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On the Impact of the Number of the Constellation Shells on Standalone LEO-PNT Positioning Metrics

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***Abstract*—Low Earth Orbit Positioning, Navigation and Timing (LEO-PNT) is an emerging paradigm in wireless navigation community, aiming at systems that both complement the existing Global Navigation Satellite Systems (GNSS) and can act as alternative global positioning methods in the events of outages or discontinuous availability of GNSS. Such limited availability can of GNSS can occur, for example, in indoor scenarios or deep outdoor canyons, or in the presence of strong jammers in GNSS bands. LEO-PNT solutions have been studied so far either in the context of signals of opportunity, where existing LEO mega-constellation signals can be re-used and repurposed, in an opportunistic way, also for positioning purposes, or in terms of standalone LEO-PNT solutions, where novel single-shell and multi-shell constellations are designed for the sole purpose of positioning, navigation, and tracking applications. In both approaches, the constellation geometry, as measured by the Geometric Dilution of Precision (GDOP) metric, the 4-fold coverage, meaning the percentage of Earth points having at least four satellites in view, and the carrier-to-noise ratio at the receiver are important positioning metrics. The focus of this paper is on analyzing the impact of increasing the number of constellation shells on the positioning metrics when the overall number of satellites in the orbits is fixed. The analysis is done with an advanced constellation simulator, under indoor and outdoor scenarios. Five heuristic constellations are introduced and compared with three benchmarks from the literature: two benchmark constellations based on Pareto optimization approaches and one commercial constellation. The focus is on small-sized constellations with less than 300 satellites. We find out that two-shell and three-shell heuristic approaches can reach satisfactory performance metrics under a wide range of orbital altitudes, and that more than three shells in the constellations are not necessarily bringing in additional improvements.**

I. INTRODUCTION AND MOTIVATION

Low Earth Orbits (LEO) span between around 160 km and 2000 km above the Earth, with most of the LEO satellites placed above 500 km altitudes, to avoid strong atmospheric drag effects. This drag force opposes the satellite's motion, causing it to lose energy and gradually decrease in altitude, but it is less and less strong at orbital altitudes above 500 km [1]. As a result, most LEO satellites now launched on the sky are placed at orbital altitudes above 500 km.According to Orbiting Now data[1], as of September 2024, there are 7894 satellites in LEO, representing close to 39 times more LEO satellites than Medium Earth Orbit (MEO) satellites currently on orbits.

[1]https://orbit.ing-now.com/#main

LEO signals have traditionally been used for narrowband and broadband communications and Earth-sensing applications, but they have also gained attention for positioning, navigation, and timing (PNT) purposes over the past five years or so [2]–[4]. LEO-PNT solutions are of particular interest in the context of complementing the existing GNSS, when GNSS signals are suffering from outages, due to, for example, strong interferences such as jamming [5] and spoofing [6], or their difficulty to deal well with challenging environments such as Non Line of Sight (NLOS) and indoor scenarios. A variety of applications can be envisioned for future LEO constellations, as depicted in Fig. 1, and they can be grouped under three categories: a) positioning and tracking applications, such as for modern intelligent transport systems [7] or water management [8]; b) sensing and monitoring [9]–[11]; and c) broadband and narrowband communications [12]–[14]. The focus in this paper is on the first category, and one application of particular interest in our projects is the low-cost equal-access and affordable localization of water sources and tracking of water purification devices and mobile workforce in Africa, as described in our previous work [8] in LEDSOL project on "Enabling clean and sustainable water through smart UV/LED disinfection and solar energy utilization". Therefore, the use case adopted in here will focus on the continent of Africa, but the findings can be generalized to other regions in a straightforward manner.

Among the main performance metrics identified so far in the context of LEO-PNT, those that have appeared the most often in the research literature are the Geometric Dilution of Precision (GDOP) [15]–[19], the one-fold or four-fold coverage [20]–[22], and the Carrier-to-Noise ratio (C/N_0) [21]–[23]. These are also the three performance metrics we have selected in this study.

In the context of satellite constellations, a constellation **shell** refers to a group of satellites that share the same orbital characteristics, such as altitude h and inclination i. This is the definition we also adopt in this paper: by a shell, we understand a unique (h, i) pair. While our studies will focus on shells with varying altitudes, we will also consider as a benchmark a small-sized three-shell constellation as reported as Pareto optimal in [15], where the authors used the same altitude of 1250 km in all three shells, but used a different inclination per each shell.

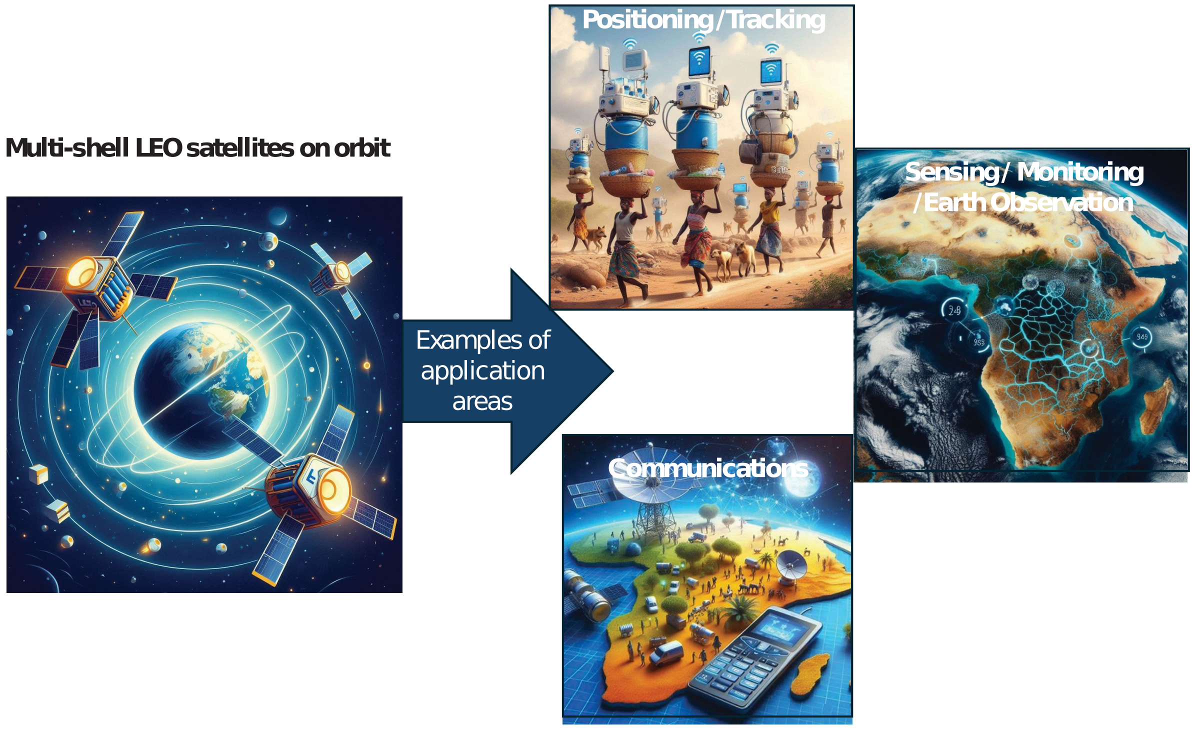

Fig. 1. Examples of applications for future multi-shell LEO constellations in the fields of positioning/tracking, sensing/monitoring/Earth observation and broadband and narrowband communications. Plot partially created with Copilot AI.

According to the literature, low-latitude receivers are better served by satellites with low inclinations [24], while polar latitudes are better served by satellites with high inclinations. The low-inclinations orbits are efficient for covering regions near the equator because they take advantage of the Earth's rotation, requiring less energy for the launch and maintenance of satellites in orbits. Similarly, high inclination orbits, including polar orbits (with inclinations close to 90^o), allow satellites to pass over both poles on each revolution. This ensures comprehensive coverage of the Earth's surface, including the polar regions. For example, the authors in [24] showed that a low inclination of around 24^o offers optimal coverage for near-equatorial regions. Using this value as a starting point, and with a focus on Africa, where latitudes range from about -40^o to about $+40^o$, this paper will assume orbital inclinations between 25^o and 55^o.

Another determining constellation parameter is the number of planes per shell, N_{planes}. Low-cost LEO-PNT constellations should aim to minimize both the overall number of satellites N_{sat} over all shells and the number of planes per shell N_{planes} [15], [21]. This is because a lower number of satellites reduces the launch and maintenance costs, and launching multiple satellites on the same orbital plane can further cut expenses by reducing the number of separate launches required. However, there is a research gap in the literature regarding the impact of the number of shells in constellation design. While most studies focus on optimizing satellite distribution and plane configurations, the influence of multi-shell architectures on performance, coverage, and cost-efficiency has not been thoroughly explored. Understanding how varying the number of shells affects PNT-related performance metrics like coverage, C/N_0, and GDOP could offer valuable insights for designing more efficient and cost-effective LEO constellations.

The commercial emerging LEO-PNT constellations, such as Xona Pulsar and China Centispace (described in the section II) are currently assumed to have between one and three shells [4], though not much public information exists. Also, our recent Pareto multi-target optimization studies [21] as well as the recent studies in [15] converged to three-shell constellations as a good tradeoff between various positioning performance metrics, such as GDOP, coverage and/or C/N_0 as well as the cost aspects (minimizing N_{sats} and N_{planes}). However, the studies so far have either focused on fixed altitudes ([15]) or focused mostly on medium- and large-sized constellations (e.g., above 350 satellites) [21], which are not the most cost-effective solutions as desired in various applications for Africa, such as positioning for water management purposes [8].

Thus, the focus in this paper is on a small-sized heuristically designed constellation of only 240 satellites (by analogy with the 246 satellite small constellation considered in [15]) and the two research questions (RQ) we address in here are:

RQ1 To what extent can the GDOP, coverage and C/N_0 be improved by distributing a fixed number of satellites (i.e.,

240) over several shells? We consider one to five shells, and we keep the total number of orbital planes over all shells constant (i.e., 20 orbital planes, distributed over N_{shells} constellation shells, with $N_{shells} = 1, \ldots, 5$).

RQ2 Compared to Pareto-optimized solutions found in the literature and a commercial LEO-PNT constellation, how much worse are such heuristic multi-shell constellations in terms of three positioning metrics: GDOP, coverage, and C/N_0?

As the path losses as well as the launching costs are increasing when the satellite altitudes increase, we only consider three reference altitudes for the first shell, namely 550 Km, 800 km, and 1250 km, and we assume that each successive shell in the multi-shell approach is 100 km above the previous shell.

The main contributions of this paper are:

- This study presents, for the first time in the literature, to the best of the Authors' knowledge, an analysis of how distributing a fixed number of satellites across multiple orbital shells impacts the positioning performance of LEO-PNT constellations. The key hypothesis is that while distributing satellites into higher orbits may improve geometry and coverage, the C/N_0 from satellites at higher altitudes tends to be lower compared to those at lower orbits, potentially compromising both geometry and coverage. This tradeoff has not been addressed so far in the literature under the assumption of a fixed and low number of satellites in the constellation, which is the novelty of this study. To address this, we compare various multi-shell constellations, ranging from 1 to 5 shells, using three benchmarks from the literature: a Pareto optimal constellation based on a three-metric optimization process from [15], another Pareto optimal constellation based on a six-metric optimization process from [21], and a commercial LEO-PNT constellation, Centispace. All of the mentioned constellations, including our multi-shell designs are small-scale, comprising fewer than 300 satellites in total from all the shells. This restriction keeps the study within realistic constellations;
- In addition, the GDOP, coverage, and C/N_0 metrics of multi-shell constellations are compared in two different scenarios (a rural NLOS and an indoor NLOS) considering users distributed throughout the African continent. The results are evaluated against target nominal thresholds for both indoor and outdoor propagation models.
- Comparing several multi-shell constellations, with 1 to 5 shells, using three benchmarks from the literature: a Pareto optimal constellation based on a three-metric optimization process from [15], another Pareto optimal constellation based on a six-metric optimization process from [21], and a commercial LEO-PNT constellation, Centispace. All these, including our multi-shell constellations, are small-sized constellations, with less than 300 satellites in all the orbits from all the shells.

We remark that the description of the Pareto optimization weights and methodology used in [15], [21] is outside the scope of this paper and interested Readers are referred to the above-cited Pareto-related papers for mode details. The Pareto-optimal solutions are taken here as benchmark for our heuristic designs.

The rest of the paper is organized as follows: Section II gives an overview of existing and emerging LEO constellations designed for PNT applications, or, what is typically referred to as standalone LEO-PNT constellations, Section III describes our constellation simulator and presents the simulation-based results, and Section IV discusses the findings and presents the conclusions of this work.

II. Existing and emerging LEO-PNT constellation - an overview

There are currently two main approaches in the current literature about LEO-PNT design [2], [4]:

1) One approach is relying on existing LEO constellations currently in use for other purposes, such as broadband communications, and use them as signals of opportunity for positioning [25]–[27]. For example, LEO mega-constellations such as Starlink/SpaceX or Kuiper/Amazon are particularly attractive due to their large number of satellites and excellent coverage. If a LEO-PNT business model were to introduce user fees for using such mega-constellations as signals of opportunity, the user costs associated with such large constellations could easily become prohibitive, as a recent study in [28] showed, especially for low user adoption rates. Therefore, the use of mega constellations as signals of opportunity for positioning is outside the scope of this paper.
2) The second approach, which starts to be adopted more and more, is to build small-to-medium sized dedicated LEO-PNT constellations, preferably with less than 350 satellites in total, which are fully meant for positioning applications [2], [4]. This is the approach we focus upon in this paper. The next part in this section discusses the current and emerging LEO-PNT constellations that have gained commercial or research interest.

Table I gives an overview of current and planned LEO-PNT constellations, as of September 2024; the information collected in the table was based on public data, such as the recent research papers [4] and [29] as well as public blogs and press releases, which are not cited here for clarity reasons because the information on such web pages is continuously updated. In Table I, N_{sat} stands for the number of satellites (if multiple shells, the number of satellites per each shell is also shown, when known), N_{planes} is the number of orbital planes, i is the orbital inclination per each plane, given in degrees, h is the orbital altitude, given in Km, f_c is the carrier frequency in GHz, and TBD stands for 'to be defined' and it means that it is not available in the public documents.

The main observations one can draw from the parameters collected in Table I are the followings:

- Most of the current and emerging standalone LEO-PNT constellations are aiming at a small constellation size,

TABLE I. OVERVIEW OF THE PLANNED LEO-PNT CONSTELLATIONS (STATUS AS OF SEPTEMBER 2024), IN ALPHABETICAL ORDER

Constellation	N_{sats}	N_{planes}	N_{shells}	$i[^o]$	h [km]	f_c [GHz] **(band name)**	**Walker type**
Centispace, China	120/30/40* Total: 190	12/3/4	3	55/87.4/30	875/1100/1100	1.1 and 1.5 (L band)	Delta
Geely/GeeSpace, China	72/168 Total: 240	$3/TBD$	2	85/50	620/620	TBD (L & S bands)	Star
Iridium Next Satelles, US	66	6	1	86.4	780	1.6 (L band)	Star
IRIS^2 ESA, EU	200	TBD	$1-3$	TBD	TBD	TBD (L, C, Ku, and Ka bands)	Delta
OneWeb UK	648	18	1	86.4	1200	around 13 (Ku band)	Star
TrustPoint US	300	TBD	$1-3$	TBD	TBD, below 900	TBD (C band)	Delta
Xona/Pulsar US	300	6	$1-3$	TBD	TBD, below 1200	TBD (L & C bands)	Delta

* if a constellation has multiple shells, the values per each shell are shown in the table.

with a total number of satellites N_{sat} below 300. By standalone constellations we refer to the novel LEO-PNT designs, not to LEO constellations which can be repurposed also for positioning, e.g., via a signals-of-opportunity approach. The only exception size-wise (from Table I) is OneWeb constellation from UK, but this is a constellation that originated for broadband communications applications, and it is now reconsidered also for PNT applications, thus, it is not strictly a standalone LEO-PNT constellation.

- The LEO-PNT constellations are typically multi-shell constellations, which achieves better geometry and coverage; currently, the maximum number of shells in use has been 3. In our studies, we will investigate up to five shells with heuristic configurations.
- The commercial LEO-PNT satellites are typically launched at altitudes above 620 km and below 1200km.
- There is a large variety in the adopted frequency bands, but most of the existing LEO-PNT constellations include the L-band (1 to 2 GHz) specific to GNSS. This is because the path losses increase with the carrier frequency, and indoor applications with limited receiver sensitivity can be realized only at low carrier frequencies (e.g., below 5 GHz).

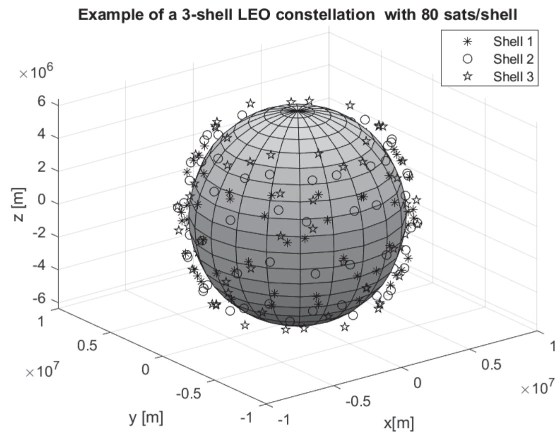

Fig. 2. Example of a distribution of 240 satellites in a three-shell Walker-star constellation generated with our simulator.

III. SIMULATION-BASED RESULTS WITH FOCUS ON A USER DISTRIBUTION IN AFRICA

Our simulations are based on an in-house constellation simulator built in Matlab, and which supports both LEO and MEO altitudes, i.e., from 200 to 23000 km. The orbit propagation in our simulator follows a SGP4 orbit propagator, standing for "Simplified General Perturbation 4" model, and it generates the satellite positions and velocities in time, starting from a user-defined initial time. SGP4 accounts for various perturbations, including the Earth's shape (oblateness), the atmospheric drag, the solar radiation pressure, and gravitational influences from the Sun and Moon. SGP4 relies on analytical models that use simplified equations to approximate the effects of these various perturbations, and it offers a good tradeoff between accuracy and complexity.

In terms of the constellation topology, we focused on Walker topologies, which are widely used for LEO and GNSS satellite systems. There are two Walker topologies possible: Walker star and Walker delta. In Walker-star topology, the ascending nodes of the orbital planes are distributed over a 180-degree span and such a configuration is particularly effective for achieving global coverage, especially in polar regions. Walker star topology is often used for constellations that need to cover high-latitude areas. In Walker-delta topology, the ascending nodes of the orbital planes are distributed over the full 360-degree range and such configuration provides symmetrical coverage and can be flexibly adapted to different orbital inclinations, making it suitable for covering low-latitude areas. As Centispace and the small-sized constellation derived based on Pareto optimization in [15] both use Walker delta topology, (and as Walker delta is more versatile for various inclinations and low-latitude coverage, while Walker star is optimized for

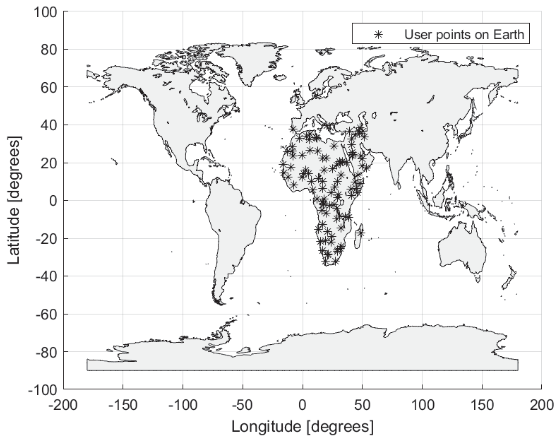

Fig. 3. Example of a distribution of the user points in the simulations, 100 user points.

polar coverage), we have adopted a Walker delta topology for the heuristic configurations in our studies here. An example of the satellite distributions on three shells using Walker delta topology at altitudes 550 km, 650 km, and 750 km is illustrated in Fig. 2.

Our simulator also includes a Quadriga channel model[2] expanded by us with rain and fog attenuation models in accordance with 3GPP specifications[3] as well as researcher-defined user distributions on Earth, which can follow a uniform distribution, a grid distribution, or can read an input track from a NMEA file. In our simulations, we assumed a uniform distribution mostly over Africa, as illustrated in Fig. 3; few points fall outside Africa because the user coordinates were defined based on maximum and minimum latitude and longitudes characterizing Africa and using the Matlab in-build command *worldmap*, which allows defining a custom geographic region by specifying latitude and longitude limits.

Table III lists the five heuristic constellations we are investigating, together with the three selected benchmarks. The heuristic constellations were designed starting from a small-sized constellation of 240 satellites and assuming 20 orbital planes. These satellites and planes were distributed across $N_{shells} = 1, \ldots, 5$ shells, with inclinations suitable for lower-latitude regions, namely between 25^o and 55^o. We remark that, if a constellation has multiple shells, the values per each shell are shown in Table III. The benchmark constellations obtained via Pareto-optimization use different approaches. Pareto 3, taken from [15], uses a modified NSGA-II Pareto-optimization algorithm together with a process they name "fine tuning" to obtain their Pareto-front. Pareto 6, taken from [21], uses the NSGA-III Pareto-optimization algorithm together with the adaptive weighting algorithm ADaW [30] to obtain its Pareto-front. Readers are encouraged to refer to the original publications for detailed information of these optimizations.

[2]https://quadriga-channel-model.de/
[3]www.3gpp.org

For a fair comparison between the different constellations, we used unified channel parameters as shown in Table III, with B_W notation standing for the receiver bandwidth in MHz, the EIRP standing for the transmitter's Effective Isotropic Radiated Power (an omnidirectional antenna was assumed on-board of satellites), the P_R standing for the receiver sensitivity (a patch antenna was assumed at the receiver side) and α_{min} standing for the minimum satellite elevation considered for GDOP. We choose $\alpha_{min} = 5^o$ similar with [15]; a higher minimum elevation angle would deteriorate the results in terms of GDOP.

From all the channels supported by Quadriga channel models, we have down-selected two representative cases as below

1) An Indoor channel model with an indoor penetration distance of 50 m, representing a worst-case propagation scenario
2) An outdoor Rural NLOS channel model, representing a moderately challenging scenario.

Figs. 4, 5, and 6 compare the five heuristic constellations from Table III with the three benchmarks, also shown in Table III: two constellations based on Pareto optimization with different metrics (Pareto 3 for the three-metric optimization of [15] and Pareto 6 for the six-metric optimization of [21]) and with a commercial constellation (Centispace). The comparisons are in terms of GDOP (Fig. 4), Coverage (Fig. 5, given in percentages), and C/N_0 (Fig. 6, given in dB-Hz). For clarity, in the figures' legend, the heuristic constellations are only referred to via the altitude of the first shell, h_1. The left-hand plots in Figs. 4, 5, and 6 are for the Indoor scenario, while the right-hand plots are for the Rural NLOS scenario. All statistics were computed over 1000 runs, corresponding to 100 user points uniformly distributed (mainly across Africa) and 10 constellation points, corresponding to a $20'$ orbital trajectory, with consecutive the points spaced $2'$ apart.

Each figure shows also a nominal target threshold of the considered metric (in dashed line) as well as the target operational region (in gray) in order to find out which constellations are operational and which are falling short within the design targets.

Table III shows a comparison between the 'best' heuristic constellation and the three selected benchmarks. The 'best' configuration here was selected by minimizing the mean square error (MSE) between the heuristic metrics and the average over the two Pareto constellation metrics as follows:

$$[\widehat{h_1}, \widehat{N_{shells}}] = min_{h_1 \in \{550,800,1250\}, s \in \{1,\ldots,5\}} MSE(h_1, s) \tag{1}$$

with h_1 being the altitude of the closest-to-Earth shell, s being the number of shells and MSE($\cdot$) defined as

$$\begin{aligned} MSE(h_1, s) = (GDOP(h_1, s) - GDOP_{av}).^2 + \\ (Cov(h_1, s) - Cov_{av}).^2 + \\ (C/N_0(h_1, s) - CN0_{av}).^2 \end{aligned} \tag{2}$$

where GDOP, Cov, and C/N_0 are the geometric dilution of precision, coverage and carrier-to-noise-ratio metrics, respec-

TABLE II. CONSTELLATION PARAMETERS USED IN THE SIMULATIONS; h_1 HAS BEEN A MODEL PARAMETER FOR THE FIRST SHELL ALTITUDE, WITH VALUES 550, 800 AND 1250 KM.

Constellation	**Total** N_{sats}	N_{sat}/shell	N_{shells}	$i[^o]$	h [km]	N_{planes}	**Walker type**
Heuristic 1	240	240	1	30	h_1	20	Delta
Heuristic 2	240	120/120	2	30/40	h_1/h_1+100	10/10	all Delta
Heuristic 3	240	80/80/80	3	30/40/50	$h_1/h_1+100/h_1+200$	5/10/5	all Delta
Heuristic 4	240	60/60/60/60	4	30/40/50/55	$h_1/h_1+100/h_1+200/$ h_1+300	5/5/5/5	all Delta
Heuristic 5	240	48/48/48/48/48	5	25/30/40/50/55	$h_1/h_1+100/h_1+200/$ h_1+300/h_1+400	4/4/4/4/4	all Delta
Pareto 3 [15], (benchmark)	246	36/114/96*	3	6/46/82	1250/1250/1250	2/6/6	all Delta
Centispace [4], (benchmark)	190	120/30/40*	3	55/87.4/30	875/1100/1100	12/3/4	all Delta
Pareto 6 [21], (benchmark)	281	132/99/50*	3	34/78/80	1790/1442/1286	11/11/10	Star/Delta/ Delta

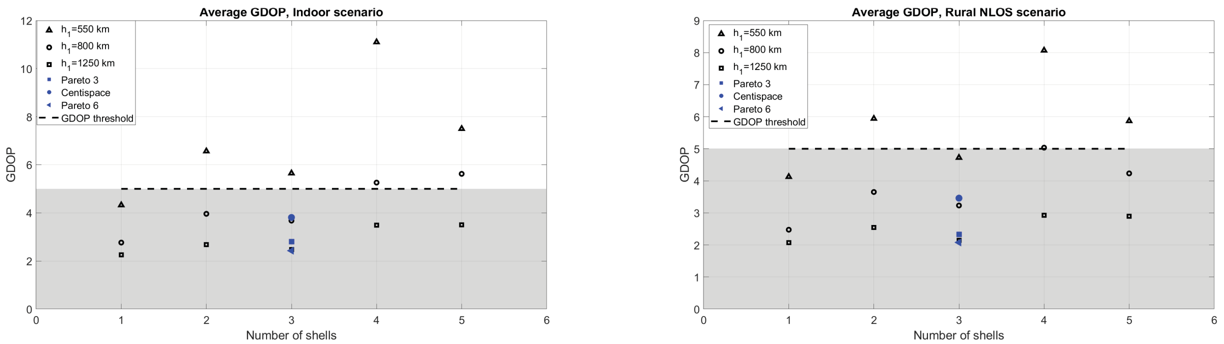

Fig. 4. GDOP values. Left-hand plot: indoor scenario; right-hand plot: rural NLOS scenario. The gray area is the target area of good performance.

TABLE III. ADDITIONAL PARAMETERS USED IN THE SIMULATIONS AND COMMON TO ALL CONSTELLATIONS.

f_c [GHz]	B_W [MHz]	Tx EIRP [dBm]	Rx P_R [dBm]	α_{min} $[^o]$
1.5	10	51	-165	5

tively and $GDOP_{av}$, Cov_{av} and $CN0_{av}$ are the average GDOP, Coverage and C/N_0 values over the two considered Pareto constellations (Pareto 3 and Pareto 6).

IV. DISCUSSIONS AND CONCLUSIONS

The main observations one can draw by analyzing Figs. 4, 5, and 6, as well as considering Table III, are as follows:

- If the lowest orbital altitude h_1 is higher or equal to 800 km, the GDOP targets can be achieved for $1-3$-shell heuristic constellations in both outdoor and indoor scenarios;
- The average four-fold coverage target of minimum 95% can be reached with $2-3$ shell constellations and for all considered h_1 values; however, with a single-shell constellation, such minimum coverage is only achieved for $h_1 \leq 800$ km because the signal coming from higher orbits would not meet the receiver sensitivity criterion;
- The average C/N_0, as expected, decreases with an increase in h_1 and in the number of shells, because in a multi-shell configuration, each added shell is at a higher altitude than the previous one. Rural NLOS C/N_0 targets are achieved by all considered constellation configurations, but indoor C/N_0 targets are only satisfied at $h_1 = 550$ km by all constellations, or, within a small error margin, also at $h_1 = 800$ km by $1-3$-shell constellations;
- The best heuristic configurations from Table III are rather close to both Pareto-based optimized constellations, showing that an engineer heuristic approach can give a good intuition in designing future LEO-PNT constellations;
- Centispace, with 50 satellites less than the heuristic ones considered here, is not meeting the indoor C/N_0 targets and suffers from a worse coverage for indoors than the heuristic constellations considered, but it exhibits a good GDOP both for indoors and outdoors, and it is comparable with the heuristic one at $h_1 = 800$ and three

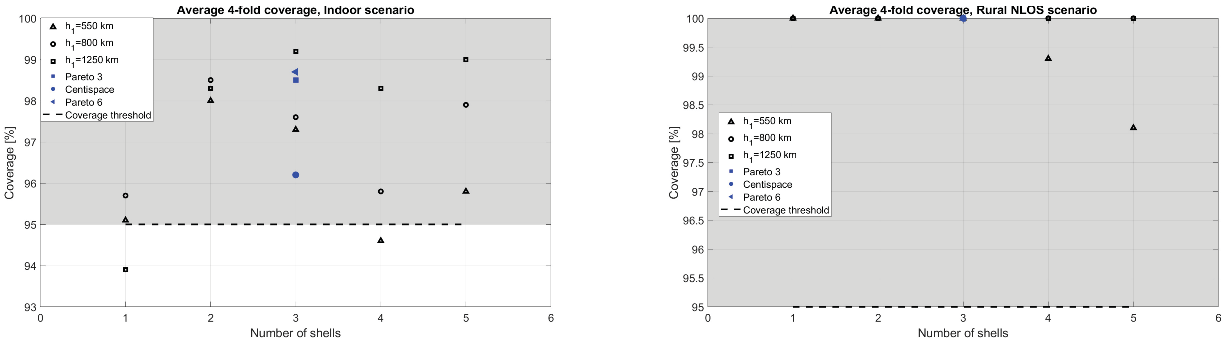

Fig. 5. Coverage values. Left-hand plot: indoor scenario; right-hand plot: rural NLOS scenario. The gray area is the target area of good performance.

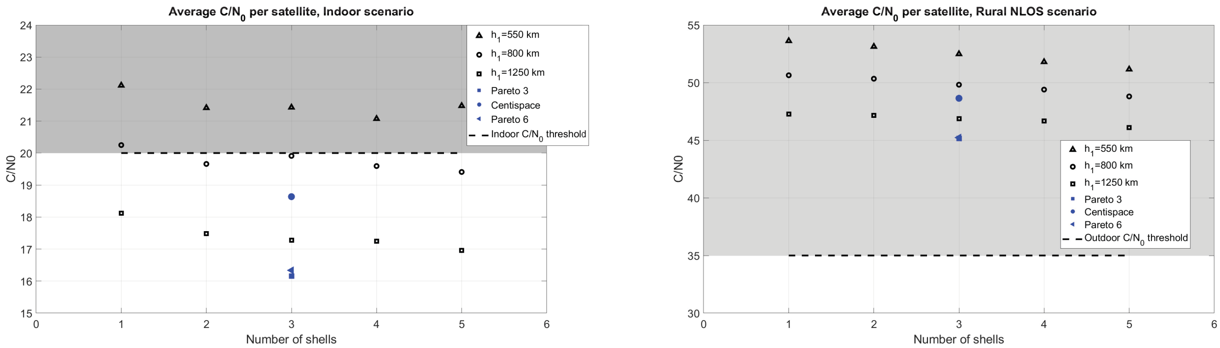

Fig. 6. C/N_0 values. Left-hand plot: indoor scenario; right-hand plot: rural NLOS scenario. The gray area is the target area of good performance.

TABLE IV. COMPARISON OF THE HEURISTIC BEST CONSTELLATION WITH THE BENCHMARKS

Indoor scenario						
	GDOP [-]	C/N_0 [dB-Hz]	Coverage [%]	N_{shells}	N_{planes} [-]	h_1 [km]
Best Heuristic	2.5	17.3	99.2	3	20	1250
Pareto 3	2.8	16.2	98.5	3	14	1250
Centispace	3.8	18.6	96.2	3	19	975
Pareto 6	2.4	16.3	98.7	3	32	1286
Outdoor (Rural NLOS) scenario						
	GDOP [-]	C/N_0 [dB-Hz]	Coverage [%]	N_{shells}	N_{planes} [-]	h_1 [km]
Best Heuristic	2.9	46.1	100	5	20	1250
Pareto 3	2.3	45.1	100	3	14	1250
Centispace	3.5	48.6	100	3	19	975
Pareto 6	2.1	45.2	100	3	32	1286

shells.

With respect to **RQ1**, our findings have shown that spreading a fixed number of available satellites over two or three shells can improve the coverage compared to single-shell configurations, but spreading them over more than three shells does not bring significant improvements, if any. In terms of GDOP, configurations of up to three shells have satisfactory GDOP values as long as $h_1 \geq 800$ km, but increasing further the number of shell is again not bringing additional benefits.

With respect to **RQ2**, we found out that heuristic constellations of up to three shells in indoor scenarios and up to five shells in outdoor scenarios can reach quite close the performance of the constellations derived based on Pareto optimization from the literature and can slightly outperform existing commercial constellations such as Centispace, for the considered performance metrics. Nevertheless, other aspects such as the deployment and maintenance costs of the satellites in orbit need further investigations.

Putting all these observations together, a design recommendation for a heuristic approach is to focus only on two and three-shell constellations, as increasing further the number of shells does not seem beneficial, and aiming at an orbital altitude of at least 800 km.

Future work will focus on the impact of decreasing the number of satellites N_{sat} and studying the achievable performance metrics with less than 100 satellites in the constellation.

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