Satellite Constellation Optimization for 6G and Beyond Satellite Networks

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***Abstract*—6G technology will integrate satellite networks to provide global coverage, support Direct-to-Device communication in coverage gaps, and enable massive IoT connectivity. This paper presents an optimization strategy for designing satellite constellations to minimize the number of satellites while meeting 6G user needs for unmodified handheld devices. Key factors in the optimization include orbital geometry, satellite antenna specifications, and quality-of-service metrics such as signal-to-noise ratio, satellite visibility, and the number of visible satellites. Simulation results indicate that to provide service to a handheld device at any location on Earth's surface, a satellite operating in the S-Band requires 4337 VLEO satellites at an altitude of 183.4 km to achieve a data rate of 18 Mbps and 574 LEO satellites at an altitude of 558.68 km to achieve a data rate of 7.5 Mbps.**

I. INTRODUCTION

The 6G system will incorporate satellite networks to enable global, massive connectivity, particularly by providing coverage for underserved and unserved areas with limited or no access to 6G services [1]. Furthermore, a 6G satellite system is expected to provide voice and data services to handheld devices, such as smartphones and wearables, as well as to vehicles, without requiring any modifications to their hardware or software [2]. Hence, to deliver 6G services and meet the link budget for unmodified handheld devices, it is essential for satellite operators to design an optimal satellite constellation. This includes selecting the appropriate satellite altitude, determining the number of satellites in the constellation, and assessing factors such as satellite coverage, visibility, and the number of satellites visible to a user at any given time. Additionally, the design needs to ensure adequate signal quality and low latency. Furthermore, the constellation design also affects the satellite payload's antenna requirements, thereby indirectly affecting the DC battery, processors, and RF chain. Hence, an optimal satellite constellation design must account for the payload architecture, including antenna requirements, as well as the above-mentioned service requirements.

Several studies have been conducted regarding satellite satellite constellation design based on orbital geometry. In [3], a Walker Delta and Walker Star constellation was proposed with parameters for orbital planes, satellite spacing, and phasing to ensure uniform global coverage with a minimal number of satellites. In [4], a rosette constellation design is introduced, providing a framework for distributing satellites to achieve consistent ground coverage patterns. However, these designs primarily focus on geometry and do not consider the satellite antenna payload and the user service requirements.

On the other hand, in [5], a design for a satellite constellation in Low Earth Orbit (LEO) is presented that optimizes the system's downlink capacity by accounting for both orbital parameters and payload antenna constraints. However, it focuses on optimizing the number of satellites by examining the relationship between satellite coverage and the required number of antennas. Furthermore, a quality-of-service (QoS)-driven satellite constellation design for LEO satellite Internet of Things (IoT) has been proposed in [6]. However, both proposed solutions in [5] and [6] do not explore the impact of key factors, such as satellite altitude (in [6], it is limited to IoT applications), number of antennas, beamwidth, satellite visibility, and the number of satellites visible at any given time, on the provision of 6G services for unmodified handheld devices. Furthermore, these papers do not provide detailed information on the number of satellites required for global coverage, as the values of the aforementioned factors change.

In this paper, we propose an optimal satellite constellation design that accounts for orbital geometry, satellite payload requirements, and quality-of-service metrics, including the signal-to-noise ratio (SNR), as well as satellite visibility time and the number of satellites visible to a ground user at the same time, which are critical for flexible connectivity and handover management. The paper's contributions are described as follows.

- We propose a satellite constellation algorithm to optimize the number of satellites required for global coverage while meeting the 6G Handheld devices.
- We developed a mathematical model to determine the minimum number of satellites visible to a ground user as a function of altitude. Additionally, we develop a mathematical model to determine the number of antennas required for satellite coverage as a function of satellite altitude and beam radius.
- Finally, we provided extensive numerical results of the proposed algorithm for constellation design.

The paper is organized as follows: Section II outlines the scenario model. Section III presents the problem formulation along with the proposed solution. The simulation results are discussed in Section IV. Finally, Section V summarizes the contributions of the paper.

II. SCENARIO MODEL

We consider optimizing satellite constellations to enable the provision of 6G services for handheld devices worldwide. This involves several important considerations, including satellite coverage, the duration each satellite is visible to a user (satellite time visibility), the minimum number of visible satellites at any given time, specifications for satellite payload antennas, and service quality requirements for users. The specific requirements for the constellation optimization are discussed as follows:

A. *Satellite coverage and time visibility requirement*

Here, we determine the satellite coverage area and visibility time as a function of satellite altitude. Fig. 1 illustrates the geometry involved in calculating satellite coverage based on altitude. The coverage radius can be expressed as $R_s = R_E\theta$, where R_E is the radius of the Earth and θ is the central angle measured in radians. This angle θ is determined as a function of the elevation angle δ and the satellite's altitude H as follows.

$$\theta = \left(\frac{\pi}{2} - \delta - \arcsin\left(\frac{R_E}{R_E + H}\cos\delta\right)\right). \tag{1}$$

While considering the coverage radius, the satellite time visibility for a user located at the edge of the coverage is given by

$$T_{vis} = \frac{2R_s}{v}, \tag{2}$$

where $v = \sqrt{\frac{GM}{R_E+H}}$ is the orbital velocity, with G being the gravitational constant and M representing the mass of the Earth.

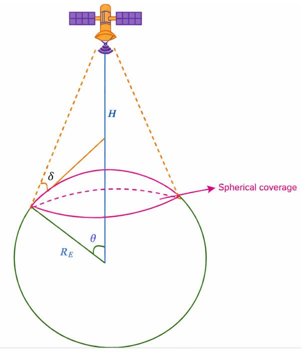

Fig. 1. Coverage geometry [7].

B. *Satellite constellation design requirement*

We consider a Walker-star constellation denoted as I: T/P/F, where I represents the orbital inclination, T is the total number of satellites, F is the phasing between satellites in adjacent planes, and P is the number of equally spaced geometric planes distributed over a span of 180 degrees. Given an elevation angle δ, the values for T and P are determined as follows:

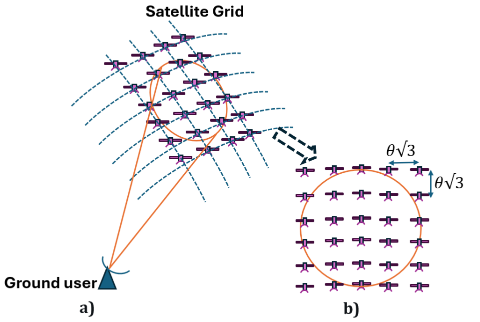

Fig. 2. a) The number of satellites that the user can view simultaneously. b)Gauss circle problem.

$$T = \left\lceil \frac{\pi}{\sqrt{3}\theta} \right\rceil \left\lceil \frac{2\pi}{\sqrt{3}\theta} \right\rceil, \tag{3}$$

$$P = \left\lceil \frac{\pi}{\sqrt{3}\theta} \right\rceil. \tag{4}$$

The value of F can range from 0 to $P-1$, and it is chosen to minimize the maximum distance between adjacent satellites [7].

C. *Number of satellite visibility requirements*

A satellite constellation with multiple satellites visible to a user provides flexible connectivity. For instance, if one satellite is affected by rain fading, the user can switch to another satellite. Additionally, it enhances dual connectivity. On the other hand, this setup allows a gateway device to connect to multiple satellites. In this context, consider Fig. 2, which illustrates the number of satellites visible to a user at any given time. The user achieves a perfect circular view of satellites when located at 0 degrees latitude and longitude. In this case, we can obtain the minimum number of visible satellites (M_{sat}). Determining the number of satellites within the circle is analogous to the Gauss circle problem, which involves counting the number of integer lattice points within a circle centered at the origin. This can be approximated as follows.

$$M_{sat} \approx \frac{A_{circle} - A_{boundary}}{A_{grid}} \tag{5}$$

where $A_{circle} = \pi\hat{\theta}^2$, $A_{boundary} = \pi\hat{\theta}$, and $A_{grid} = 3\theta^2$, which can be simplified as

$$M_{sat} \approx \pi\left(\frac{\hat{\theta}}{\theta\sqrt{3}} + 1\right)^2 - \pi\left(\frac{\hat{\theta}}{\theta\sqrt{3}} + 1\right). \tag{6}$$

Where $\hat{\theta}$ represents the circle of a specified radius, determined as follows:

$$\hat{\theta} = \left(\frac{\pi}{2} - \hat{\delta} - \arcsin\left(\frac{R_E}{R_E + H}\cos\hat{\delta}\right)\right). \tag{7}$$

Where $\hat{\delta} < \delta$ represents the minimum elevation angle required for a ground user to be visible from a satellite[1].

D. Satellite payload requirements

Fig. 3 illustrates a generic digital payload comprising several components, including a filter, a low-noise amplifier, a mixer, and a gain controller, along with analog-to-digital converters (ADCs), digital-to-analog converters (DACs), and digital processors. These digital processors perform functions such as digital beamforming, modulation and demodulation, channelization, and routing or switching. A typical payload of this type is a regenerative onboard processor. Alternatively, if the payload does not provide modulation and demodulation capabilities, it is known as a Digital Transparent Payload (DTP) [8].

The number of antennas significantly influences the satellite's digital payload. For instance, as the number of antennas increases, the required number of RF chains (including ADCs/DACs and power amplifiers) also increases. This increases the requirement for high DC power, which affects the satellite's battery and solar panel design. Consequently, this impact extends to the satellite's overall mass and cost. For this reason, we consider the satellite's payload requirements as a function of the number of antennas. More antennas can enhance coverage and improve service quality, but it also increase the satellite's mass and cost. Conversely, reducing the number of antennas leads to diminished coverage and service quality. Therefore, our focus is on determining the necessary number of antennas to meet both coverage and service quality requirements for the satellite.

In the above context, consider the payload equipped with a rectangular planar array. For large planar arrays, the directivity D can be approximated using the half-power beamwidths (HPBW) in the azimuth and elevation planes [9]:

$$D \approx \frac{32,400}{\Theta_{\text{HPBW, az}} \times \Theta_{\text{HPBW, el}}}, \tag{8}$$

where $\theta_{\text{HPBW, az}}$ and $\theta_{\text{HPBW, el}}$ are refers the half-power beamwidth in the azimuth plane (in degrees) and elevation plane (in degrees), respectively. Given the radius of the beam R_{beam}, the half-power beamwidth for the azimuth and elevation plane is approximated as

$$\Theta_{\text{HPBW}} = 2\arctan\left(\frac{\sin\left(\frac{R_{beam}}{R_E}\right)}{\frac{H}{R_E} + 1 - \cos\left(\frac{R_{beam}}{R_E}\right)}\right). \tag{9}$$

On the other hand, the directivity of an antenna can also be expressed in terms of its physical aperture area A_p and aperture efficiency η_A [9]:

$$D = \frac{4\pi\eta_A A_p}{\lambda^2} \tag{10}$$

By equating the two expressions for directivity, we can solve for the physical aperture area A_p in terms of the beamwidths, wavelength, and aperture efficiency:

$$A_p = \frac{32,400\lambda^2}{4\pi\eta_A \Theta^2_{\text{HPBW}}}. \tag{11}$$

Hence, the total number of elements N that a payload is equipped with is determined as the ratio of the total aperture area to the area occupied by a single element.

$$N = \frac{A_p}{A_{\text{element}}}. \tag{12}$$

With uniform element spacing of rectangular planner array ($d_x = d_y = d_{\text{element}}$), thus $A_{\text{element}} = d^2_{\text{element}}$ and d_{element} is the maximum allowable element spacing to ensure that grating lobes fall outside the field of view (FoV) is given by [10], [11]:

$$d \leq \frac{\lambda}{2\sin(\theta_{\max})}, \tag{13}$$

where $\theta_{\max} = \arcsin\left(\frac{R_E}{R_E+H}\cos\delta\right)$, the maximum steering angle, which is half of the total FoV angle. Hence, N becomes

$$N = \frac{32,400\lambda^2}{4\pi\eta_A \left(\frac{\lambda}{\frac{2R_E}{R_E+H}\cos\hat{\delta}}\right)^2 \Theta^2_{\text{HPBW}}} \tag{14}$$

The gain of the satellite antenna at the edge of the beam is given by.

$$G_{tx}[dB] = G_{\text{element}} + 10 * \log 10(N) - 3, \tag{15}$$

where $G_{element}$ the gain of the antenna element.

E. Quality-of-service requirements

Assuming clear sky channel conditions, the SNR received by a user located at the coverage edge of the satellite is given by:

$$\gamma = \frac{P_{tx}}{\sigma^2}\frac{G_{rx}G_{tx}}{(\frac{4\pi d}{\lambda})^2}. \tag{16}$$

where P_{tx} is the transmitted power, λ is the wavelength, G_{rx} is the user antenna gain in linear, σ^2 is the noise, and d is the distance from the user to the satellite, which is determined as

$$d = \sqrt{R_E^2 + (R_E+H)^2 - 2R_E(R_E+H)cos(\hat{\theta})}. \tag{17}$$

The SNR γ must meet the minimum quality of service defined by the operator, γ_{QoS}. Therefore, the condition $\gamma \geq \gamma_{QoS}$ must be satisfied, and the chosen altitude of the satellite should comply with the following inequality.

$$\begin{aligned} &R_E^2 + (R_E+H)^2 - 2R_E(R_E+H)cos(\hat{\theta}) \\ &\leq \frac{P_{tx}}{\sigma^2}\frac{G_{rx}G_{tx}}{(\frac{4\pi\sqrt{\gamma_{QoS}}}{\lambda})^2}. \end{aligned} \tag{18}$$

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[1] Note that in eq. (6), 1 is included to account for the endpoint. For example, given a diameter L and a step size Δ, the number of points is equivalent to $\frac{L}{\Delta} + 1$.

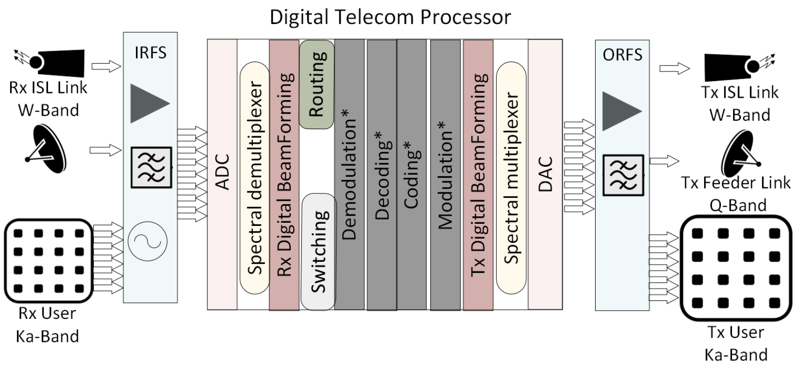

Fig. 3. Generic regenerative digital payload system. * Modules used for Regenerative Transparent Payload

III. PROBLEM FORMULATION AND PROPOSED SOLUTION

In this work, our objective is to minimize the total number of satellites required to operate in space while ensuring that several criteria are met. These criteria include the quality of service SNR (γ_{QoS}), the minimum satellite visibility time (T_{vis}^{mini}), the minimum number of satellites that must be visible to a user at the same time (M_{sat}^{mini}), and the constraint on the number of antennas allowed on the satellite payload ($N_{antennas}^{max}$). In this context, we formulate the following optimization problem.

$$\begin{aligned}
&\underset{H,P_{tx},\delta,\hat{\delta}}{\texttt{minimize}} \quad T\\
&\texttt{s.t.}\\
&\qquad L1:\\
&\qquad R_E^2+(R_E+H)^2-2R_E(R_E+H)cos(\hat{\theta})\\
&\qquad \leq \frac{P_{tx}}{\sigma^2}\frac{G_{rx}G_{tx}}{(\frac{4\pi\sqrt{\gamma_{QoS}}}{\lambda})^2},\\
&\qquad G_{tx}=G_{element}\frac{32,400\lambda^2}{8\pi\eta_A\left(\frac{\lambda}{\frac{2R_E}{R_E+H}\cos\hat{\delta}}\right)^2\Theta^2_{\text{HPBW}}},\\
&\qquad L2:\frac{2R_s}{v}\geq T_{vis}^{mini},\\
&\qquad L3:\pi\left(\frac{\hat{\theta}}{\theta\sqrt{3}}+1\right)^2-\pi\left(\frac{\hat{\theta}}{\theta\sqrt{3}}+1\right)\geq M_{sat}^{mini},\\
&\qquad \hat{\theta}=\left(\frac{\pi}{2}-\hat{\delta}-\arcsin\left(\frac{R_E}{R_E+H}\cos\hat{\delta}\right)\right),\\
&\qquad \theta=\left(\frac{\pi}{2}-\delta-\arcsin\left(\frac{R_E}{R_E+H}\cos\delta\right)\right),\\
&\qquad L4:\frac{32,400\lambda^2}{4\pi\eta_A\left(\frac{\lambda}{\frac{R_E}{R_E+H}\cos\hat{\delta}}\right)^2\Theta^2_{\text{HPBW}}}\leq N_{antennas}^{max},\\
&\qquad L5:H_{min}\leq H\leq H_{max}.
\end{aligned}\tag{19}$$

Problem (19) is nonconvex and cannot be solved directly using convex optimization methods. However, given the value of P_{tx}, δ and $\hat{\delta}$, the optimization problem is dependent only on H. In this case, we can determine the value of H that minimizes the objective function T while satisfying the constraints of $L1$, $L2$, $L3$, and $L4$. To solve the problem, we follow the following steps

- Step 1: Discretize constraint $L5$ into K points, $\mathcal{H}=\{H_1,H_2,\ldots,H_k,H_K\}$, with $H_1=H_{min}$ and $H_K=H_{max}$.
- Step 2: Expressing the inequality constraints $L1$,$L2$,$L3$, and $L4$ in ratio form with a lower bound of 0, as follows.

$$\begin{aligned}
&L1:\gamma^{ratio}=\frac{\frac{P_{tx}}{\sigma^2}\frac{G_{rx}G_{tx}}{(\frac{4\pi\sqrt{\gamma_{QoS}}}{\lambda})^2}}{d^2}-1\geq 0,\\
&L2:T^{ratio}=\frac{\frac{2R_s}{v}}{T_{vis}^{mini}}-1\geq 0,\\
&L3:M^{ratio}=\frac{\pi\left(\frac{\hat{\theta}}{\theta\sqrt{3}}+1\right)^2-\pi\left(\frac{\hat{\theta}}{\theta\sqrt{3}}+1\right)}{M_{sat}^{mini}}-1\geq 0,\\
&L4:N^{ratio}=\frac{\frac{32,400\lambda^2}{4\pi\eta_A\left(\frac{\lambda}{\frac{R_E}{R_E+H}\cos\hat{\delta}}\right)^2\Theta^2_{\text{HPBW}}}}{N_{antennas}^{max}}-1\geq 0
\end{aligned}\tag{20}$$

- Step 3:Calculate the value of each ratio for each H_k and then sum these values as follows.

$$\begin{aligned}
S_k=&\min\left(\gamma^{ratio}(H_k),0\right)+\min\left(T^{ratio}(H_k),0\right)+\\
&\min\left(M^{ratio}(H_k),0\right)+\min\left(N^{ratio}(H_k),0\right)
\end{aligned}\tag{21}$$

- Step 4: Determine the maximum value of H_k that satisfies $S_k=0$. Note that higher altitudes provide a larger central angle θ, which minimizes the total number of satellites T.

IV. SIMULATION RESULTS

In the simulation setting, we consider a non-geostationary (NGSO) satellite with altitudes ranging from $H_{\text{min}}=150$ km to $H_{\text{max}}=1200$ km. The minimum user elevation angle, $\hat{\delta}$, is set at 10° (0.1745 radians), while the elevation angle for satellite constellation design, δ, is set at 35° (0.6109 radians). The user bandwidth is taken to be 5 MHz, with carrier frequency operations in the S-band at 2 GHz. The satellite transmit power per user is 4 W, and the user antenna gain is 0 dBi. The noise power density is -197 dBW/Hz. Furthermore, the antenna element gain $G_{\text{element}} = 6$dB and the beam radius R_{beam} set be so that $\theta_{\text{HPBW}} = 4.41276^\circ$ [12].

Figs. 4 and 5 show the results of the satellite constellation optimization, which satisfies the handheld user SNR γ_{QoS} requirements at the edge of coverage while ensuring the minimum number of satellite visibilities required by the satellite operators to provide flexible connectivity to users.

Fig. 4 illustrates the optimal satellite altitude H_{optimal} necessary for operation to achieve the desired SNR at the coverage edge. For a high SNR requirement, such as SNR $= 10$ dB, the satellite altitude should be lower, specifically at 184 km. This is because satellites at lower altitudes experience lower path loss, resulting in a higher SNR. In contrast, as satellite altitude increases, path loss increases, leading to lower SNR that may not meet the user's requirements. On the other hand, at a lower SNR requirement, the satellite's operating altitude can be higher. However, this also depends on the minimum number of satellite visibility required for user connectivity. For instance, at an SNR of 1.6 dB, possible satellite altitudes include 184 km, 249 km, 341 km, 477 km, or 646 km, thus a user at any location can view at least 9, 8, 7, 6, and 5 satellites simultaneously, respectively.

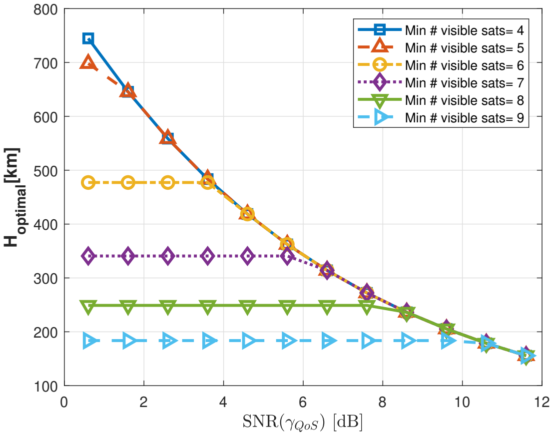

Fig. 4. Satellite Altitude vs. SNR at the Coverage Edge.

The factors of user SNR and the number of satellite visibility requirements not only influence satellite altitude operations but also impact the total number of satellites needed to ensure continuous global coverage across Earth's surface, as depicted in Fig. 5. With lower SNR and fewer satellite visibility requirements, only a limited number of satellites is needed. However, as either or both of these requirements increase, the number of satellites necessary for continuous coverage also increases. The high number of required satellites is due to two main reasons: first, satellites must operate at a lower altitude to achieve a higher SNR; second, to have more satellites visible at a time, a larger number of satellites must be launched, which means these satellites also need to operate at a lower altitude to fit within the constellation. For instance, at 11.6 dB SNR with a minimum of 9 satellites visible to a user at any given time, a total of 5941 satellites are needed to operate at an altitude of 156 km. In comparison, only 448 satellites at an altitude of 646 km are required to achieve an SNR of 1.6 dB with a minimum of 5 satellites visible to a user at any given time.

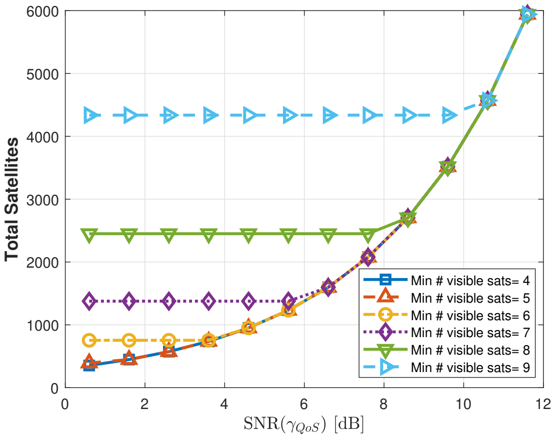

Fig. 5. Number of Satellites for Continuous coverage at Minimum SNR.

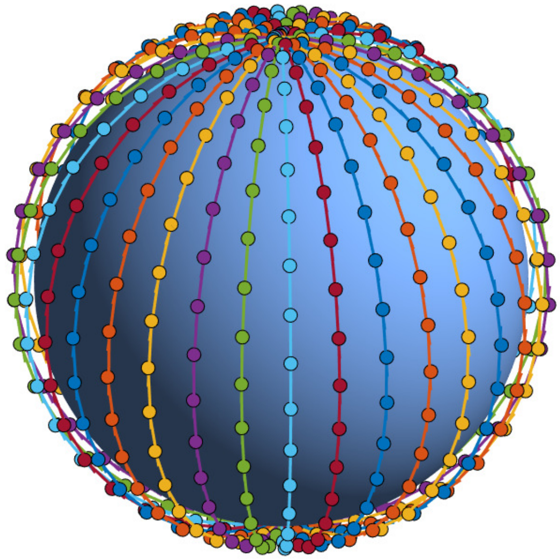

Fig. 6. Example of a satellite constellation with 574 satellites at an altitude of 558.68 km.

Another critical factor in optimizing satellite constellations is the payload antennas and the satellites' visibility time, as illustrated in Table I. When considering the same beamwidth,

$\theta_{\text{HPBW}} = 4.41276°$, it is evident that the number of antennas required at lower altitudes is greater than at higher altitudes. This difference arises because the inter-element spacing d_{element} in equation (13) is smaller at lower altitudes compared to higher ones. Furthermore, the diameter of the antenna aperture remains approximately the same across all satellite altitudes, with the relationship $d_{\text{element}} \times \#$ Antennas $\approx 1.93\,m$. Though the beamwidth, $\theta_{\text{HPBW}} = 4.41276°$ is the same, the radius of the beam at the surface of the earth increases when the altitude of the satellite increases.

Furthermore, the satellite's coverage area is larger at higher altitudes, resulting in longer visibility times. For example, at an altitude of 558.68 km, the visibility time is 444 seconds, while at 183.7 km, it drops to 195 seconds. A significant advantage of longer visibility time is that it reduces the frequency of handover between satellites to serve a user, thereby improving handover management. In contrast, when satellites operate at lower altitudes, a user can view more satellites simultaneously with better SNR, providing more flexible connectivity than at higher altitudes. However, the tradeoff is that lower altitudes result in shorter visibility times, necessitating more frequent handovers between satellites. This situation demonstrates the tradeoff involved in optimizing satellite constellations.

Generally, to provide high-capacity, high-quality service and flexible connectivity, satellites should ideally operate in Very Low Earth Orbit (VLEO). For example, at VLEO altitudes of 184 km, users can receive data at 18 Mbps with a high-quality SNR of 10.4 dB and flexibility in connectivity (a user can view at least 9 satellites). For moderate capacity, a satellite constellation shown in Fig. 6, at a LEO altitude of 558 km, can offer speeds of 7.5 Mbps while maintaining flexible connectivity, satellite visibility time, the number of antennas, and QoS. Ultimately, it is up to the satellite operator to determine which satellite constellation to implement.

TABLE I
SATELLITE CONSTELLATION OPTIMIZATION RESULT

H_{opt}(km)	Satellites	R$_{beam}[km]$	# Antennas	Min # visible sats (in Avg)	Satellite Visibility Time [s]	SNR (γ) [dB] at coverage edge	Capacity per user [Mbps]
183.7	4337	7.0774	607	9	195	10.4	17.9
205.32	3515	7.9105	603	8.6	213	9.6	16.69
236.24	2703	9.1019	598	8.2	237	8.61	15.23
249.02	2450	9.5945	595	8	247	8.23	14.68
272.19	2077	10.4872	591	7.7	264	7.6	13.78
314.05	1597	12.0998	584	7.3	294	6.6	12.39
340.74	1377	13.1283	579	7	312	6.03	11.62
362.25	1232	13.9569	575	6.8	326	5.6	11.06
418.65	951	16.1301	566	6.4	362	4.6	9.79
477.18	754	18.3856	556	6	397	3.7	8.71
483.54	484	18.6303	555	5.96	401	3.6	8.59
558.68	574	21.5256	543	5.6	444	2.6	7.478
645.55	448	24.8730	530	5.2	490	1.6	6.45
698.03	393	26.8954	522	5	517	1.06	5.934
744.74	353	28.6953	515	4.8	539	0.6	5.516

V. CONCLUSION

This paper presents an optimization strategy for designing satellite constellations for 6G and beyond satellite networks. The primary objective is to minimize the number of operational satellites while accounting for orbital geometry, satellite antenna specifications, SNR, and the number of visible satellites. We developed mathematical models to determine the minimum number of satellite visibility and the number of antennas required for satellite coverage. Using the proposed optimization strategy, we conducted extensive simulations, and the results show that, for 6G Handheld devices that require high-capacity, high-quality service and flexible connectivity, satellites should ideally operate in VLEO. On the other hand, the LEO satellite can be flexible, to provide 6G service with moderate capacity, while maintaining flexible connectivity, satellite visibility time, the number of antennas, and QoS. However, there is a trade-off between selecting VLEO and LEO, and it is up to the satellite operator to determine which satellite constellation to implement.

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