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The Future of Broadband Connectivity: Terrestrial Networks vs Satellite Constellations

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Abstract

This paper looks at the landscape of broadband connectivity as consumers welcome disruptive newcomers, the satellite service providers, into the telecommunication and internet ecosystem. It highlights the developments that have made it possible for satellites communication to form a competitive alternative for terrestrial broadband internet services. We motivate discussions on ways and approaches to ensure terrestrial mobile operators construct effective strategy in integrating and working with the newcomers for interconnecting their terrestrial nodes with those of the satellite service providers. We discuss some technology and business perspectives for a healthy co-existence, and postulate that customers' finances (price consideration) and perception of quality of experience and satisfaction may be the battleground for satellites and terrestrial service providers. Finally, it is concluded that, in the history of human endeavor, smart and effective cooperation has always been the best strategy to fight extinction.

Keywords

Broadband Internet, Satellites, Mobile Operators, Terrestrial, Aerial

1. Introduction

Telecommunication companies are operating in a dynamic business landscape. The consumers of their services are very sophisticated and price-conscious. The dynamic nature of the telecom service requirements was highlighted most recently by the coronavirus disease of 2019 (tagged COVID-19). Based on the COVID-19 situation, there has been a significant increase in the volume and number of ways of consuming telecom services. For instance, there is a continuing and greater need for connectivity to areas outside the central business districts, e.g., rural areas, even for business-related engagements. The need to connect the remotest parts of the rural areas has never been more pressing. This boost in connectivity consumption due to COVID-19 has indeed left one main lesson for humanity. That is, there could be other more efficient ways of conducting our businesses and social affairs than what we sometimes consider to be the norm in the pre-COVID-19 time.

Studies, e.g., [1] has reported that significant usage increase (about 87%) in online services during the COVID-19 pandemic, especially for services such as video streaming, video calls and conferencing, web browsing, and social media. This fact underscores the need for continuous modernization or improvement in service delivery and technology adoption as an essential part of the pre-occupations of telecom service providers, which will help ensure low cost per bit, or dollar per service for profitability. Here, we mention cost/service as the traditional bit or byte as the basis for mobile service pricing is no longer tenable. Telecom service providers, or mobile network operators (MNO) have to build agility and entrench dynamism in their business portfolios for profitability.

As documented in [2], although mobile internet connectivity continues to grow, with close to 4.9 billion people currently connected (2021 International Telecommunication Union (ITU) figures), a significant portion of the close to 8 billion people on the planet earth are still not connected. Into the broadband internet service offering frays, jumped in new and threatening to be competitive newcomers, the satellite broadband internet providers, such as Starlinks, OneWeb, Amazon, among others. More often than not, the satellite internet service providers have tried to position their business model as serving the unserved, or under-served. For instance, SpaceX's Starlink claims that they intend to mesh with terrestrial telecom services to fill in the coverage gaps. A claim amplified by OneWeb [3] is that they will be serving the hardest-to-serve customers. Furthermore, there are continuing efforts and agitation by the United Nations to connect the uncovered, unserved, and under-served to the internet [4]. Back in 2015, the majority (54%) of the world population was not connected to the internet, this number has been reduced to about 43% in 2019 [4]. Although this is an improvement, this figure represents billions of people that still belong to the unconnected category. When the unconnected figure is dissected further, it is observed that globally, more than 63% of the households are unconnected in the rural areas [4]. The number of unconnected is much higher in the developing economies such as countries in Africa, Caribbeans, and South Asia than in the developed economies. The proponents of the satellites broadband internet services argue that they target the under-served and unserved segments of the market. This position exposes a different market proposition entirely, and presents clear food for thoughts for the terrestrial network operators. The key question is, will the rural customers alone bring profitability?

The most recent ITU's facts and figures report puts about 2.9 billion people, representing 37% of the world population [2], in the unconnected category. This is due to various reasons, and among the major ones is the cost of end-user devices and connectivity, or simply put affordability. The study in [5] reveals that even in high-income countries, affordability poses a major challenge. The following relevant questions quickly emerge. Will this unconnected segment of the planet's inhabitants, who are largely rural dwellers, form a sufficient market base for satellite broadband profitability? Would the satellite services not be extended to the urban and central business districts? The answers to these questions are obvious. Thus, the struggle between satellite broadband service providers and the traditional MNOs will have to reach the pockets of the consumers. It may all reduce to whom, of these two contenders—terrestrial or satellites—would win the minds of the consumers through the provision of seamless, personalized, secure, and quality experience in addition to being soft on their finances.

In the following sections of this article we firstly, present an overview of the development in the satellite communication industry positioning it as a viable competitive way of providing broadband internet services, and secondly, we discuss the role of novel and intelligent deployments that should inform the layers of concept and technologies that will form the evolving aerial architecture for the integrated terrestrial and non-terrestrial networks. Thirdly, we submit that cooperation between satellite service providers and terrestrial network operators could be a win-win strategy to utilize the communication resources to the benefit of humanity, by providing connectivity to all, including under-served and unserved. Finally, we highlight some of the challenges and opportunities that require careful attention as we welcome the era of complete land-space integrated communication network.

2. Covering the Globe—Broadband Connectivity

2.1. Why and How Satellites Move from a Non Option to a Viable Option

In the eighties, and until very recently, launching a kilogram (Kg) of payload to space attracts an exorbitantly high fee, in the order of hundreds of thousands US dollars. With such a fee, it will be difficult to establish a profitable proposition for price-sensitive, consumer-centric telecommunication ventures, especially the ones to serve the rural inhabitants. Innovation and technology evolution has allowed smaller and micro satellites to be built. Smaller and effective launch payload significantly impacts the cost dynamics of the satellite communication business, invoking the economies of scale lever. Thus, over the period, 1980 - till now, there has been a significant drop in cost, and the $/payload continues on the downward trajectory as depicted in **Figure 1** [6]. Today, it is much easy to arrange and launch some small, light flat-panel satellites, at a relatively low operational altitude (**Table 1**). The most innovative and revolutionizing part is the breakthrough in reusable rockets that SpaceX has masterfully crafted and commercialized. Until recently such venture can be very capital intensive and uncompetitive.

Extrapolating the current trend in launch cost, it is possible that the cost of a launch will be negligible in few years. This singular fact is enough for satellites business operators to pose stiff competitions to the terrestrial network service

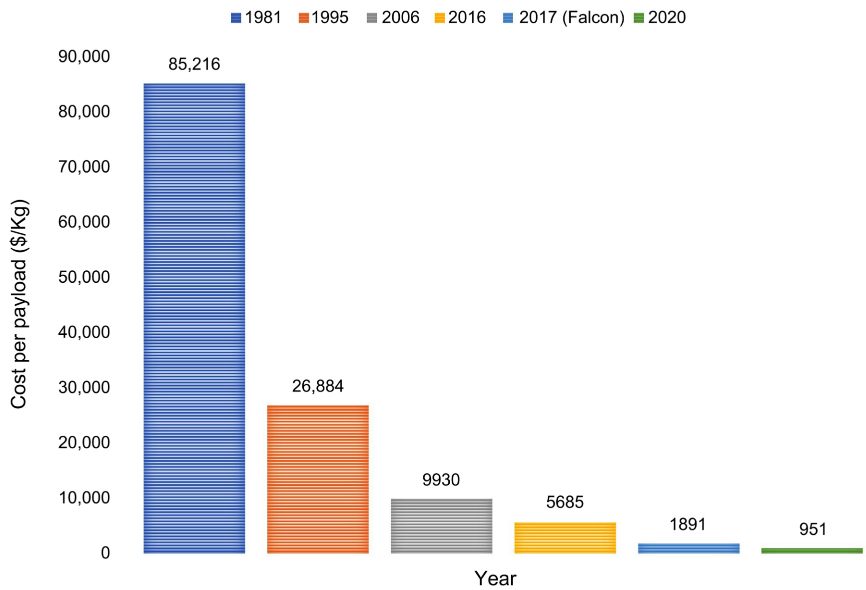

Figure 1. Cost of launching a rocket payload.

Table 1. The impact of reusable rocket launch on space launch cost [6] [7].

System	Shuttle	Falcon (Fal) 9	Reusable Fal 9	Fal Heavy	Reusable Fal Heavy
Cost/launch (in $ M)	1200	62	6	90	9
Payload in LEO (Kg)	1600	22.8	14.8	54.4 (63.8) [7]	35.4
$/Kg (in $ M)	75	2.72	0.40	1.65	0.25
Relative cost efficiency	1.00	27.50	187.50	45.45	300.00

providers especially, if the cost of deploying space constellations competes favourably with that of terrestrial networks, and equally important, if all communication key performance metrics, such as latency and throughput, are comparable.

Furthermore, **Table 1** shows that Falcon 9 has reduced the launch cost by a factor of 27.5, while reusable rockets could produce a cost reduction as much as 300 times compared to shuttle's cost per Kg of payload. Satellites deployment race is only beginning. For instance, OneWeb's recent launch (February 2022) brings to about 420 satellites in orbit of the close to 650 planned for the initial constellation, and expected for full global coverage before end of 2022 [3]. Amazon is positioning their project kuiper for low earth orbit (LEO) massive deployment that will network over 3200 satellites in its constellation (**Table 2**). Over the longer term, many players will operate thousands of satellites. Many of the players have either acquired operational licenses or are in the process of applying for telecom services' licences (e.g., Starlink, in Canada).

2.2. The New Frontiers in Broadband Internet Services

Figure 2 depicts cellular network coverage on land and the coverage that satellite constellations will provide. Terrestrial mobile network operators (TMNO) usually and extensively deploy their access points, cellular base stations (macros or micro) in the coverage service areas. These are the interfaces between the users and the core network.

However, natural terrains and man-made obstacles may not always allow the neat hexagonal layout shown in Figure 2 or even allow complete coverage of the landmass. Thus, even in cities, terrestrial operators could face deployment challenges. With aerial deployments coming into the picture, service coverage can be truly ubiquitous using satellites tessellation. Satellite network operator will not have to think about municipality, civil leases, rents, security of sites, among their challenges. The cost of these aspects of network ownership, most often constitutes the bulk of the capital expenditure for terrestrial network deployments.

Table 2. Data sheet for satellites services, expected performance, and frequency of operations.

Main Players	OneWeb	Starlinks	Viasat	Amazon	Kepler
Target (launched or active)	2000 (>420)	42,000 (>2000)	288	>3200	140
Frequency/band	Ku and Ka	Ka Ku and V12,000 (600)	Ka	Ka	
Satellite Position	LEO (1200 Km)	LEO, VLEO	LEO	LEO	LEO
Speed	50 Mbps	100 Mbps		LEO	
Latency	50 ms	20 ms [7]	30 ms	50 ms	50 ms
Launch Year	2019	2019	2018		2018

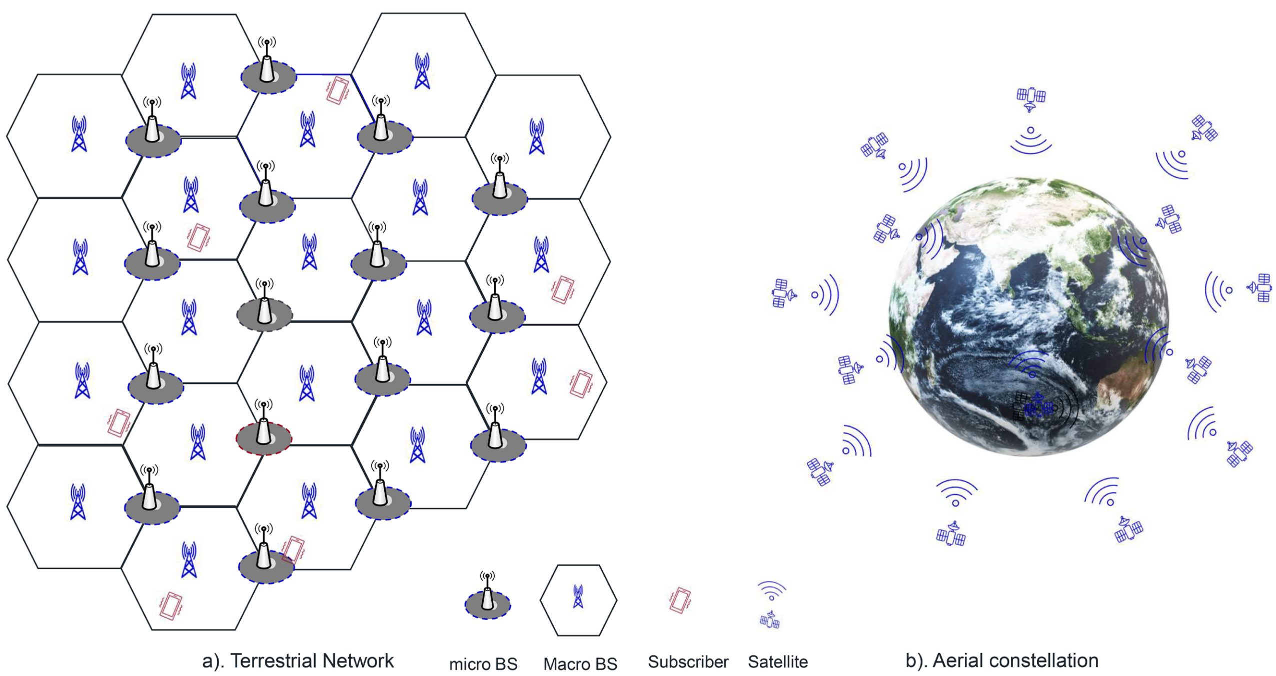

Figure 2. Terrestrial network and satellite constellations.

3. The Terrestrial and Space Network—The Challenges and Opportunities

A number of factors are driving both the technology and business aspects of aerial and satellite communication services. The dimension and impact of COVID-19-inspired new ways of service demands are already evident. The activities of the main players are presented in **Table 2**. Amazon's LEO constellation tagged as project Kuiper plans to provide broadband connectivity using over 3200 satellites. In their renewed mission, project Kuiper has recently secured rockets to facilitate the launching of the multitude of satellites into orbits [8]. The business model for project Kuiper extends beyond providing internet connectivity to remote or hard-to-reach areas; it includes offering broadband services to government agencies, households, enterprises/businesses, and terrestrial network operators. Slightly ahead in this race is SpaceX's Starlink, which has already deployed over 2000 of their planned 42,000 satellites into orbit (See **Table 2**).

In the following discussions, some of the challenges and opportunities are briefly presented.

3.1. Spectrum Availability

Most of the LEOs will be utilizing the Ka (12 - 18 GHz) bands Ku (26 - 40 GHz) bands as shown in **Table 2**. These frequency bands are relatively low, which provides many technical benefits. Among these benefits is the use of reasonably sized system of antennas, which translates to lower cost of Customer-Premises Equipment (CPE) and access points. Furthermore, these antenna systems can be adopted in such a way to perform advanced signal processing such as the use of multi-input multi-output (MIMO) and directed beam-forming. Although beam-forming will contribute to the data throughput improvement per user, it will unfortunately reduce the coverage footprints of a satellite, thereby requiring larger number of satellites in a constellation. On the user side however, to make the CPE more intelligent, electronically steerable antennas, which will facilitate tracking of large numbers of satellites using finer beams can be deployed. This will unfortunately increase the cost of CPEs, an undesirable business proposition, especially for rural-inspired internet service offering.

5G and satellite co-existence is an important part of the 3GPP standard efforts. In addition to the mm-wave band for the 5G, much lower frequency, the sub 6 GHz, are also required in the 5G ecosystem. In some markets, the United States in particular, air travel agencies are nursing concerns regarding the use of some of these frequency bands. Although this fear is unfounded as many studies (including FCC investigations) have shown, it needs to be swiftly resolved. The airline industry fears that frequency-related (interference) challenges could disrupt air traffic operations to the tune of hundreds of thousands of flights affecting millions of air travellers. As such the use of C-band (*i.e.*, the frequency band 3500 - 4200 MHz) for 5G operations has been delayed at the behest of Federal Aviation Administration [9]. This situation is expected to change once every unfounded fear has been dispelled, through for example, proper awareness.

3.2. New Business Propositions

SpaceX's Starlink unit has started testing its internet service with a number of aircrafts in order to provide in-flight connectivity to airlines [10]. OneWeb has listed a number of business areas including the enterprise, government, maritime, and aviation [3]. These are neither rural customers nor under-privileged segments of the planet earth. It appears satellite constellations have left the rural connectivity objective of satellites to the urban reach of the terrestrial operators. Should this not be a concern for terrestrial network operators?

Let us consider some other areas of business exploit. Terrestrial operators can extract opportunities by re-inventing network operations. For instance, a use case for aerial network deployment, from the perspective of incumbent operators is motivated in [11] where the authors explain how unmanned aerial vehicle (UAV) technology can be adopted in easing the traffic distribution part of the supply chain. Given the volume of this market, significant number of cargo UAVs will be in the airspace. Thus, seamless, ultra-low latency and reliable connectivity will be essential for effective operations. Besides, the operators could also adopt such cargo delivery UAV as aerial base-stations to move capacities to where and when they are needed, like the drones RAN (Radio Access Network) described below in Section 5. Ultra-low latency connectivity as being discussed for 5G and 6G will be an important asset for the terrestrial network operators.

Still on the business propositions, terrestrial network operators need to do more than providing the traditional or native telecom services to stay ahead of the curve [12]. For instance, it is observed that telecom companies that have better valuation have moved from core business of providing data or connectivity into offering digital business and services, such as gaming and creating a niche in the financial market through technology innovation and adoption. This fintech (the marriage between finance and technology) that we have seen could extend from mobile banking, investment apps, and insurance, to a host of many of the endless arrays of monetary applications.

3.3. Backhauling

Figure 3 shows another possible convergence between satellites and advanced cellular technologies such as the 5G and beyond, where satellites are adopted to backhaul capacity from remote locations to the terrestrial network core. Some operators across the globe have started considering connectivity through beam and gateway handovers in satellite constellations. Trial of this nature is essential to establish interoperability of the satellite solutions with the terrestrial network. It can also help to quantify the key performance metrics, like throughput, latency, and jitter. The cooperative synergy between both entities will be truly mutual and complementary.

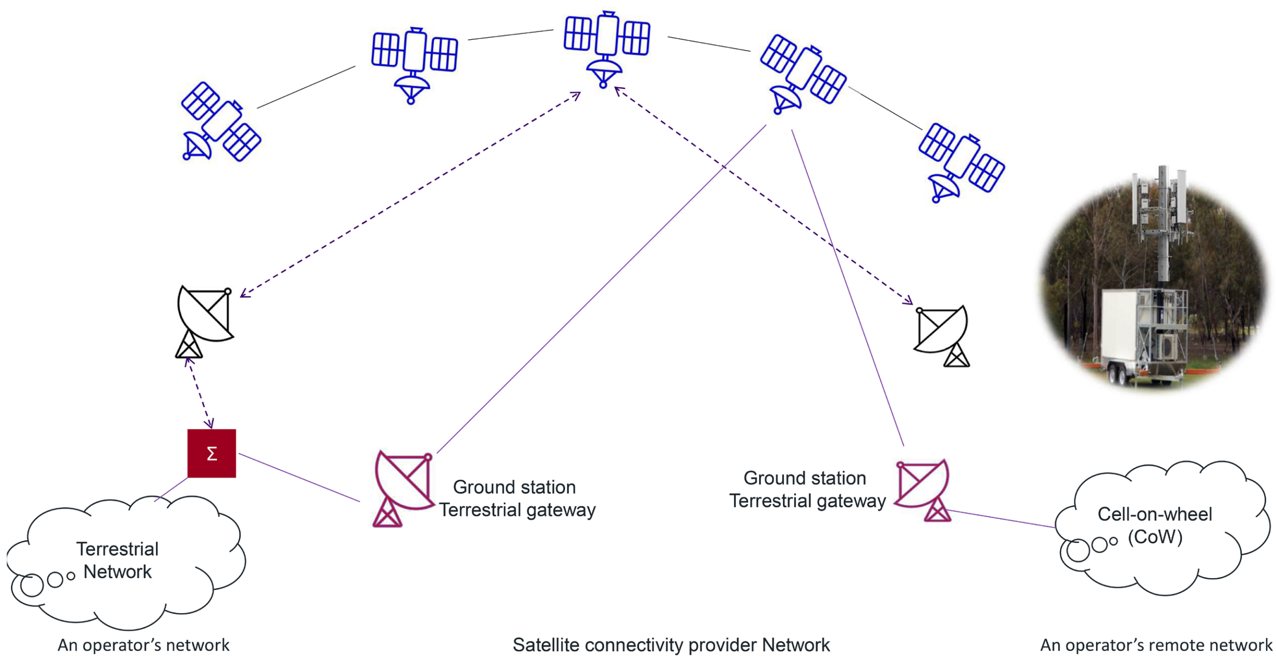

Figure 3. Terrestrial network depending on aerial nodes for backhauling.

3.4. Energy or Power

The satellites, like any communication nodes, need power to communicate with their terrestrial terminals. Solar is an immediate cost effective source of power. However, in the absence of solar light, these satellites will need to rely on-board battery for their energy supply. The need to make provision for such power consumption places weight or size requirements on the satellite battery. The heavy dependency on such battery to carry the satellite in such solar outage could contribute to the cost of satellite developments.

3.5. Customers Premises Equipment (CPE)

As explained previously, the cost of consumer CPEs to ensure reasonable satellite-to-satellite handover could mount a significant challenge for the constellation providers, even if the monthly subscription costs for satellite access and terrestrial solutions are comparable [13]. Similarly, Boston Consulting Group (BCG) report [12] has projected that by 2030, the cost of an end-user terminal will be in the range of $130 and $300. Considering these number, BCG believes considerable research in developing low-cost devices to position LEO constellation as an affordable solution, if bridging the connectivity divide has to be fully realized. However, outside the consumer space, constellation providers could find huge markets with enterprises such as those operating ships, airplanes, and trains, where the cost of CPEs might be secondary issue, thereby enabling these vehicles to have rich broadband connections. These are markets that MNOs have not fully monetized. This implies that terrestrial network deployment needs to go beyond the flat (terrestrial) business architecture to harvesting all possible degrees of freedoms, land, sky, and space, in an integrated way.

4. Integrated Network—Comprising Space, Aerial, and Terrestrial Nodes

Figure 4 shows an architecture comprising of the integrated satellite and terrestrial network, featuring airbornes, spaceborne and heterogenous terrestrial access points. In the below discussions, we briefly present some of these components and their relationship in the overall future network. We also motivate discussion on the opportunities that can be exploited from the degrees of freedom that are presented by this truly heterogeneous architecture.

4.1. Drones

As depicted in Figure 4 and elaborately discussed in [14], cell-on-wings (COW) or drone-cell network will be an important addition to complement the terrestrial network. In the 3GPP nomenclature, satellites are considered spaceborne vehicles covering different orbits, such as Low Earth Orbits (LEO), Medium Earth Orbits (MEO), Geostationary Earth Orbit (GEO) or Highly Elliptical Orbits (HEO), while high-altitude platform (HAP) and low-altitude platforms (LAP) are classified as airborne with altitude below 50 km [15].

Adopting flying base station or small-cells ensure the mismatch between capacity requirement and capacity availability is reduced thereby helping terrestrial operators optimize their capital expenditure (capex) in deploying their RAN. With aerial networks, operators will not need to build network for future capacity needs. The merit here is to break the expensive tradition of over-engineering

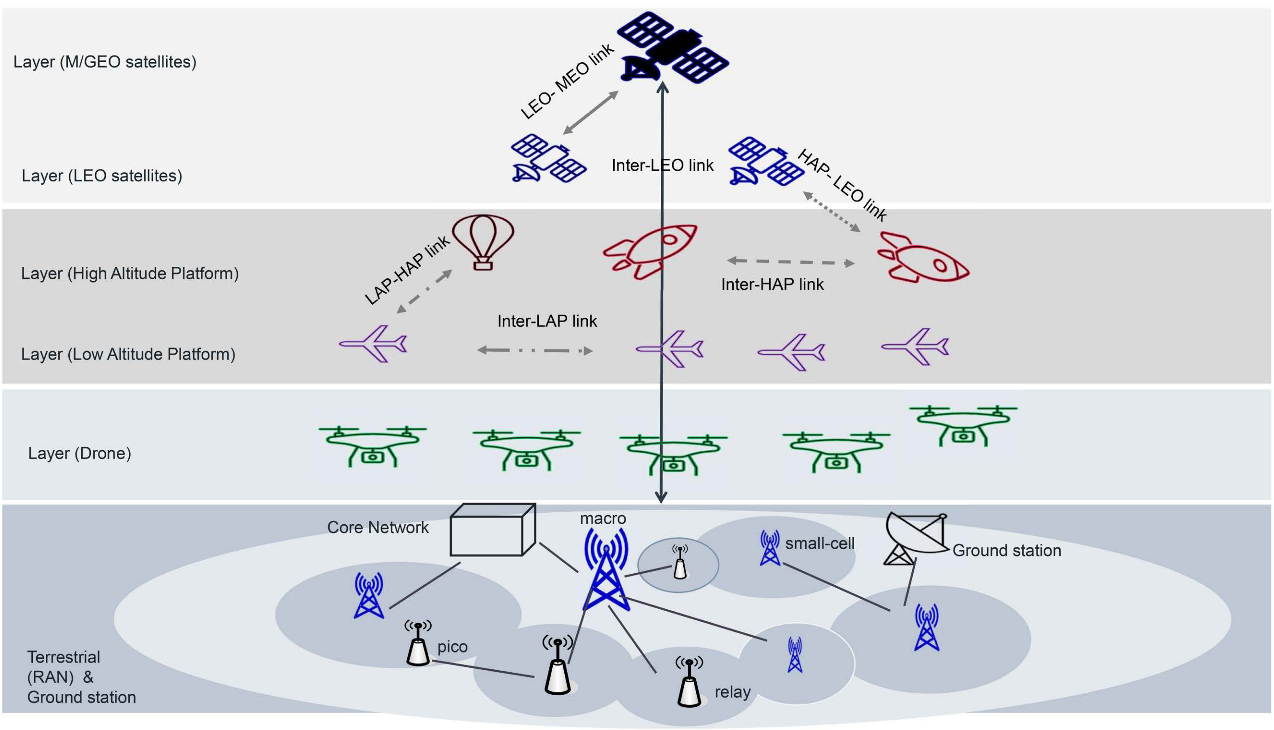

Figure 4. Vertical heterogeneous architecture of tomorrow (opportunities): integrated layer comprising space, low and high aerial, and terrestrial nodes.

RAN deployments, which has huge capex implications. Drones deployment will come with some challenges too. Works such as [16] [17] have addressed some of these challenges. For example, [16] has observed performance degradation for the neighboring ground terminals when drones facilitate connectivity for high data-rates sessions. This is due to uplink inter-cell interference due to the nature of drone-to-base station (BS) and terminal-to-BS channels. The authors discussed a low-complexity approach suitable for Open-RAN architectures, which performs joint optimization of the drone's location in space and its transmission directionality to support for example high-data rate sessions. This idea lays the foundation for more cost-effective solutions.

To alleviate the pains of network operations, it may be necessary to embed the RAN with autonomy with sufficient intelligence to manage macros, micros and picos, relays, drones, the LAP (low altitude platform), and manage differentiated experience, and maximize network performance with minimized power consumption to improve the bottomline.

4.2. SpaceMobile, High-Altitude Platforms (HAPs) and Low-Altitude Platforms (LAPs)

Rakuten and Vodafone are the lead investors in a just-announced space-based cellular broadband network called SpaceMobile. In particular Rakuten has launched BlueBird production satellites, with an objective to extend SpaceMobile's coverage across the globe using about 168 satellites [18]. This joint venture aims to launch and operate a constellation of LEO satellites to address the connectivity gap could be a strategy to be considered by many MNOs. In the same vein, T-Mobile, KDDI, and Softbank on one hand, Ericsson and Nokia on the other, are promoters of High-Altitude Platform Station (HAPS) through the HAPS alliance. In addition to promoting and advocating for HAPS with relevant authorities in various countries, these members work together to build the ecosystem for HAPS seamless integration and inter-operability by developing a common specifications and standardization documents for the HAPS infrastructure [19]. Still on collaborative strategy, Telefonica Deutschland [20] has started using Intelsat satellites to connect their customers at difficult to reach locations. Thus, satellites will now fill the gap of extending coverage and services to areas that are otherwise not accessible using only terrestrial and traditional technologies.

4.3. Non-Terrestrial Networks (NTN): Satellite-to-5G, and Satellites-to-Beyond 5G

Innovation and evolution in the mobile technologies, including cost optimization should continue to occupy and drive both terrestrial vendor and operators network deployment. The terrestrial technologies such as the 5G, and 6G and beyond, should grow from hotspot to all-scenario continuous coverage. The work in [21] has already captured the requirements from the standard perspective for the integration of the satellites with the land networks. In this work, the authors summarizes the management and orchestration requirements for the inter-working of satellite and 5G network, in the context of the 3GPP standardization efforts, and postulate 6G satellite communication networks. The next evolution of 5G, and 6G will be integrated terrestrial and non-terrestrial networks. This will comprise of the LEO satellites and very low earth orbit (VLEO) satellites forming a mega constellation in the aerial domain while the plethora of heterogenous access points forming the terrestrial domain of the new ecosystem, in a truly collaborative and complementing way as shown in **Figure 4**. With this integrated architecture, telecom connectivity or coverage will be truly ubiquitous to be able to provide good enough data rates with acceptable or required low-latency to everyone, everywhere for the specific service the subscribers demand. Standard bodies, e.g., the 3GPP are already working full time to accelerate the development of satellite network based on the 5G technology framework, which will provide seamless integration between cellular and satellite.

5. Performance: Satellite vs Terrestrial Networks

Since North America's satellite market is more developed given the operation of Starlinks and others, we have compared the reported speeds for the satellite constellations in this market for the last quarter of 2021 with those of the terrestrial networks using the metrics of uplink and downlink speeds and latencies. These performance metrics extracted from [22] are shown in **Table 3** and **Table 4**. Latency numbers are a big concern for the satellite constellations. Inarguably, high latencies in the satellite connectivity are killer for applications that require stable and low latency performance, such as video calling, gaming, live-events and video streaming. It is observed that Viasat and HughesNet appear to be using the GEO satellites rather than the LEO starlinks uses. Overall, it can be concluded that there is still some work required in getting the latency of the satellite connectivity down to acceptable values. Furthermore on the throughput front, starlink has claimed that their users can experience download speeds of between 100 Mb/s

Table 3. Q2 2021 speed performance of select cellular networks, 1 for Global, 2 for Canada, 3 for Afghanistan.

Metrics	Mobile[1]	Fixed[1]	Mobile[2]	Fixed[2]	Mobile[3]	Fixed[3]
Downlink (Mbps)	29.06	58	72.87	97.51	5.24	1.67
Uplink (Mbps)	8.53	24.27	9.17	21.63	1.84	1.84
Latency (ms)	29	10	25	11	35	24

Table 4. Global performance of terrestrial networks (Nov. 2021).

Metrics	Starlinks	HughesNet	Viasat
Downlink (Mbps)	97.23	19.70	18.13
Uplink (Mbps)	13.89	2.43	3.38
Latency (ms)	45	724	630

and 200 Mb/s with latency as low as 20 ms in most locations [7] [23]. These values may be comparable to those of the 4G, they are well below the recorded values for the 5G, where a very low latency of less than 10 ms can be experienced.

6. Conclusion and Suggestions

This paper sets out to highlight two key points. First, terrestrial telecom service providers should recognize the unfolding competition threat from the disruptive newcomers emerging from the sky. These new players are posed at providing another layer of connectivity in the provision of ICT services, a layer that should be considered a positive development, with potential to expose new opportunities. Second, we observed that innovative (in both strategy and technology adoptions) network service providers may not need to be overwhelmed with fears. What is required is to understand the threats, build strategy, invest and excite consumers with personalized, secure and innovative experience. We sample some current key performance for both global cellular networks and satellites in terms of throughput and latency. The latency inadequacy of satellites connectivity is still observed. The following submission from Elon Musc is a vital reassurance for terrestrial network operators. "The challenge for anything that is space-based is that the size of the cell is gigantic." [24]. This is "great for very low to medium-sparsity situations", but not so good for the high-density scenarios thereby making terrestrial 5G service more appealing. In conclusion, therefore, the work in 6G may come with more advanced features to push terrestrial deployments beyond Elon's view or prophesy for the 5G.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] GSMA (2020) The State of Mobile Internet Connectivity 2020. Mathematics in Science and Engineering, GSMA. https://www.gsma.com/r/wp-content/uploads/2020/09/GSMA-State-of-Mobile-Internet-Connectivity-Report-2020.pdf

[2] ITU (2022) Measuring Digital Development: Facts and Figures. ITU, International Telecommunication Union Development Sector, Geneva. https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2021.pdf

[3] OneWeb (2021) One Web. https://oneweb.net

[4] ITU (2020) Measuring Digital Development: Facts and Figures. ITU, International Telecommunication Union Development Sector, Geneva. https://www.itu.int/en/ITU-D/Statistics/Documents/facts/FactsFigures2020.pdf

[5] Rastogi, V., Bock, W. and Wilms, M. (2020) A $2 Trillion Plan to Bring Two Billion More People into the Digital Age. BCG Report, 1-6. https://www.bcg.com/publications/2020/plan-to-bring-high-speed-internet-access-to-two-billion-people

[6] Jones, H.W. (2017) Much Lower Launch Costs Make Resupply Cheaper than Recycling for Space Life Support. 47*th International Conference on Environmental Systems*, Charleston, 16-20 July 2017, 1-7. https://ntrs.nasa.gov/api/citations/20170010337/downloads/20170010337.pdf

[7] Starlinks (2021) Falcon Heavy. https://www.spacex.com/vehicles/falcon-heavy https://www.starlink.com

[8] BBC (2022) Amazon Secures Rockets for Broadband Project. https://www.bbc.com/news/technology-61009163

[9] Bicheno, S. (2022) Verizon and AT&T Forced to Delay 5G Expansion Once More. https://telecoms.com/512781/verizon-and-att-forced-to-delay-5g-expansion-once-more

[10] Bachman, J. (2021) Bloomberg: SpaceX's Starlink Is Testing Internet Service for Aircraft. https://www.bloomberg.com/news/articles/2021-11-30/spacex-s-starlink-is-testing-internet-service-for-aircraft

[11] Cherif, N., Jaafar, W., Yanikomeroglu, H. and Yongacoglu, A. (2021) 3D Aerial Highway: The Key Enabler of the Retail Industry Transformation. *IEEE Communications Magazine*, **59**, 65-71. https://doi.org/10.1109/MCOM.010.2100072 https://www.bloomberg.com/news/articles/2021-11-30/spacex-s-starlink-is-testing-internet-service-for-aircraft

[12] Werle, T., Pandey, U., Rejeb, F. and Maalouf, M. (2021) LEO Satellites: A Technology to Revolutionize Global Connectivity? BCG Report, 1-5. https://www.bcg.com/en-mideast/publications/2021/leo-satellites-unlock-connectivity-opportunity

[13] Daehnick, C., Klinghoffer, I., Maritz, B. and Wiseman, B. (2021) Large LEO Satellite Constellations: Will It Be Different This Time? https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/large-leo-satellite-constellations-will-it-be-different-this-time

[14] Bor-Yaliniz, I. and Yanikomeroglu, H. (2016) The New Frontier in RAN Heterogeneity: Multi-Tier Drone-Cells. *IEEE Communications Magazine*, **54**, 48-55. https://doi.org/10.1109/MCOM.2016.1600178CM

[15] Chuberre, N. and Michel, C. (2021) Satellite Components for the 5G System. 3GPP. https://www.3gpp.org/news-events/1933-sat_ntn

[16] Bertizzolo, L., Tran, T.X., Buczek, J., Balasubramanian, B., Jana, R., Zhou, Y. and Melodia, T. (2021) Streaming from the Air: Enabling Drone-Sourced Video Streaming Applications on 5G Open-RAN Architectures. *IEEE Transactions on Mobile Computing*, **10**, 35040-35060. https://doi.org/10.1109/TMC.2021.3129094

[17] Shi, W., Li, W., Cheng, J., Lyu, N., Zhang, F., Zhou, S., *et al.* (2019) Multi-Drone 3-D Trajectory Planning and Scheduling in Drone-Assisted Radio Access Networks. *IEEE Transactions on Vehicular Technology*, **68**, 8145-8158. https://doi.org/10.1109/TVT.2019.2925629

[18] Rakuten (2021) From Space to Your Smartphone: AST SpaceMobile's Mission to Help Connect Billions to Cellular Broadband. Rakuten Report. https://rakuten.today/blog/ast-spacemobiles-mission-to-help-connect-billions.html

[19] HAPS Alliance (2021) High-Altitude Platform Stations. https://hapsalliance.org

[20] Telefonica (2021) Telefonica Uses Intelsat Satellite to Boost Mobile Connectivity. https://www.commsupdate.com/articles/2021/12/09/telefonica-uses-intelsat-satellite-to-boost-mobile-connectivity

[21] Darwish, T., Kurt, G.K., Yanikomeroglu, H., Bellemare, M.G. and Lamontagne, G. (2021) LEO Satellites in 5G and beyond Networks: A Review from a Standardization Perspective. https://doi.org/10.1109/ACCESS.2022.3162243

[22] Speedtest (2021) Speedtest Global Index. https://www.speedtest.net/global-index

[23] Mann, A. and Pultarova, T. (2022) Starlink: SpaceX's Satellite Internet Project. https://www.space.com/spacex-starlink-satellites.html

[24] Boyle, A. (2020) SpaceX CEO Elon Musk Says There's Nothing to Fear from Starlink Broadband Satellites. Yahoo Finance. https://finance.yahoo.com/news/spacex-ceo-elon-musk-says-012902306.html