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An overview of communication and orbital composition technologies based on starlink LEO satellite constellation from a technical perspective

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Abstract. With the development of fiber optic and communication technology, densely populated areas have been provided with the good network coverage. However, rural, suburban, ocean and airborne areas still lack economical and effective means of network connectivity. Although the concept of low-orbit communication satellite constellations such as Iridium was proposed in the 1990s, it was not successful due to satellite performance and launch costs. Since 2016, SpaceX has envisioned the construction of the Starlink constellation to provide high-speed Internet services worldwide, which is now operational. This study attempts to analyze the basic theory and performance levels of several key Starlink technologies to analyze the basic characteristics of Starlink in orbital deployment, terrestrial communication, and inter-satellite communication. However, Starlink still has difficulties in various technologies. By exploring new research advances in these areas, the performance of the constellation can be optimized or new solutions can be found. An analysis of Starlink's key performance metrics shows that the key to the success of Starlink's project is the industrialization of advanced laboratory technologies and their application to the design and deployment of satellite constellations.

Keywords: LEO satellite constellation, starlink, phased array antenna, free space optical communication, satellite orbital plane.

1. Introduction

The current low-orbit satellite constellation has undergone two phases: from the 1990s to the early 21st century; and after 2015, especially after 2020, when the development rate has been greatly enhanced. The 90s low-orbit satellite research was the initial exploration and attempt of this system [1]. This is represented by Motorola's Iridium satellite communication system, but the development of mobile networks after the 1990s envisaged the full advantage of low-orbit satellite constellations that provide services directly to users [2]. The operating costs of satellite communications in the 1990s were too high, especially the rocket launch was expensive, but the number of users that could be served was extremely limited. Therefore, for a long time after the popularization of mobile networks, satellite communication services were mainly provided using the Geostationary Orbit (GEO) satellites, only three of which were theoretically able to cover the Earth. While GEO satellites were expensive and could not provide high-speed Internet services due to the very high communication latency and low bandwidth of satellites located in 36,000km near-earth orbit. The new Low Earth Orbit (LEO) satellite communication

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constellation is an innovative product after absorbing the experience of past failures. The constellations currently under construction or planned are SpaceX's Starlink, Oneweb, Amazon's Kuiper and Telesat constellations. The Starlink constellation is the largest and most advanced of these constellations. The new generation of LEO satellite constellations will mainly serve areas that cannot be covered by traditional means of communication (e.g. fiber optics, cell phones) and will replace the traditional geostationary orbit communication satellite services. At the same time, with the development of 5G to 6G communication, air-space integration and integrated communication technology between heaven and earth begin to emerge gradually. The communication satellite constellation is regarded as a key part of the Internet of Everything technology [3]. The current studies focus on analyzing the competitive dynamics among different LEO constellations and comparing the performance advantages and disadvantages among LEO constellations in terms of cost per unit capacity, ground terminal configuration, orbit design and ground coverage, and satellite operating frequency bands [4]. These studies combine the trends in the civil market as well as the performance and characteristics of the constellations to study the development prospects of LEO satellite communication constellations. This paper collates and justifies the latest research progress in the key components of these, deriving the performance targets that can be achieved by current technologies and suggesting the feasibility of current technologies to overcome the difficulties of satellite communications. The key technologies of the LEO satellite network will help to improve the performance of a single satellite and optimize the satellite network. This research has positive implications for the future development of LEO constellations since satellites also require continuous iterations to reduce operating costs and increase the number of service users as technology evolves and the number of LEO competitors continues to grow.

2. The orbit plane with coverage and rate

2.1. Height of orbital surface

Currently, the common orbital altitude of Starlink is 550km and the orbital inclination is 53°. After adjustment, Starlink will be deployed into 8 orbital layers in total, and different orbital layers have different inclination angles. Although the details are different, they can be divided into three categories: LEO orbits located around 550km at an inclination of 55 degrees, as well as 550km Sun-synchronous orbit (SSO) orbits mainly used to cover high latitudes, and 350km orbits that have not been deployed but can provide faster communication speeds [5]. It is assumed that Starlink and GEO orbiting large communication satellites have the same coding and decoding speed, and the difference in time delay depends on the distance between the satellite and the ground. The data transmission links are: user terminal — Starlink satellite and inter-satellite routing — Starlink ground station — Starlink satellite and inter-satellite routing — user terminal. The speed of light in space is known to be 299,792,458 meters per second. The transmission time from the user terminal to the satellite in 550 km orbit is about 1.83ms, and the time to complete the data transmission round trip is 1.83ms*4=7.32ms, while the orbit altitude of the geostationary communication satellite is 36000km, and the data transmission time is about 220ms [6].

2.2. Coverage density as well as rate

Four models are commonly used to estimate the coverage density and transmission rate from different perspectives. They are:

1. atmospheric model takes into account the attenuation of signals during atmospheric, cloud, tropospheric lightning and rainfall.

2.The network connectivity model is based on the modulation and coding scheme of the communication constellation.

3. Demand model grids the distribution of the world's population and assumes the proportion of Starlink users in different regions and the average bandwidth consumption of individual users.

4. A ground coverage model uses a genetic algorithm to maximize the total coverage at 95% and 99% availability.

2.3. Estimation of coverage and rate

New estimation methods are currently available for coverage density and rate, which no longer rely on specific calculations for each satellite's orbit but introduce a stochastic geometric approach that simplifies the point process of the satellite network with binomials. This process eventually yields analytic formulas for downlink network coverage and average data rates for the LEO communication constellation. The algorithm is able to obtain the general performance of a particular satellite network and gives a design guideline for the design of LEO satellite constellations such as communication bands, orbit altitude and inclination. The current distribution of Starlink can be seen as a dense uneven distribution of satellites at low and middle latitudes and a sparse uneven distribution at high latitudes. Considering the huge number of Starlink one can first model the satellites according to the uniform distribution of the spherical shell in near-Earth orbit and then according to the actual coverage density of the satellites at middle and high latitudes [7]. Finally, new parameters are introduced to obtain the LEO coverage density of the constellation.

The conversion is performed in several steps. First, the Laplace transform of the satellite distribution in the frequency domain is performed to obtain a theoretical expression between the user coverage probability and the practical data vessel lodging velocity. Subsequently, the theoretical results are validated by numerical simulations, and actual usage data from existing satellite constellations are introduced for comparison. For the case that there is an error between the data calculated by the theoretical expression and the actual satellite constellation, the reason is that the satellites at different latitudes are not covered according to a uniformly distributed model. In this case, the concept of the effective number of satellites at different latitudes is introduced, and the new expression between the coverage probability and transmission rate is obtained after correcting the theoretical expression with a new parameter [7]. As already mentioned above, due to the middle and high latitudes, the number of satellites over the user is greater than the equatorial annex. However, due to the limitation of the angle of the satellite receiver and the transmission loss of electromagnetic waves in the atmosphere, some of the satellites with too small an angle between the earth (for the overhead inclination is too large) can not actually produce an effective connection with the ground station. But in 2020, SpaceX filed with the Federal Communications Commission (FCC) that the angle between the antenna of the Starlink receiver and the earth would be reduced from 40° to 25°. This is an increase in the number of effective satellites for users at mid and high-latitudes, and a corresponding increase in Starlink's coverage and network speeds at mid and high-latitude regions.

2.4. Satellite lift and reentry

The satellite uses a solar panel-powered krypton ion thruster instead of the non-usual xenon ion thruster because it is cheaper. Satellites are typically released at an orbital altitude of 200km to 300km and then climb to their intended orbits within a few months. Starlink satellites currently have an expected lifetime of seven years, at which time they will be actively de-orbited using electric propulsion technology. When the satellite fails in orbit or after a failed active de-orbit, it quickly re-enters the atmosphere due to the attenuation of the Earth's atmospheric drag due to its lower orbital altitude [8].

3. Phased array antenna used on Starlink

3.1. Satellite phased array antenna

Phased array antennas are mainly used in satellite communication in the form of Direct Radiating Arrays (DRA) and Array Fed Reflectors (AFR). AFR uses a large deployable umbrella antenna as the fugitive reflector antenna, which combines with phased array feed arrays to form several different pointing beams, but this structure is mostly used for GEO orbiting geostationary communication satellites. The DRA transceiver signal is directly radiated, and the cost and power consumption are high through Radio Frequency (RF) beamforming network (BFN) or digital beamforming to meet the needs of LEO multipoint beam, agile beam, beam reconstruction and wide-angle scanning. For spaceborne low-orbit communication satellite constellations, which face the need for fast satellite switching and high-speed communication, traditional focal array feed reflectors (FAFRs) will face the problem of reflector deployment and feed cluster/reflector alignment [9].

From the orbital altitude and flat panel structure of Starlink, Starlink uses direct radiating array (DRA). Each satellite has four direct radiating phased array antennas. For the Starlink satellite, the lower orbit altitude of 550km requires the antenna to have a large scan angle, therefore, the satellite antenna at this orbit altitude adopts the direct radiation phased array configuration. In addition to the wide scan angle, the size and mass of the phased array antenna are greatly compressed. At the same time, if each original is fed separately, a complex feed network will be required, which increases the cost of the satellite. To obtain high end-of-coverage (EOC) directionality, low Sidelobe Levels level and grating flap rejection level DRA, fractal technology can be used as a basic process and different generators can be combined to finally obtain an array of “hybrid-fractal” antenna arrays. Fractal arrays not only have multi-band and low side lope characteristics, but also can use algorithms to achieve fast beamforming.

3.2. User receiver

For receivers, electrically scanned arrays (ESA) have the advantages of fast beam scanning capability, low profile and high conformal capability compared to mechanically scanned antennas. When ground equipment and LEO satellites communicate, ESA generated circularly polarized (CP) radiation energy couple minimizes the physical alignment of antenna polarization, thus reducing the polarization loss. By manipulating the field distribution of the antenna radiation aperture, the antenna beam can be shaped and steered in a specific direction [10]. Thus, the ESA manipulates the electromagnetic field by controlling the excitation amplitude and phase of the antenna elements, so the transmission loss from the active component to the heat sink is significantly reduced. According to the user disassembly of the Starlink receiver, it has an ESA antenna structure and has about 500 Transmitter and Receiver (T/R) components.

However, ESA have encountered two major difficulties in the process of performance improvement. Firstly, due to the increase in operating frequency, the coupling between components is increasing, resulting in a reduction in source impedance matching and beam pointing accuracy during scanning, and causing problems such as distorted radiation patterns and increased scanning blind spots, ultimately affecting the performance of the ESA antenna [11]. For circularly polarized CP antennas, component inter-coupling in wideband design can seriously reduce polarization purity. The second difficulty is that as the integration complexity increases, the component spacing and size are also reduced, resulting in heat dissipation problems, limiting the performance. This difficulty is circumvented by using wafer technology to manufacture multi-channel beamforming chips, or by using controlled channels to combine multiple components to reduce the number of channels and ultimately avoid gate flaps.

These two difficulties can be overcome by Metantennas made of metamaterials with unique electromagnetic properties. For example, dispersion-engineered resonant metantennas are used to achieve antenna miniaturization and beam scanning. For Ka-band (i.e., Starlink operating band), a high-bandwidth compact metatantenna can be developed with reference to the idea of high-bandwidth low-frequency antennas for application to circularly polarized phased array antennas [11]. Two square patch arrays are printed on the top and bottom sides of the substrate to form a dense metasurface. The double-layer metasurface and enhanced capacitive coupling allow the antenna to be evenly miniaturized. Broadband CP waves are generated by single series stripline fed cross-slot coupling structure. The 8×8 CP phased array antennas are fabricated using broadband compact antennas, while every 8×2 antennas form a subarray and are driven by a 16×1 RF board. The test results show that the bandwidth and ambiguity resolution of the wideband compact metatennas are greatly improved compared to conventional patch antennas using the same substrate. Metantennas achieve broadband CP radiation with low original coupling, while another example significantly reduces the number of phase shifters on a large aperture. Both techniques enhance the performance of phased array antennas at the receiver [12].

3.3. Terrestrial injection stations

Starlink uses Adaptive Coding and Modulation (ACM) for the connection between the satellite and ground receiver. Starlink chooses Modulation and Coding(MODCOD) to maximize throughput for any orbital position and atmospheric conditions. Coverage and transmission rates for satellites can be improved when satellites are equipped with dual active antennas and when user receivers can operate at lower minimum elevation angles. In some previous capacity calculations, intra- and cross-plane inter-satellite links (ISL) links have contributed significantly to the capacity increase and transmission rate of a constellation of communication satellites. Optical ISL has been incorporated into the current launch of v1.5 satellites.

Previous calculations indicate that the maximum total system throughput (saleable capacity) for the OneWeb, Telesat and SpaceX constellations is 1.56 Tbps, 2.66 Tbp, and 23.7 Tbps, respectively. SpaceX would need more than 123 [13]. To date, SpaceX has submitted applications for 32 domestic U.S. ground stations that have been approved in multiple states, according to FCC filings. The documents show that most of the gateway stations are connected using 1.5-meter antennas. Starlink will use the Ka band for gateway communications (17.8-19.3 GHz and 27.5-30.0 GHz for downlink and uplink, respectively) and the Ku band for user links (10.7-12.7 GHz and 14.0-14.5 GHz for downlink and downlink, respectively). Of course, with the development of the Starlink laser link, the distribution, number and use of ground gateway stations will vary with Starlink's own satellite control, operation and maintenance of the ground stations, and the number of gateway stations can be lower than the theoretical calculation of at least 123 [14].

4. Free space optical communication and network

4.1. Space optical communication

Currently, SpaceX's V1.5 star chain is equipped with inter-satellite laser communication and inter-satellite laser equipment to achieve high-speed connections between different satellites and to overcome ground station constraints. SpaceX has never announced the technical details of the laser link except for the previous experimental satellites. The large-scale application of laser link in LEO is an unprecedented task. We can study the laser link of the star link with the existing Free Space Optical Communication (FSO) technology.

For a global communication system, inter-satellite communication requires high bandwidth and low latency to provide network services. Compared to conventional RF communications with millimeter waves (already a very short band), optical communication systems offer greater user carrying capacity because the wavelength of light is much smaller than the wavelength of electromagnetic waves. The first is the enormous bandwidth. Current laser communication technology has several specific wavelengths, i.e., 800nm, 1000nm, 1550nm or so. For the space environment, satellites work more wavelengths in the 820nm–920nm range [15]. We already know that the bandwidth of RF communication can reach 20% of the carrier frequency. If laser communication technology can reach this ratio, allowing bandwidth to reach thousands of terahertz level, and then after the use of wavelength division multiplexing Bandwidth can even be further increased. Currently for optical transmission distance and transmission rate, optical transmitter and receiver play a decisive role. From the test results of Optical Inter-Orbit communication engineering test satellite, which uses the 819nm band, a communication speed of 2.048Mbps was obtained [15]. But this is not enough for the satellite chain, so SpaceX has apparently significantly improved the performance of the laser transceiver on the satellite, as evidenced by the successful service of hundreds of thousands of users in the V1.5 version of the satellite.

Compared to RF antennas, laser communication links have a smaller size and lower power consumption. According to the positive correlation between divergence and λ/DR, the wavelength of light is much smaller than RF so it has less scattering. Secondly, optical communication has higher antenna gain when the antenna size is the same. The reason for this is that the antenna gain is inversely proportional to the square of the wavelength of the carrier frequency, and optical communication can theoretically reduce the antenna size to 8 orders of magnitude of the millimeter wave antenna compared to the millimeter wave. The smaller divergence brings smaller antenna size, the higher frequency brings

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higher antenna gain, and the end result is that the energy consumption and weight of optical communication is less than RF communication [16]. This is critical for Starlink satellites because the flat panel design of Starlink allows for a limited amount of space and power to be available for inter-satellite communication systems. Compared to RF communications, laser communication links have a highly directional laser beam that is less susceptible to interception, and spectrum analyzers and RF meters cannot detect FSO communications. So the FSO laser link has high security and anti-interference. At the same time, spectrum resources are currently very crowded. For example, Starlink's downlink spectrum signals have already conflicted with individual bands of 5G. This can reduce development costs and waiting times since the spectrum for optical systems does not need to be approved by the International Telecommunication Union (ITU) or local authorities.

4.2. Current technical difficulties and solutions

Inter-satellite links do not need to consider a series of problems such as weather effects, human eye safety, atmospheric turbulence, and light speed divergence. However, there is still a need to solve the problems of Point-ahead-angle (PAA), Doppler shift, capture and tracking, background radiation and satellite platform stability. Especially for a near-Earth orbit constellation like Starlink, the relative velocity between satellites is large, so solving the laser capture and tracking problem becomes a key point. The solutions to each problem will be introduced next [16].

Pioneer angle: For Starlink, which has a large relative motion speed, the laser beam needs to compensate the time of light transmission between two satellites when it is shot from one satellite to another, so that it can accurately hit the other satellite. Therefore, a leading angle called PAA is introduced, and studies have shown that the leading angle of LEO satellites is about tens of micro-radians [14].

Doppler shift: Due to the relative velocity between the satellite transmitting the laser beam and the receiving satellite, the resulting Doppler effect causes the frequency of the receiving optical signal to change, which in turn causes data loss and frequency synchronization problems. This problem can be solved by optical phase-locked loop (OPLL) or optical injection phase-lock loop (OIPLL), which is a combination of optical phase-locked loop and optical injection.

Vibration and tracking: The vibration is caused by Starlink's own solar panels and particle thrusters, as well as various relative intensity noises (RIN), thermal noise, dark current scattering noise, signal scattering noise, and background scattering noise generated by the laser link. These noises can amplify the laser alignment errors. This type of error can be addressed by various tracking methods, such as Discriminative Correlation (DC) tracking, pulse tracking, square law tracking, coherent tracking, tone tracking, feedforward tracking, and frame tracking, but the tracking method used by Starlink is not known at this time [17].

Although the atmospheric impact of optical communication on the ground does not have to be considered at 550km orbit due to the huge relative movement between different orbiting Starlink satellites and the limited power supply due to the solar panels on the finite surface level of the satellite, existing studies show that the use of phase coherence techniques (e.g., zero or outlier) can save energy and increase link capacity compared to direct detection, and the techniques have been validated by satellites. Several major technical challenges currently have solutions.

5. Discussion

But for the future constellation of tens of thousands of satellites in space, each satellite will have to use intra- and cross-plane inter-satellite links (ISL) links for information transfer using space free optical communication [18]. With the use of laser links, information will not simply be sent from a receiver to a satellite, which will downlink to a ground station that can connect to the satellite, and then to the Internet via fiber optics. Rather, it will be transmitted between satellites, or multiple satellites relayed before going downstream [19]. Therefore, we need to find the optimal link between satellites and allocate the link traffic to maximize the traffic carrying capacity. Usually, the nearest satellite is not efficient in transmitting signals and is prone to congestion, so two ideas of topology design and optimal routing are introduced. Topology design is represented as a mixed integer optimization problem with a minimum-maximum objective function subject to a set of linear constraints. When the topology with the best performance appears, it implies optimal routing, a routing pattern that distributes the total traffic in the network in the most balanced way, so that the load on the most bottleneck links in the network is minimized, allowing the network to satisfy the given traffic demand to the maximum extent. But this algorithm grows exponentially with the complexity of the satellite network. The second scheme, on the other hand, is an improvement of the first one. The initial topology is performed first, with the goal of routing between Starlink's satellites with the minimum number of hops. The principle is that nodes with higher traffic demands are connected using fewer hops. This initial topology selection problem can be approximated as an integer linear programming problem. The maximum usage of the links is minimized by using the optimal routing problem, so that the traffic on each link should be distributed as evenly as possible. Finally, performance improvements are obtained using simulated annealing, which accepts new topologies with a higher probability of higher objective function values [19].

6. Conclusion

It can be concluded from the paper that the transmission bandwidth of the constellation is significantly increased by benefiting from the free-space optical communication capture technology and the improved performance of the laser transceiver. Advances in phased array antenna technology and cost reductions have led to a significant increase in the communication bandwidth of a single satellite while the cost is reduced due to vertical production. At the same time, the use of recoverable rockets or a new generation of commercial rockets has led to a corresponding reduction in satellite launch costs, enabling its LEO satellite network to meet the time constraints and large scale of the network. But we also note that artificial intelligence technologies, especially algorithms that emerge with large-scale satellite constellations, have significantly optimized satellite networking models. Although the current deployment speed of Starlink is still limited by the launch vehicle, there are criticisms in the astronomical community due to light pollution from space. However, with the rapid iteration of satellites, current experimental innovations can be rapidly applied to the Starlink constellation, allowing the vision of Starlink's global high-speed satellite communications network to be realized. In this paper, it is not possible to analyze the specific technical details and performance parameters of Starlink, but only to list the existing analysis methods and technical solutions. Next, targeted analysis and predictions can be obtained after modeling and simulating the performance of the constellation using the analysis methods in existing studies, combined with some electronic component configurations and parameters already disclosed by Starlink.

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