

Multilayer Satellite Constellation Design for Multipurpose Applications [†]

Mansoor Jamal , Ernestina Cianca , Tommaso Rossi  and Mauro De Sanctis * 

Department of Electronics Engineering, University of Rome “Tor Vergata”, 00133 Rome, Italy; mansoor.jamal@students.uniroma2.eu (M.J.); cianca@ing.uniroma2.it (E.C.); tommaso.rossi@uniroma2.it (T.R.)

* Correspondence: mauro.de.sanctis@uniroma2.it

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Abstract

Low and Medium Earth Orbit (LEO/MEO) satellite constellations have emerged as a compelling architectural paradigm for delivering multipurpose services. In this study, we investigate the joint optimization of communication and positioning performance metrics in a multilayer LEO/MEO constellation equipped with inter-satellite links (ISLs). A genetic algorithm framework is employed to optimize key constellation design variables, including the number of satellites per orbital plane, the number of planes, and the inter-plane phase offsets across layers, to minimize end-to-end user latency and Geometric Dilution of Precision (GDOP), subject to coverage and total satellite count constraints. Numerical results highlight the trade-offs among different architectural options.

Keywords: multilayer satellite constellations; LEO/MEO systems; inter-satellite links (ISLs); latency optimization; GDOP; PNT performance; genetic algorithms; constellation design; mega-constellations; network topology

1. Introduction

Emerging 6G networks are evolving toward integrated terrestrial and non-terrestrial infrastructures, featuring multilayer architectures that enable communication, navigation, and sensing convergence. This integration supports ubiquitous coverage and efficient use of resources, creating opportunities for multipurpose satellite constellations. Concurrently, the commercial growth of LEO constellations has demonstrated their potential for global broadband services, while research explores their use for Positioning, Navigation, and Timing (PNT) applications. In Ref. [1], optimal LEO constellation configurations capable of providing PNT services have been identified.

In this framework, multipurpose constellations offer operational efficiency by supporting multiple services with a single infrastructure, thereby reducing costs and enhancing space sustainability [2]. However, designing such systems presents challenges, as communication and navigation requirements often conflict, particularly regarding latency and Geometric Dilution of Precision (GDOP). In single-layer architectures, lower orbital altitudes generally minimize latency, whereas higher altitudes improve GDOP. As a result, no single-layer constellation can simultaneously achieve optimal performance for both services.

This paper investigates whether multilayer architectures can achieve better trade-offs. Through a two-layer constellation study, we demonstrate that combining low- and



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high-altitude satellites simultaneously improves both latency and GDOP, highlighting the advantages of integrated designs.

The paper is organized as follows. Section 2 introduces multipurpose constellations. Section 3 reviews related works. Section 4 presents the system model. Section 5 formulates the optimization problem and presents the simulation results, and Section 6 concludes with future research directions.

2. Multipurpose Constellations

Multipurpose constellations integrate diverse services, including communications, PNT, surveillance, and Earth observation, onto shared satellite platforms. This integrated approach improves system versatility while optimizing orbital resources.

The architecture relies on three principles: a multilayer design (LEO/MEO/GEO integration), distributed networking, and high-speed ISLs for routing and redundancy. LEO constellations provide low-latency global coverage with reduced delays and improved user access compared to GEO/MEO systems [3], making them essential for next-generation networks facing growing broadband and IoT demands.

Multilayer constellations enable traffic-aware backhaul provisioning, reducing satellite counts while maintaining throughput. Positioning accuracy is another key objective, and the geometric diversity of satellites improves the precision of navigation services. When enhanced with ISLs, these networks support low-latency multi-hop routing while improving user positioning geometry [4].

Motivated by these benefits, this paper jointly optimizes communication latency and positioning performance in multilayer LEO/MEO constellations with ISLs. We propose a genetic algorithm framework to optimize the number of satellites per plane, the number of planes, and inter-plane phase offsets, minimizing end-to-end latency and GDOP under coverage and satellite count constraints.

3. Related Works

In Ref. [5], the authors introduced a multilayer staged deployment framework for satellite constellations that facilitates flexible, incremental expansion to accommodate uncertain global internet demand while simultaneously reducing overall deployment expenditures. A dual-layer satellite constellation with satellites at different altitudes and inclinations was proposed to improve coverage and reduce redundancy, determining the minimum number of satellites per orbit needed for continuous global coverage [6,7].

The study in Ref. [8] examined the impact of inter-satellite links (ISLs) in dense LEO networks, showing how intra-orbital, adjacent, nearby, and crossing-plane ISLs can significantly enhance communication performance while also revealing how the maximum ISL distance reshapes network topology and latency.

In Ref. [9], the authors investigated a traffic-aware multilayer LEO satellite-terrestrial network in which dense satellites provide high-capacity backhaul for terrestrial users. Using stochastic geometry and queueing theory, they analyzed the average backhaul capacity and proposed a multilayer constellation design that minimizes the number of satellites while ensuring seamless coverage.

The study in Ref. [10] examined the rapid growth of non-geostationary satellite constellations and the growing importance of radio-frequency-based inter-satellite links (ISLs) for handling heterogeneous traffic, with a particular focus on large-scale constellations using massive numbers of ISLs.

4. System Model

Satellite positions and velocities are computed across all orbital shells using a two-body propagator with Keplerian orbital elements. This enables the analysis of network coverage and topological characteristics using relative and absolute motion parameters.

4.1. ISL Connection

Figure 1 illustrates the inter-satellite link (ISL) geometry model, where d_{perp} denotes the perpendicular distance from the Earth center to the ISL path, R_e is the Earth radius, h_{atm} represents the atmospheric boundary height, f_D is the Doppler shift caused by the relative motion between satellites, and d_{ISL} is the distance between the two connected satellites. For an ISL between any two satellites to be established at a given snapshot, the following conditions must be simultaneously satisfied:

1. ISLs require $d_{\text{perp}} > R_e$ to remain above the atmospheric boundary $h_{\text{atm}} = 100$ km.
2. The Doppler shift f_D must be below $f_{\text{max}} = 20$ MHz (1% of the 2 GHz receiver bandwidth).
3. The ISL distance $d_{\text{ISL}} \leq d_{\text{max}} = 3000$ km, based on link budget constraints.

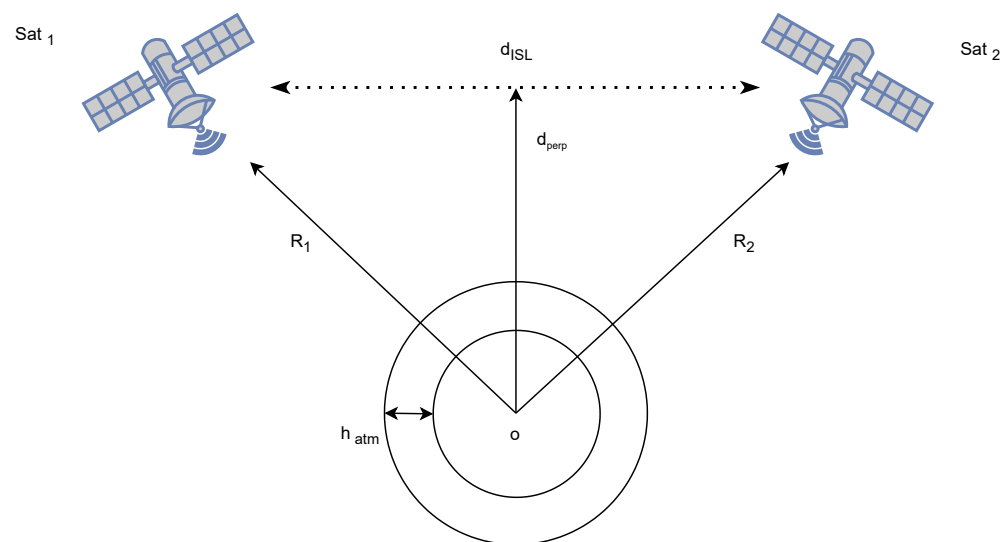


Figure 1. Inter-satellite link (ISL) geometry model.

The above conditions can be mathematically expressed as

$$\begin{cases} d_{\text{perp}} > R_e + h_{\text{atm}}, \\ f_D \leq f_{\text{max}}, \\ d_{\text{ISL}} \leq d_{\text{max}}. \end{cases} \quad (1)$$

where

$$d_{\text{perp}} = \sqrt{\frac{R_1^2 + R_2^2}{2} - \frac{d_{\text{ISL}}^2}{4} - \frac{(R_2^2 - R_1^2)^2}{4d_{\text{ISL}}^2}} \quad (2)$$

and $R_1 = R_e + h_{\text{sat1}}$ and $R_2 = R_e + h_{\text{sat2}}$.

4.2. GDOP Analysis and Satellite Visibility

Geometric Dilution of Precision (GDOP) quantifies how satellite–receiver geometry affects positioning accuracy. Lower values indicate better satellite distribution and more reliable position estimates [11].

The geometry matrix $\mathbf{H}$ is constructed using line-of-sight unit vectors from the receiver to each satellite:

$$\mathbf{H} = \begin{bmatrix} e_1^x & e_1^y & e_1^z & 1 \\ e_2^x & e_2^y & e_2^z & 1 \\ \vdots & \vdots & \vdots & \vdots \\ e_n^x & e_n^y & e_n^z & 1 \end{bmatrix}, \quad (3)$$

where the unit vector components (e^x, e^y, e^z) are computed from the satellite and receiver coordinates.

GDOP is then calculated as

$$\text{GDOP} = \sqrt{\text{tr}((\mathbf{H}^T \mathbf{H})^{-1})}, \quad (4)$$

where $\text{tr}(\cdot)$ denotes the trace of a matrix.

GDOP (η_P) is evaluated only when a sufficient number of satellites are visible. Satellites above 10° elevation are considered visible; epochs with fewer than four visible satellites are discarded. Table 1 [1] categorizes GDOP quality.

Table 1. GDOP quality classification.

GDOP Range	Rating
<1	Ideal
1–2	Excellent
2–5	Good
5–10	Moderate

4.3. Latency and Queuing Delay Evaluation

Network performance is characterized by end-to-end latency η_L , including the queuing delay along the multi-hop ISL path.

Latency computation includes:

- **Queuing delay:** Each satellite uses an M/M/1 queue with Poisson arrivals (λ) and service rate μ [12]:

$$D_{\text{queue}} = \frac{\rho}{\mu - \lambda}, \quad \rho = \frac{\lambda}{\mu}. \quad (5)$$

- **Multi-hop aggregation:** The total queuing delay is summed along the shortest path (Dijkstra's algorithm on the ISL graph).

Overall latency: $\eta_L = \text{Propagation Delay} + \text{Total Queuing Delay}$.

5. Satellite Constellation Design

Satellite constellation design ensures continuous global coverage through structured arrangements of altitude, orbital planes, and phasing. The scalable Walker Delta framework provides an analytically tractable method for distributing satellites across orbital planes [13,14].

A Walker constellation is defined by the three parameters $N/p/f$, where N is the total number of satellites, p is the number of orbital planes, $t = N/p$ is the number of satellites per plane, and f is the inter-plane phasing factor. This configuration enables quasi-uniform global coverage through a systematic distribution of satellites.

5.1. Optimization Strategy

We investigate a multilayer constellation for global coverage and end-to-end communication. A genetic algorithm is used to optimize the number of satellites per plane, the

number of planes, and phase offsets, evaluating each configuration based on combined communication latency and positioning accuracy metrics. Key simulation parameters are listed in Table 2.

Table 2. Simulation and design parameters for the two-layer constellations.

Parameter	Value
Users	500 users evenly distributed on the Earth's surface
Number of sats per plane:	t_1, t_2
Number of planes:	p_1, p_2
Phase offsets:	f_1, f_2
Altitudes Scenario 1:	$h_1 = 600 \text{ km}, h_2 = 1200 \text{ km}$
Altitudes Scenario 2:	$h_1 = 1200 \text{ km}, h_2 = 8000 \text{ km}$
Inclinations Scenario 1:	$i_1 = 50 \text{ deg}, i_2 = 81 \text{ deg}$
Inclinations Scenario 2:	$i_1 = 50 \text{ deg}, i_2 = 81 \text{ deg}$

5.2. Parameter Selection for GA

The GA parameters in Table 3 balance exploration and convergence. The population size and number of generations ensure a broad search, while crossover, mutation, and tournament selection maintain diversity. Convergence criteria terminate the optimization when improvements become negligible.

Table 3. Genetic algorithm parameters.

Parameter	Value
MaxGenerations	50
PopulationSize	40
CrossoverFraction	0.8
Mutation Function	Uniform (rate = 0.1)
Selection Function	Tournament (size = 4)
FunctionTolerance	1×10^{-4}
MaxStallGenerations	20

5.3. Objective Function Formulation

The GA uses the objective function $\eta = \eta_L \times \eta_P$, penalizing infeasible configurations and simulating feasible ones to compute latency and GDOP. The optimization variables are $\mathbf{x} = \{t_1, p_1, t_2, p_2, f_1, f_2\}$, representing satellites per plane, planes, and phase offsets for both layers:

$$\eta(\mathbf{x}) = \eta_L(\mathbf{x}) \times \eta_P(\mathbf{x}) \quad (6)$$

This formulation ensures that the GA selects constellations that minimize latency and GDOP simultaneously.

5.4. Simulation Results

5.4.1. Scenario 1

The first scenario concerns the optimization of a two-layer satellite constellation with the parameters reported in Table 2, considering the constraint $d_{\max} = 3500 \text{ km}$. From the GA-optimized results shown in Table 4, we observe that:

- A higher number of satellites in the lower layer helps reduce latency but increases GDOP
- A higher number of satellites in the upper layer leads to a better GDOP; latency increases, but at a much slower rate than GDOP.

To better understand the impact of different satellite distributions in the two layers on latency, we derive the network topology and the Probability Density Function (PDF) and cumulative distribution function (CDF) of the ISL distances for different satellite distributions in the two layers, namely for the configurations referred to as Run 1, Run 5, and Run 11 in Table 4. The results are shown in Figures 2–4. From Figures 2–4, it is clear that when most satellites are in the higher layer, the concentration of ISL distances shifts toward higher values. However, in Figure 2, the probability of a high ISL distance is also relatively high. Thus, it can be expected that different satellite distributions have only a small impact on latency. Therefore, in the scenario considered, a good trade-off is achieved by placing most satellites in the upper layer, which minimizes GDOP with an acceptable increase in latency.

Table 4. GA optimization results for the multilayer satellite constellations in Scenario 1.

Run	t_1	p_1	t_2	p_2	f_1	f_2	Ratio	n_1	n_2	η_P	η_L	η
1	29	10	0	0	8	0	1.00–0.00	290	0	6.73	0.037	0.249
2	25	11	5	3	8	2	0.95–0.05	275	15	6.74	0.039	0.265
3	23	10	12	5	2	3	0.80–0.20	230	60	4.98	0.040	0.199
4	20	11	14	5	4	4	0.75–0.25	220	70	4.22	0.039	0.167
5	17	10	24	5	6	2	0.60–0.40	170	120	3.54	0.039	0.141
6	15	10	20	7	0	1	0.50–0.50	150	140	3.11	0.040	0.125
7	9	12	14	13	3	2	0.40–0.60	108	182	3.02	0.042	0.128
8	9	9	19	11	0	0	0.30–0.70	81	209	2.47	0.042	0.103
9	8	7	26	9	5	6	0.20–0.80	56	234	2.48	0.040	0.104
10	10	3	20	13	2	3	0.10–0.90	30	260	2.36	0.043	0.102
11	0	0	22	13	0	5	0.00–1.00	0	286	2.28	0.044	0.100

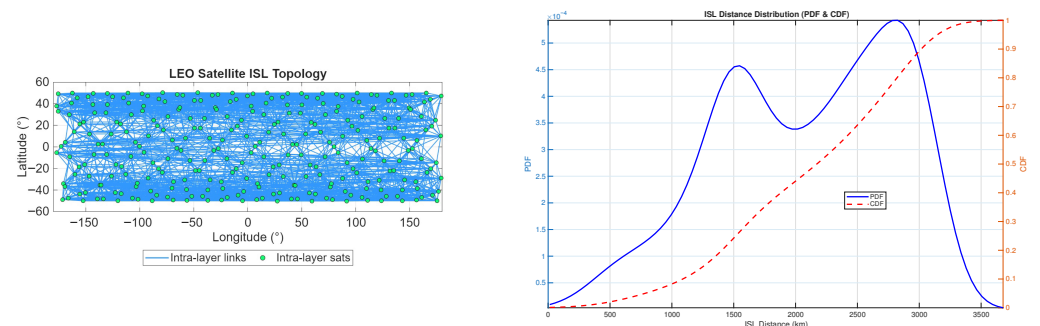


Figure 2. Network characteristics for Run 1: (left) network topology and (right) ISL distance distribution.

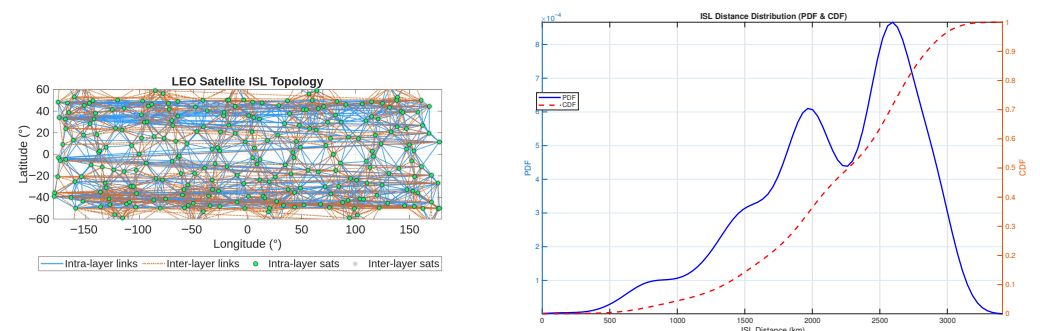


Figure 3. Network characteristics for Run 5: (left) network topology and (right) ISL distance distribution.

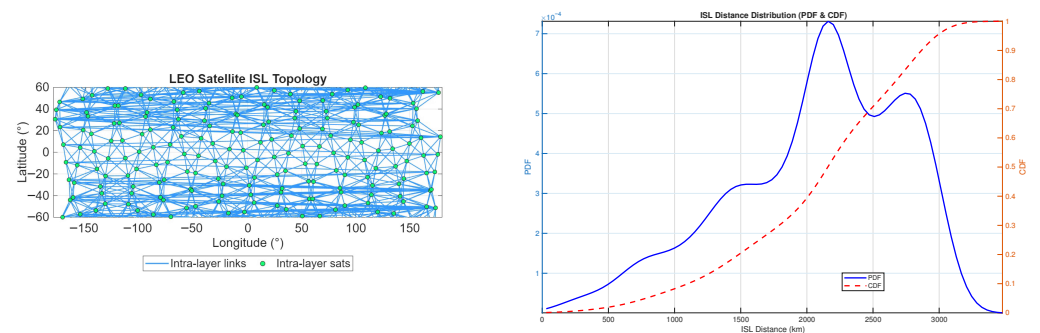


Figure 4. Network characteristics for Run 11: (left) network topology and (right) ISL distance distribution.

5.4.2. Scenario 2

The second scenario concerns the optimization of an IRIS² inspired two-layer satellite constellation with the parameters reported in Table 2, considering the constraint $d_{\max} = 6000$ km.

The results (Table 5) show that:

- Lower-layer dominance yields a high GDOP but low latency.
- A greater number of upper-layer satellites improves GDOP significantly.
- Fully upper-layer configurations increase latency substantially.

The balanced (0.5–0.5) architecture achieves the best trade-off, demonstrating that IRIS²-style constellations benefit from integrating both altitude layers rather than relying on a single LEO or MEO layer.

Table 5. GA optimization results for the multilayer satellite constellations in Scenario 2.

Run	t_1	p_1	t_2	p_2	f_1	f_2	Ratio	n_1	n_2	η_P	η_L	η
1	25	11	5	3	8	2	0.95–0.05	275	15	1.626	0.040	0.066
2	20	7	15	10	6	3	0.5–0.5	140	150	1.006	0.041	0.041
3	0	0	29	10	0	9	0.0–1.0	0	290	0.801	0.088	0.070

6. Conclusions

This paper presents a framework for jointly optimizing communication and positioning performance in multilayer satellite constellations. Using a composite objective function $\eta = \eta_L \times \eta_P$, we demonstrate that integrated design is essential for multipurpose networks. A genetic algorithm is used to optimize Walker constellation parameters—the number of satellites per plane, the number of planes, and inter-plane phasing—across two orbital layers under fixed satellite and ISL constraints.

Simulations for a dual-layer LEO constellation (600 km and 1200 km) reveal key trade-offs: lower-layer dominance minimizes latency but degrades GDOP, whereas an upper-layer emphasis improves GDOP at the expense of a moderate increase in latency. The best performance occurs with balanced or upper-skewed distributions, highlighting the limitations of single-layer designs.

An IRIS²-inspired scenario (1200 km and 8000 km) further underscores the value of architectural heterogeneity. While a pure MEO configuration provides superior GDOP, it suffers from high latency; balanced multilayer deployments offer the best overall trade-off. These findings confirm that the proposed GA-based approach effectively explores the design space for multilayer constellations, providing insights for future multipurpose satellite network development.

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Abbreviations

The following abbreviations are used in this manuscript:

LEO	Low Earth Orbit
MEO	Medium Earth Orbit
GEO	Geostationary Earth Orbit
RAAN	Right Ascension of the Ascending Node
ISL	Inter Satellite Link
GDOP	Geometric Dilution of Precision
IoT	Internet of Things
GA	Genetic Algorithm
LOS	Line of Sight

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