routing points, satellites communicate with each other with FSO (free spcace optics) to form a network itself. Satellite internet access seems to be very promising, one satellite covers a large area on earth and data rate in these days is enough for the majority of basic applications. The monthly fee of Starlink compared to existing satellite internet service is acceptable, while performance of Starlink exceeds them completely.

5) Fixed cellular : Fixed wireless is a way to connect two fixed points or locations, it uses larger antennas (directional) at both transmitter and receiver to make sure the beam pointing at receiver is narrow enough to focus transmit power and provide higher spectral efficiency [18]. Fixed wireless technologies such as WiMAX demands a set of brand new infrastructures to deploy, which does not require fiber optics, making it impossible to develop. Though less popular than LTE, WiMAX is now cost efficient to provide internet access for rural areas, working as last-mile connection. [19]

Microwave inks are often used in TV broadcasting, it was developed in the WWII, now usually served as backhaul and backbone links, it serves rural areas without need for cable or fiber optics, also economically favorable. Licensed microwave links have little interference at its operation spectrum such as 2.4 GHz or 5.8 GHz, which guanantees its reliability. Point to point microwave is a replacement for fiber or cable when they are not feasible [21].

D. Risks and concerns

The technologies discussed above are technologies able to provide internet access to rural areas, but in order to provide broadband to those areas, they need detailed discussion.

Dial-up operates on infrastructures that deployed decades ago, this kind of facilities might still be available in some remote areas or communities, the capability of dial-up is so limited that broadband is defined as ”faster than

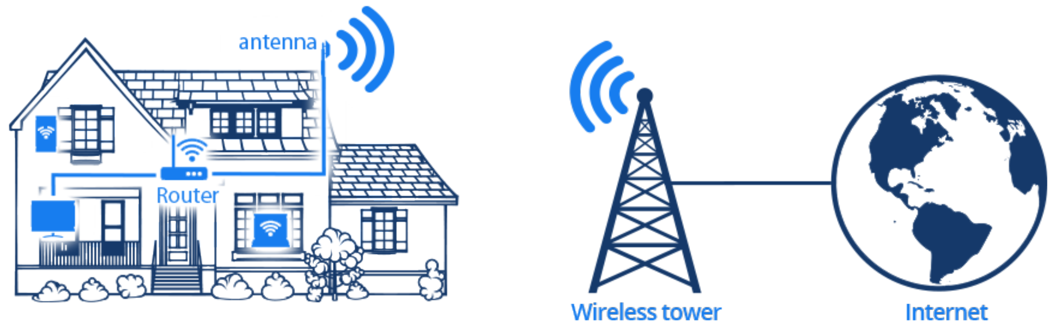

Figure 4: Typical architecture of broadband fixed wireless [20]

dial-up”. DSL is one of the common ways for broadband, but telephone lines suffer from serious attenuation and also prone to interference, it is often set up for a neighborhood using one DSLAM. In this case, in some areas where households locate far away with each other is not suitable for DSL.

Fiber optic is considered as one of the game changers in broadband connectivity, but fiber optics also suffers from several problems. One obvious problem is its fragility, the material makes it prone to damage. In order to connect rural and remote communities, hundreds of kilometers of fiber is needed to deploy over mountains and all kinds of terrains, having greater probability to damage. Another issue is cost, deploying a fiber optic network requires specialists and advanced equipments and therefore expensive. [22]

Satellite access internet has shown to be satisifying in performance as Starlink launching more satellites to the space. Because Starlink is using LEO satellite, it requires much more satellites than GEO satellite to form a permanent internet connection. Therefore, the cost is massive, and can bring down a company. Satellite communication links attenuate badly when there’s rain or snow on the path (called rain fade), this effects mainly K_a band and K_u band. [15] Therefore tropical users have satellite service operates on lower frequency band to compromise for a lower path loss. Satellite communication relies on LOS (light of sight), objectives can decay the signal or ruin the link, so if user is surrounded by obstacles, e.g., user in a forest, satellite access internet won’t be first choice.

Like satellite communication, fixed wireless also requires LOS access between transmitter and receiver, and environmental changes like rain or fog also decays the performance. According to Mitchell [23], service fees for fixed wireless is higher than other options like fiber. This technology is not spectral efficient and expensive to deploy, this can be an option when other methods are not available.

E. Barriers of broadband connectivity

In the above discussion, we have covered several possible options for R&R connectivity, basically these methods of communication are facing similiar problems. Connecting households in rural areas means signal needs to propagate a long distance, in order to overcome the pathlosss, we need to choose media properly. Metal media like cooper wire is common way to propagate signal, but also faces unacceptable pathloss and interference. Air is another common way to carry signals, but almost all the technologies use air as media like satellite communication and fixed wireless require LOS. A better way is through fiber optics, fiber has low pathloss and high bandwidth. But the barrier for deploying fiber is infrastructure, infrastructure like this is usually costing and requires policy from government. Another technology barrier is bandwidth, existing infrastructure like telephone lines support dial-up, but the speed can not even support basic applications like video calls. The low profit can also be an issue of looking for an internet provider, people living in rural and remote areas are usually financially challenged, then monthly fee cannot be too much that no one can afford. However, low-profit even non-profit makes it difficult to find service provider because maintaince also requires fund.

F. R&R connectivity situation in other countries

Russia has the biggest national territorial area among all countries in the world, with Siberia region one of the most sparsely populated region in the world. Broadband internet access is also an issue for Russian people. According to a report by the World Bank [24], Russia has the greatest digital divide in the aspect of broadband

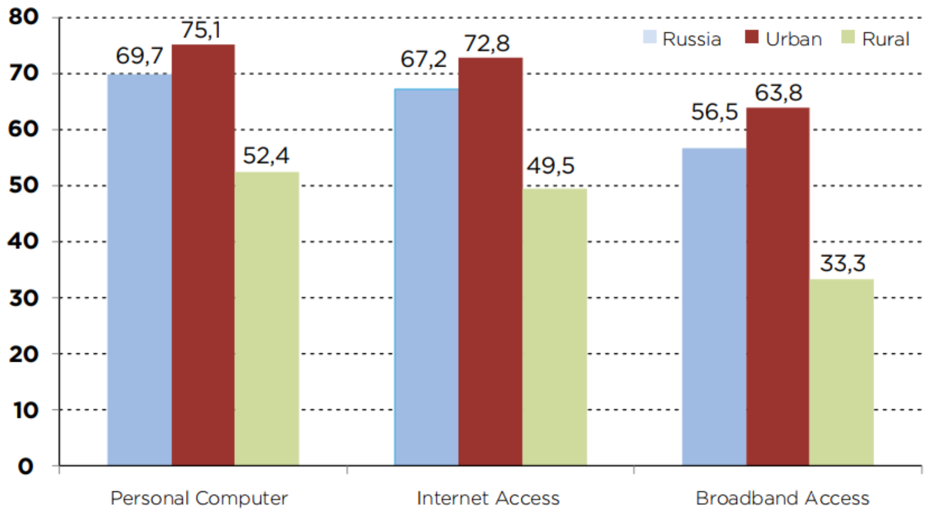

Figure 5: ICT use in Russian households in 2013 [24]

	2013		2014		2015		2016		2017	
	Pop.	%	Pop.	%	Pop.	%	Pop.	%	Pop.	%
United States	263.971	83.6%	284.246	89.4%	287.853	89.9%	296.373	91.9%	304.405	93.5%
Rural Areas	29.077	47.6%	37.174	60.3%	38.271	61.5%	42.677	67.8%	46.960	73.6%
Urban Areas	234.893	92.3%	247.072	96.4%	249.582	96.7%	253.695	97.7%	257.446	98.3%
Tribal Lands	1.449	37.1%	2.245	57.1%	2.290	57.8%	2.520	63.1%	2.727	67.9%
Pop. Evaluated	315.596		317.954		320.289		322.518		325.716	

Figure 6: Deployment (Millions) of Fixed Terrestrial 25 Mbps/3 Mbps Services [25]

penetration, the fixed broadband penetration rate gap between leading region and the worst region is 300 times. However, this gap is smaller when it comes to mobile broadband. In Fig. 5, we can see the biggest divide between urban and rural for Russian households appears in broadband connectivity, which is almost two times. In order to narrow the gap, Russian government's plan to connect rural areas is focusing on fiber optics, and for part of rural areas use satellite and mobile broadband.

Despite the fact that USA is the most developed country in the world, America has a large portion of population living in rural area. According to a report by FCC in 2019 [25], in 2013, 47.6% of Americans living in rural area have access to 25Mbps/3Mbps broadband, the figure for tribal lands is even lower, 37.1%. In 2017, 73.6% of people in rural area are covered with broadband, and the figure for tribal lands increased to 67.9%. The situation of mobile broadband with speed of 5Mbps/1Mbps is better, up to 2017, almost all Americans have access to this mobile broadband.

III. Current Satellite Systems

A. Constellations

A satellite constellation is defined as a system composed of a set of satellites providing global coverage (at least one satellite is available anywhere on Earth at any time) [26]. We can categorize constellations by its orbit altitude, there are constellations composed of repectively LEO (low Earth orbit), MEO (medium Earth orbit) and GEO (geosynchronous orbit) satellites. Famous constellations like the Global Positioning System (GPS) is MEO satellite constellation, and Starlink by SpaceX is a LEO satellite constellation.

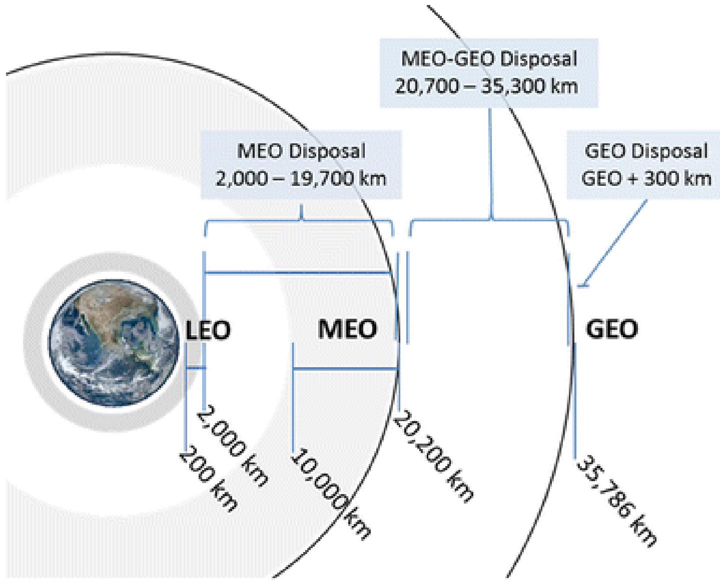

Figure 7: Altitude of different orbit configurations [27]

Traditional satelite constellations are composed of GEO satellites, first GEO satellite Syncom 3 was launched by NASA [28] in 1964 (the first LEO satellite and also the first artificial Earth satellite Sputnik was launched in 1957), but first GEO satellite for communication was Syncom 3. Geostationary satellites orbit at 22,236 miles (35786 km) above the Earth, satellite communication used to be mainly based on GEO satellites network because satellite is fixed relative to Earth [29], that is one property of Geostationary orbit. GEO satellites have a good coverage due to its distance from Earth, with three GEO satellites man can cover most of the Earth surface on which human activities happen. While the number of LEO and MEO satellites required to proide the same coverage is much bigger (SpaceX plans to launch and deploy 44000 LEO satellites to build its satellite network for internet service). As MEO and LEO satellites are moving relative to Earth all the time, continuous internet service or connection also requires more number of satellites in case of blockage by horizon. Furthermore, stationary satellites with respect to ground saves a lot of trouble tracking satellite. However, GEO satellites have unacceptable time delay for some real-time applications like video conferences and online gaming. We can simply divide the distance by speed of light and find out signal travels from ground to satellite and back requires 0.238 seconds, almost a quarter of one second. But this is not a problem for applications like television broadcasting and weather forecasting, and they are also very important applications achieved by GEO satellites.

Low Earth orbit refers to geocentric orbits with altitude below 2000 km, therefore communication through LEO satellites can have low latency, according to numerical computation, the latency will be 13 milliseconds at most. The advertised latency of Starlink is between 20 to 40ms, and promised to reduce to 20ms very soon. The short distance enables a possibility to chase for higher rate because of lower pathloss. Base on 20dB pathloss per decade in free space assumption, altitude of GEO satellite is about 18 times that of LEO satellite, so pathloss for LEO satellite is 25dB lower than GEO satellite. Because of the low altitude, deploying a LEO satellite is less expensive and demanding than GEO satellite, with the emerging technology miniaturizing communication satellites, cost of deploying satellite network decreased greatly, because one launcher can be shared by multiple satellites (highest number achieved is 143 satellites in one launch).

There are other famous LEO constellations such as Kepler, which aims at data backhauling, IOT business and remote connectivity. The company launched the first commercial LEO satellite operating in K_u-band, as the goal of the company is global data service, their micro satellites (based on CubeSat standard to deliver connectivity) have high bandwidth and high capacity allowing them to provide delay-tolerant massive data transfer service around the globe. Kepler recently achieved 38 Mbps downlink and 120 Mbps uplink in the Arctic with a 2.4m VSAT. Despite the high capacity, Kepler does not provide broadband service, its network is optimized for data storage and transfer. Software defined radio (SDR) is the enabler technology of Kepler to build a global IOT communication system able to adapt communication methods and protocols across regions, ease the global communication disparity. SDR provides flexibility to operators and users by replacing components implemented by hardware to software,

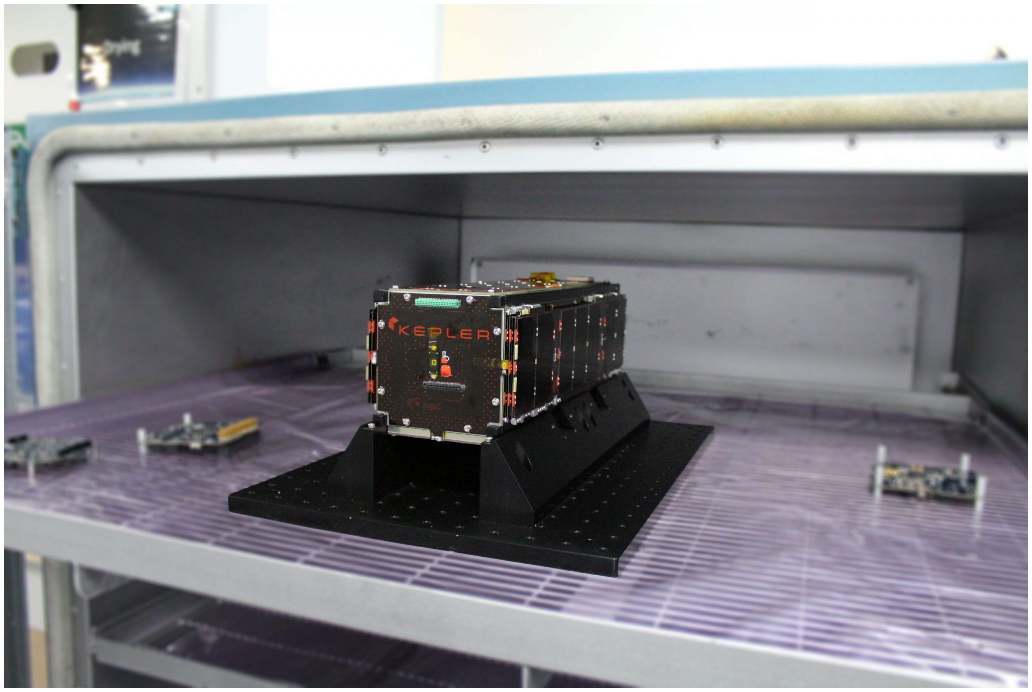

Figure 8: Nanosatellite of Kepler [30]

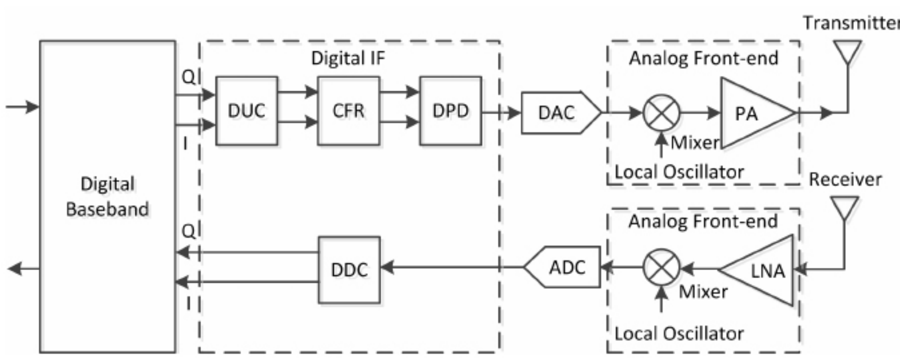

Figure 9: Block diagram of a general SDR (Software Defined Radio) [35]

such as filter and modulator, so that switching communication systems is simply done by downloading waveform instead of changing a new set of hardware. A typical SDR system is composed of analog hardware, DSP, general purpose processors and FPGA, the set of hardware can be reused for different satellite systems by just implementing their waveforms and protocols, that's how Kepler is able to have global connectivity. Because different countries and regions in the world are using different frequency bands or spectrum, and current satellite internet services are mostly dedicated to country, then operators have to limit their operation spectrum to what is available in this country. Therefore each constellation has hardware designed for its operation spectrum and can't provide service for other regions with different spectrum. While this barrier is broken by Kepler with their SDR [31]–[34]. Starlink constellation has been tested by some subscribers in rural area and the speed can achieve 120 Mbps downlink and with latency only 20-40ms. Kepler can provide broadband data service for areas like Arctic and oceans, where expeditions will set foot on.

B. Architecture of satellite communication

Satellite communication (SatCom) systems work in two network configurations, mesh and star. Satellites work as relay, set up direct links between nodes and help them communicate to each other directly, the topology is called

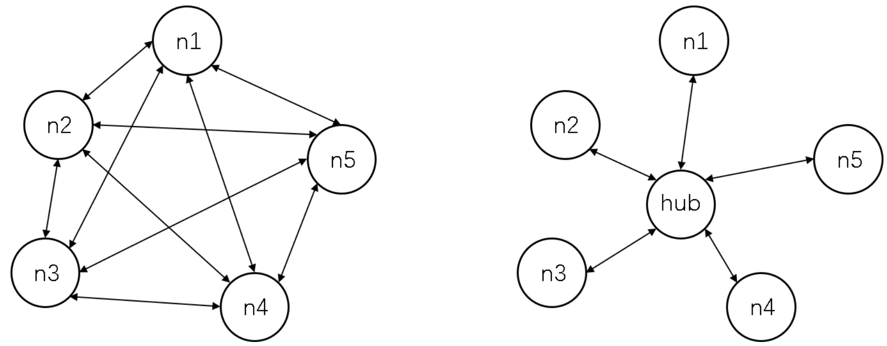

Figure 10: Mesh topology (left) and star topology (right) for SatCom systems, with all the links have satellite as relay

mesh configuration. If satellites work in star configuration, two remote nodes communicate to each other through a central station, or a hub. Because of the cost effectiveness, most practical satellite communication systems use star topology. In both cases, there's no inter satellite communication, satellites just work as relays, but we can introduce communication between them and cooperatively perform more complicated tasks [29].

The common architecture [29] for a satellite communication system with star topology consists of three segments as shown in Fig. 3, space segment, user segment and ground segment. The space segment is the constellation, or the satellites, except the power system and control system, the transponder acts as a relay. The transponder receives signal from ground station, which is sender of the information, and satellite receives the message in one frequency, amplifies and transmits it in another frequency (most of the new proposals of SatCom systems use a K_u-band for user link, use K_a-band for feeder links" architecture [36], like Starlink use K_u-band beam for user, K_a-band beams for gateway according to the FCC 2020 filing [37]) to the receiver of this information, satellite acts as relay between them. The ground segment is composed of a number of ground stations or gateways (GW) and of course facilities for control and other operations. A gateway or hub receives signal and transform to data then send to internet and vise versa, so gateway provides connection to internet backbone.

Most new proposed systems chose an integrated space-terrestrial mode, which means that all the transmissions between satellites and ground servers pass through gateways, then gateways function as the bridge connecting space and ground segments. However, for megaconstellations composed of huge number of satellites, like Starlink has planned 44,000 satellites, each LEO satellite only covers a small area of Earth. If there is no inter satellite communication (ISL), a large number of gateways is required [38]. With ISL, satellite is able to connect non-LOS gateway and also able to handover tasks and data to next satellite coming to its position, therefore number of gateways is reduced and one gateway can also be shared by several satellites. Thus, shared gate way among all satellites in the constellation enables us to cut the gateway number thereby minimize deployment and operating cost, as gateway construction and operating is expensive. However, for a large constellation if gateway number is limited, required number of hops to finish one transmission increases, the undesired result is more delay for the communication. This is the tradeoff between gateway number and ISL usage.

C. *Inter satellite links*

So far, the effert has focused on completing terrestrial network coverage, which usually causes serious waste of terrestrial and satellite resources. It is essential to build SatCom system as a multilayer network with terrestrial and space segment (integrated space-terrestrial network). Traditional satellite acts as relay, there's limited on-board processing capability, but new generation of constellation like Starlink has strong on-board processing power (every batch of 60 satellites launched contains more than 4,000 Linux computers [39]), so they are able to control the incoming information and then redistribute it. Once satellites are equipped with on board processing capability, ISL can be formed and the system becomes a switching network in space, each satellite acts as a router node. It is prefered that long distance communication implemented by SatCom with ISL, because frequently hopping back and forth between satellite and ground station causes delay. A satellite network with ISL using laser can have less latency than a terrestrial fiber optics network over a distance more than 3,000 km [40].

There are two commonly known types of communication between satellites, one is inter layer link (ILL), the other one is intra orbit link (IOL). IOL means communication happens between satellites in the same type of orbit or in the same relative altitude, like LEO to LEO and GEO to GEO. ILL means communication happens between satellites in different types of orbit or satellites have different relative altitude to each other, like LEO to GEO and LEO to MEO [41]. ISL would allow both ILL and IOL, the combination of them can bypass the conjested part of the network and allow coorporation between systems to increase quality of service (QOS), decrease the unavailability of service and integrate different services in one system.

Currently implemented SatCom technologies use two methods, radio frequency (RF) communication and optical (laser) communication. In space, both electromagnetic wave and light travels through vacumm, thus ISL links would suffer from less atenuation than ground-satellite link, this attenuation is refered to as free space loss. Radio frequency techniques are well developed, in order to reach higher data rate, large bandwidth is required. Due to the lower pathloss and little blockage than on Earth, we can use higher frequency like V band (40-75GHz), also allows to avoid interference with operations happen in other bands.

D. Free Space Optics (FSO)

Except RF, we can also set up ISL by laser, outdoor optical wireless communication is called free space optics (FSO) [40], there are four types of FSO [42], what we are talking about is space FSO, satellite-to-satellite FSO link. The FSO link is also refered to as laser inter satellite links (LISL). Using laser has several benefits, higher bandwidth due to optic communication, smaller antenna size, little interference and lower transmit power. Smaller antenna size and lower power requirement allows us to shrink satellite size so that more satellites can be fit in one launch and save cost for deploying satellites. Current constellations like Starlink chooses to use LISL to achieve a lower latency and a integrated network. Starlink is a mega-constellation, it covers almost everywhere on Earth, including rural areas that terrestrial networks can't reach. Second, despite the fact that fiber optics has really high bandwidth, the speed of light in vacuum is 47% higher than in fiber [43].

Satellites travel in the orbital plane, inside the plane satellites stay in the same altitude and move in the same direction. In the same altitude there can be multiple orbital planes, satellites on these different orbital planes will move at crossed path [42]. According to FCC filing, Starlink plans to install four laser communication components on one satellite so that it can connect up to two satellites in its orbital plane and two neighbors in different orbital planes. According to analysis [43], two most likely candidates for setting up LISL are the two neighbors on the same orbital plane, the one ahead and the one behind. The next choices are satellites at both sides on the neighboring orbit plane because they remain in range, but should choose neighbor sitellite in a direction as orthogonal as possible. So the four links make up a mesh network. But Satrlink has two orbit directions, notrheast and southeast, the second layer is 40 km below the upper layer, so there are two mesh networks moving to almost orthogonal directions. As there's no local connectivity between the two networks, it's reasonable to set up the last link between meshes. Like we said, Starlink is consisted of two layers, one is on top of another. Due to requirement of coverage and astronomy theory, the two layers orbit along southeast and northeast. To show this straight forward, in Fig. 11, the satellite on upper layer heading northeast connects to four satellites horizontally and one satellite vertically.

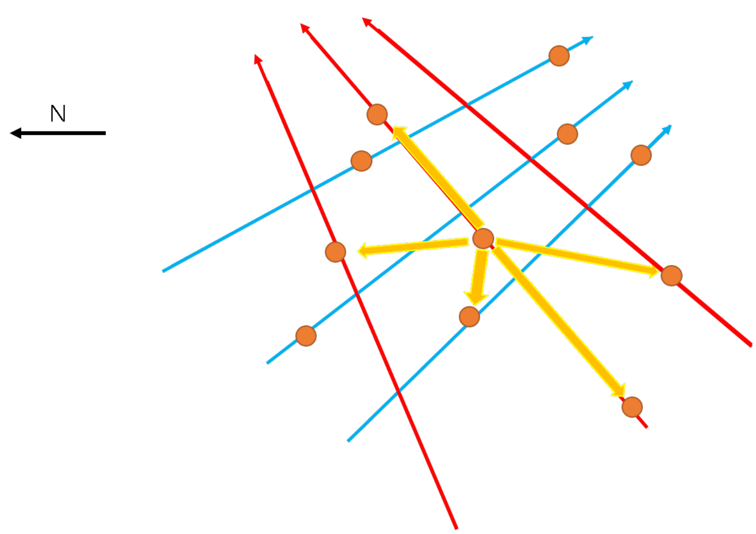

Figure 11: A simple explaination of satellite mesh network

However, the laser links between two mesh networks change frequently, when two cities far from each other communicate through the satellites above them, if the two satellites are on different orbit direction, the fifth link does not stay long as the satellites move, and this causes more latency than usual. A better strategy is to connect to a satellite lower in the sky in the direction of destination.

LEO satellites can travel in a very fast speed, at about 27,000 kilometers per hour, it completes a circuit around Earth in 90 to 120 minutes [44]. Thus, satellites in different orbital planes and in different orbit directions can move in a fast relative speed, resulting in problems like Doppler shift, point-ahead angle (PAA) and acquisition, tracking, and pointing (ATP) [42]. LISL uses laser beams with small width causes divergence during the communication between two relatively moving satellites. When one satellite tries to respond to received signal from another satellite, the loaction offset caused by relative movement between them during the respond time should be considered. A precise ATP system is required to track this movement and generate this offset. To make the situation worse, in communication between inter orbital plane satellites and inter orbit satellites there will be Doppler shift, the frequency change in the received signal caused by relative velocity between them.

E. Antennas

Traditional satellite services like broadcast satellite service (BSS) providing downlink beams over its coverage region uses contoured beam coverage. The transition from broadcast to broadband services marks the transition to multibeam antenna (MBA) coverage, the narrower beams of which enable both higher gains and frequency reuse. In the last two decades, there's a significant growth for both commercial and military purposes [45]. MBA covers the geographic region using a large number of spot beams instead of a single beam.

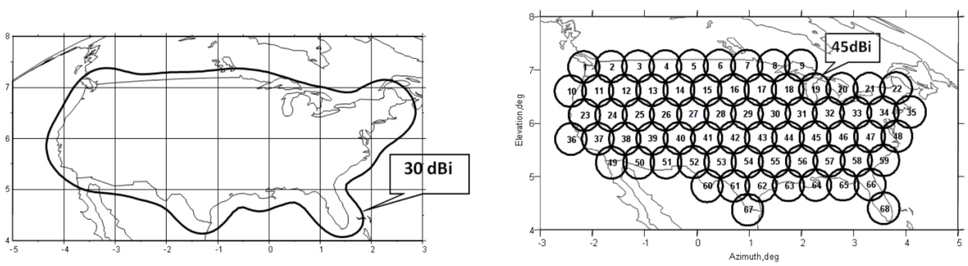

Figure 12: Contoured beam coverage (left) and multibeam antenna coverage (right) [45]

Fig. 12 shows an illustration of multibeam coverage and contoured beam coverage. The contoured beam has a gain of 30 dBi while each of the spot beams of the MBA has a gain of 45 dBi, dBi of a direction is the gain of a directional antenna in that direction compared with isotropic antenna which has 0 dBi. Therefore, MBA provides extra 15 dB gain. Notice that in the MBA figure, there are 68 spot beams, in order to supress cell-edge interference, 4 cell reuse scheme is used, then the same spectrum is reused 17 times in the entire coverage area. So with same spectrum allocated to operator, MBA can provide users 17 times the bandwidth.

F. Technical requirements

1) ULA pattern: In electromagnetic theory, a plane wave arrives at an linear array of antennas with order, namely, different antenna elements recives signal in different time, and this causes phase difference in the received component and causes attenuation in some cases. Assume we have a linear array with N elements and distance between two elements is d, every element is an isotropic antenna, signal comes at an angle θ with broadside, we have a model like Fig. 13.

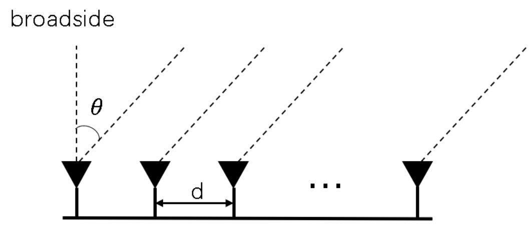

Figure 13: Array of antennas

There will be phse differences between elements, wavefront arrives at first antenna, after traveling $\Delta l = d \sin\theta$, wavefront arrives the second element. Therefore, this difference in propagation distance results in a difference in phase, and this difference between two antennas is the same. We assume radian frequency is ω, to travel Δl, signal needs time $\Delta t = \Delta l / c$, where c is speed of light, then phse difference $\Delta\phi$:

$$\Delta\phi = \omega\Delta t = \frac{2\pi f_c \Delta l}{c} = 2\pi\frac{d}{\lambda}\sin\theta \tag{1}$$

where λ is wave length and f_c is carrier frequency, after receiving the signal, receiver will multiply each entry with a constant, that is called receiver filter, and this operation is called beam forming. We call the receive filter $\boldsymbol{w} \in \mathbb{C}^{N\times 1}$, bold font represents vector, and structure of receiver is shown as Fig. 14.

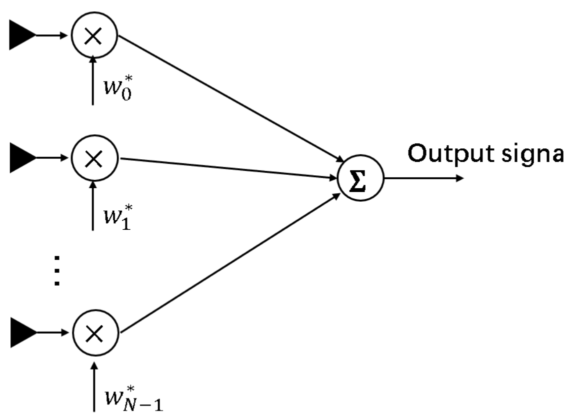

Figure 14: Beamforming model

Received signal is $\boldsymbol{S} \in \mathbb{R}^{N\times 1}$, output of beamformer is r We can also represent beamforming as

$$r = \sum_{i=1}^{N} w^* S_i = \boldsymbol{w}^+ \boldsymbol{S} \tag{2}$$

Assume our filter $\boldsymbol{w} = [1, 1, \cdots, 1]^T$, and a fixed signal $s \times [1, 1, \cdots, 1]^T$, the received signal is

$$r = s\sum_{i=1}^{N} e^{j\Delta\phi} = s\sum_{i=1}^{N} e^{j2\pi\frac{d}{\lambda}\sin\theta} \tag{3}$$

Therefore, we have antenna pattern or ULA pattern

$$F(\theta) = \frac{|\sum_{i=1}^{N} e^{j\Delta\phi}|}{max\{|\sum_{i=1}^{N} e^{j\Delta\phi}|\}} = \left|\frac{\sin(n\pi\frac{d}{\lambda}\sin\theta)}{n\sin(\pi\frac{d}{\lambda}\sin\theta)}\right| \tag{4}$$

It can be seen in the following figure

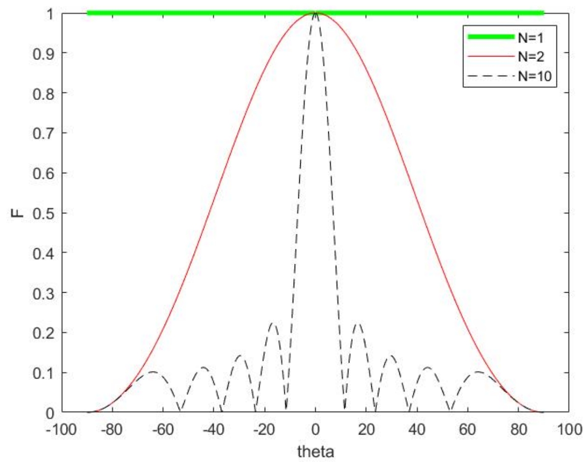

Figure 15: Antenna pattern with $d = \frac{\lambda}{2}$, and shown with $n = 1, 2, 10$

If we change $\boldsymbol{w}$, we can control this pattern and change the maximum response angle to where we need, this is called beam steering, this means, if we want the transmit or receive beam to point towards θ_0, we can let $w_i = e^{j(i-1)2\pi\frac{d}{\lambda}\sin\theta_0}$, and this is shown below

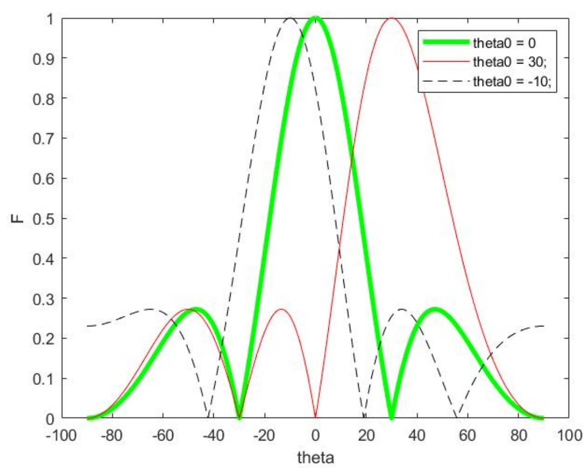

Figure 16: Antenna pattern with beam steering, $d = \frac{\lambda}{2}$, and shown with $\theta_0 = 0, 30, -10$

When we have a two dimensional phased array like in Fig. 17, with ϕ azimuth and θ polar steering angle, the received signal becomes

$$r = s \sum_{j=1}^{N} \sum_{i=1}^{N} e^{j2\pi\frac{x_{ij}\cos\phi + y_{ij}\sin\phi}{\lambda}\sin\theta} \tag{5}$$

where x_{ij} and y_{ij} are the x and y coordinates of the element. We show a beam pattern of a 16×16 2D array in Fig. 18

2) Latency: As analyzed in [42], the phase 1 of Starlink will orbit at altitude of 550 km, SpaceX made another proposal to FCC [37], it applied to move all its satellites orbiting at altitude from 1,110 km to 1,325km to altitude from 540km to 570km. Therefore, we use this new value 570km to do the analysis again. The speed of light in fiber is 47% slower than it is in vacuum, is $\frac{c}{1.4675} = 204287876 m/s$ (refractive index of glass is 1.52). In the orbital plane with altitude h equals 570km that we are concerning, only 20 satellites are on the plane, under uniform spacing assumption, 18° between satellites. Radius of Earth r is 6,378km. The distance between two adjacent satellites is computed by $2(r+h)\sin(\frac{\theta\pi}{360})$, where θ is angle between neighbor satellites as shown in 20. Notice

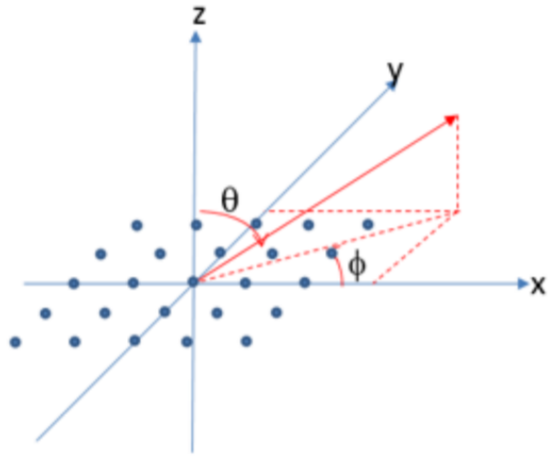

Figure 17: An example of 2D phased array

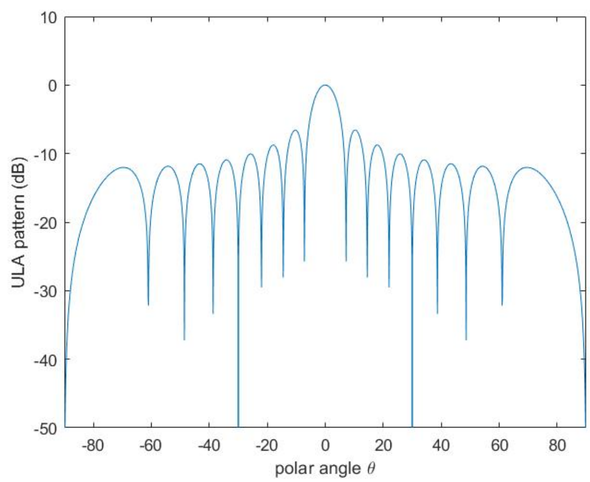

Figure 18: Antenna pattern of a 16×16 array with azimuth $\phi = 0°$

that when computing, satellite to ground is also counted, so additional 1140km is included in distance. The arc distance between two points right below the two satellites is computed by $2\pi r \frac{\theta}{360}$. The computation refers to model in Fig. 19

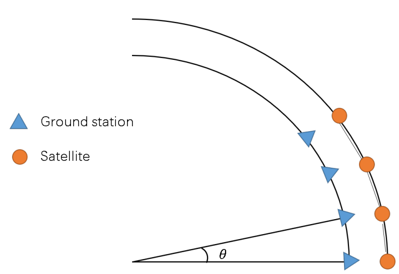

Figure 19: Model of satellite routing and ground station routing

Propagation time of terrestrial and satellite network are listed in the table I, as we can see, satellite network with LISL outperforms fiber optics from the second hop.

SpaceX Proposed Modification					
Orbital Planes	72	72	36	6	4
Satellites per plane	22	22	20	58	43
Altitude	550 km	540 km	570 km	560 km	560 km
Inclination	53º	53.2º	70º	97.6º	97.6º

Figure 20: Summary of proposed modified constellation [37]

Table I: Comparison of latency

No. of Hops	θ (degrees)	Satellite Network with LISL			Terrestrial Fiber Optics Network		
		Hop Distance (km)	End-toEnd		Hop Distance (km)	End-to-End	
			Distance(km)	Latency (ms)		Distance (km)	Latency (ms)
1	18	2174	3314	11	2004	2004	9.8
2	36	4347	5487	18.3	4007	4007	19.6
3	54	6521	7661	25.5	6011	6011	29.4
4	72	8695	9835	32.8	8015	8015	39.2
5	90	10869	12009	40	10020	10020	49
6	108	13043	14183	47.3	12022	12022	58.8

3) Link budget computation: According to the Fcc filing of Starlink, EIRP in 4kHz is -15.6 [dBW/4kHz] at K_u band, and we assume a bandwidth of 1GHz, we have EIRP of 38.4 dBW, in the file shows spreading loss is 131.9 dB, we have -93.5 dBW at the receiver, or -63.5 dBm. Because noise power is power spectral density times bandwidth, we have noise power -84dBm. Therefore, SNR at receiver without interference is 20.5 dB. In this case, we achieve spectral efficiency of 6.82 bit/s/Hz, with 1GHz bandwidth, we achieve 6.82 Gbps data rate. That is not realistic, but for any bandwidth, this SNR is always 20.5dB, see following

$$SNR = EIRP[dBW/4kHz] + BW[dB] - Loss[dB] - (N_0[dBm/Hz] + BW[dB]) \tag{6}$$

Parameter	Nadir	25° ES elev
EIRP density [dBW/Hz]	-56.4	-51.6
EIRP in 4kHz [dBW/4kHz]	-20.4	-15.6
EIRP in 1MHz [dBW/MHz]	3.6	8.4
Distance to Earth [km]	540.0	1105.2
Spreading loss [dB]	125.6	131.9
PFD in 4 kHz [dB(W/m^2/4kHz)]	-146.0	-147.4
PFD in 1 MHz [dB(W/m^2/1MHz)]	-122.0	-123.4

Figure 21: EIRP at K_u band and parameters [37]

Therefore, to achieve 300 Mbps datarate, each user needs at least 44MHz bandwidth

IV. Future Satellite Systems

A. *Typical usage scenarios for broadband connectivity in 2030s*

After the full deployment of Starlink, global connectivity is achieved, rural and remote areas have comparable broadband speed as urban area. Then satellite access internet will be used to conduct inter-continent video calls due to its low latency. As VR and AR will become more developed and more popular, new technologies will be developed like immersed virtual reality with haptic sense and other senses, bringing us applications like digital twin and virtual world. Applications like them will be available for people around the world and require strong broadband and very low latency, which can be achieved by a satellite network. Satellite network can provide low latency broadband for people in rural and remote area to access these applications, it achieves global connectivity literatelly.

Figure 22: A demonstration of digital twin [46]

B. Envisioned satellite technologies in 2030s for broadband connectivity to R&R regions.

Moore observed that number of transistors in an integrated circuit doubles about every two years, then it is reasonable to believe that before 2030, processing speed of software will be faster than hardware. Then for the next generation technology, software defined radio will play a more important role in satellite communication. Smaller sized satellites with strong processing power computer onboard will be deployed to form smaller sized cells and a network optimized for broadband. Because SDR will be as fast as hardware, processing delay is not an issue anymore. Besides, only a few microcessors are required, these satellites can be CubeSat size or even smaller, further decrease cost for launching and deployment. Smaller cells covered by smaller satellites result in higher frequency reuse. Furthermore, stronger processing power allows satellites to do more advanced operations like AI, onboard AI can be applied in routing procedure, help making routing decisions.

Another important futuristic technology is faster than Nyquist signaling (FTN), FTN has emerged in 1975 [47] where Mazo found that in binary signaling with sinc pulse, increase the transmission rate without changing pulse shape does not influence error probability, and results in a higher spectral efficiency than 1. FTN signaling has high demand for the processing power of receiver, in the procedure of sampling point recovering, a successive subtraction is conducted to recover the sample point. With proper strategy, transmission rate can double. SDR will become an enabler for this technology in the near future with shrinked hardware but more powerful processing capability.

In the next few decades, autopilot cars should be able to install phased array antenna on top and able to receive signal from satellite. Therefore, a car can become an outdoor unit when parked in front the house, and also able to provide internet access for passengers inside when driving on the road, with prerequist that mobile satellite communication technologies should be developed.

Meanwhile, to achieve capacity for MIMO multiple access channel (MAC), we need UEs transmit at the same time, then use techniques like successive interference cancellation (SIC) to tell them apart. NOMA enables multiple access in power domain or code domain, power domain NOMA is generally considered to be the most potential multiple access scheme. There is an urgent demand for massive machine-type terminals to get service by integrated terrestrial-satellite network, and studies have begun to introduce NOMA into this network.

V. Conclusion

Satellite access internet is a promising solution to provide broadband to rural and remote area. It is possible to provide lower latency than fiber optics and even higher data rate than DSL and some existing technologies. In order to achieve this, we need to introduce inter satellite links to constellation. As there will be more constellations, satellite networks will also take a significant proportion of working load of terrestrial networks, and also enable new use cases like virtual reality with more senses. As the cost of deploying satellite network decreases, we can see more terrestrial networks will be replaced by satellite access internet. With satellite network, special missions like science expedition in polar area and oceans can also be covered by internet, huge amount of experiment data can be transfered by satellite, which saves time and provides a safer option to transfer data.

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