A Comparative Study on Indoor Ranging Accuracy of LEO-PNT Systems

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***Abstract*—The prospect of using Low Earth Orbit - Position-Navigation-Timing (LEO-PNT) for indoor applications has been gaining traction in the past years, given the difficulties that Global Navigation Satellite Systems (GNSS) face in these scenarios. Inherently, LEO satellites deliver higher received power than GNSS, assuming similar carrier frequency bands, which translates to better indoor penetration capabilities and the potential of achieving an indoor PNT solution. This paper presents a comparison between various LEO-PNT system designs, comprising the choice of constellation, carrier frequency, and transmission power, and compares their performance to traditional GNSS constellations. Concise system design takeaways are provided given these extensive simulations which shed light on the requirements for LEO systems to provide the PNT solution indoors. These results show the promising potential for LEO-PNT indoors, particularly for carrier frequencies below 1.5 GHz and using the medium-sized 'Çelikbilek' constellation, along with the challenges to work at higher frequencies such as 4 GHz or 7 GHz, which are envisaged for outdoor applications.**

***Index Terms*—LEO-PNT; indoors; coverage; DOP**

I. Introduction

The space paradigm continues to expand thanks to the growth of the space industry in all its value chain, which brings the possibility of designing and launching satellites with a much reduced cost [1]. Because of this expansion, the problems and limitations of the traditional methods to obtain the PNT solution become more apparent, given that the construction of alternative systems that surpass these barriers is becoming more and more feasible.

The most common method to get a Position-Navigation-Timing (PNT) solution globally nowadays is by means of Global Navigation Satellite Systems (GNSS) satellites, since they are capable of providing high precision in a variety of situations, in particular in outdoor environments, thanks to their intricate system design [2]. Nonetheless, GNSS have still a rather limited accuracy in urban canyons and indoor environments [3], since the signal power is lowered when passing through objects, and/or for multipath and non-line-of-sight (NLoS) propagation. Furthermore, because of its lower received signal power, GNSS is highly susceptible to interferences and spoofing, and has seen an increasing amount of intentional attacks in the last few years.

These limitations in GNSS have brought attention to the use of Low Earth Orbit (LEO) platforms as PNT providers with global coverage. Particularly, due to their potential to deliver higher received power, coming from their closer proximity to Earth when compared to GNSS, LEO-PNT offers various possibilities: 1) to operate at higher carrier frequencies (f_c), where a higher two-sided bandwidth (B) is available (i.e., thus increased timing accuracy is possible), and where the amount of interferences is lower (e.g., at present, there are significantly fewer interferences present above 5 GHz carriers than below) and more effective interference/spoofing mitigation techniques based on multiple antennas can be derived, 2) to lower the satellite Equivalent Isotropic Radiated Power (EIRP) to provide similar performance as GNSS, but softening the satellite requirements and cost, while providing an added layer of security to GNSS, 3) providing a PNT solution for both indoor and urban canyon environments, and/or 4) provide higher accuracy outdoors.

From the point of view of these design options, this work aims at shedding light on the indoor positioning possibilities of LEO-PNT, and the extent to which they are compatible with the other prospects. To this end, f_c values lower than or equal to those of GNSS are considered, which is typical for indoor positioning studies, but also higher f_c values, which are usually considered for improved performance outdoors.

The indoor location services market was valued at 11.9 billion dollars in 2024, and is predicted to generate 55 billion dollars in revenue by 2030 [4], showing that indoor positioning is receiving increasing attention in the PNT world and that it provides a tremendous market potential. This rapid increase is mainly due to the need for asset tracking, as well as optimising industrial efficiency, enhancing safety and security in hazardous environments, enabling seamless positioning in railway stations, in the metro or in airports, or allowing proximity marketing and indoor analytics.

Due to the limitations of GNSS for indoor positioning, other signals not typically aimed at offering PNT solutions are

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often used for this purpose. Common examples include using Wi-Fi signals [5]–[7], which provide around 10 meter-level accuracy, Ultra-Wide-Band (UWB), which can provide mm-level accuracy but requires heavy indoor infrastructure [8], [9], Bluetooth Low Energy (BLE) [10], with accuracies comparable with or slightly better than the WiFi-based accuracies , or others such as fixed reference nodes (RNs) or RF identification devices (RFIDs) [11], [12]. GNSS is also able to overcome its indoor limitations when operating with high-sensitivity receivers [13], which can process the lower-powered signals, while using alternative sources of navigational information to mitigate the effects of multipath, such as A-GNSS [14] or Inertial Measurement Units (IMU), although still with a very limited 4-fold coverage.

However, these solutions are not tailored to the trade-off between low-complexity and high-performance needs of most devices requiring PNT, and thus the use of LEO satellites dedicated to PNT might prove to be more desirable. In other words, a GNSS-like solution indoors is preferable.

A few recent works have shown the prospective use of LEO satellites for indoor positioning. In [15], the performance of LEO satellites operating with GNSS receivers with high antenna gain is evaluated, and compared to GNSS and hybridised LEO plus GNSS, using the indoor model from [16] and showcasing the important gains of LEO in terms of Carrier-to-Noise ratio (C/N_0) and coverage. In [17], a combination of LEO with reconfigurable intelligent surfaces (RIS) is proposed, leading to improved positioning accuracy indoors.

The novelty in this work and the added value compared to the existing state-of-the-art lies on a few points: 1) assessing the impact on the indoor performance of the choice of carrier frequency, 2) evaluating the effect of the transmission power (and thereby of the satellite cost) on indoor performance, and 3) summarizing concise take-aways that delve on the choice for these parameters. These contributions answer to the main objective of this work, which is to offer a comprehensive comparison of the parameter-choice impact on the performance of LEO-PNT systems indoors, and to evaluate the best trade-off between these parameters for indoor LEO positioning.

II. Framework of the semi-analytical approach

A. Performance metrics in our analysis

The analysis in this work is based on our framework from [18] for standalone LEO-PNT and GNSS constellations, but adapted to indoor conditions. The main metrics used in this work to evaluate the performance of these constellations are the C/N_0, the Position Dilution of Precision (PDOP) and the coverage, defined by the relative amount of receivers that manage to process 4 or more satellite signals. These metrics provide a vision of the achievable PNT performance, both in terms of positioning accuracy, and resilience to spurious signals and jammers. Their relation to the LEO system design showcases the trade-off between performance and transmitter cost and complexity.

These metrics are related to the positioning accuracy, which is also simulated in this work, as portrayed in Eq. (1), while the connection between the C/N_0 and the interference robustness can be found in [19, Eq. 6.9].

$$\sigma_{\mathrm{3D,LB}} \approx \mathrm{PDOP} \cdot \sigma_{\mathrm{UERE}} \tag{1}$$

with σ_{UERE} the uncertainty in the ranging estimation, which mainly depends on the clock, ionospheric, tropospheric, orbit determination and noise errors. The reader is referred to [18] for the modeling of these errors in LEO and GNSS constellations, where commercial receivers without external error corrections were considered. Table I is included in this work for reference. For scenarios with multipath, Eq. (1) only takes into account its presence through the reduction in C/N_0, and not the displacement of the correlation peak, and thus represents a lower-bound for the positioning accuracy.

Error Source	σ_{IONO} (m)	σ_{TROPO} (m)	$\sigma_{\mathrm{CLK,\,ORB}}$ (m)	$\sigma_{\mathrm{NOISE\text{-}BL}}$ (m)
GNSS	1.2	0.5	0.8	0.5
LEO	1.2	0.5	1.8	0.5

TABLE I: Average UERE values considered in this work.

Notably, the PDOP and coverage are computed only considering received signals that surpass the receiver sensitivity, so that Eq. (1) is applicable. In this work, the receiver sensitivity is assumed to have a moderate value of -155 dBm, which allows for the detection of signals with a C/N_0 of 18.9 dB-Hz or higher [14] for GNSS-like signals; furthermore, a satellite elevation mask of 10^o is considered.

B. LEO constellations

In terms of the analysis of the dedicated LEO-PNT system design, the work in [18] presented an extensive comparison of LEO constellations for outdoor applications. The two constellations presenting the best trade-off between performance and cost, namely 'Marchionne' [20] and 'Çelikbilek' [21], are simulated also in this work. Three constellations resembling those from the industry are also simulated, particularly focusing on those with a higher amount satellites and/or lower satellite altitudes, which are presented in Table II.

TABLE II: LEO constellations considered in this work.

LEO Constellation	Number of satellites	Number of shells	Satellite altitude(s) (km)
Marchionne [20]	326	3	[1250, 1250, 1250]
Çelikbilek [21]	382	3	[1835, 1550, 1477]
Iridium-Next-like	66	1	780
OneWeb-like	648	1	1200
OneWeb-like @ 500 km	648	1	500

These constellations are simulated prospectively operating at carrier frequencies of 0.3 GHz, 1.5 GHz, 4 GHz or 7 GHz, following the literature [18], [22], but avoiding Ku/Ka bands which yield path losses that are too high for indoor applications. While the choice of a higher f_c does not directly favour the performance indoors, given that they incur in higher path losses which reduce the C/N_0 and the path losses of walls and objects indoors will already be high, such an evaluation is of interest since this choice brings strong improvements in other applications. Mainly, outdoor receivers benefit from it by making use of the higher available B, lower amount of interferences, and the possibility of adding more antennas for beamforming purposes at the receiver, from which indoor receivers could also benefit.

Another point for comparison is the satellite EIRP, given its relation with the C/N_0 and the satellite size and cost. Two representative values of 50 dBm and 67 dBm are chosen, following [18], which are prototypical of an EIRP smaller than that of GNSS [23], which can be achieved by smaller satellites such as CubeSats, or one closer to the values reported by Iridium-Next [24], [25], respectively. Starlink's EIRP lies inbetween these values, at around 57.5 dBm, depending on the channel conditions [26].

C. Indoor scenario path losses model

Following [27], the path losses of a mobile device indoors can be defined as:

$$\mathrm{PL} = \mathrm{FSPL}(d, f_c) + \mathrm{SF} + \mathrm{CL_{out}}(\theta_{\mathrm{el}}) + \mathrm{PL_g} + \mathrm{PL_s} + \mathrm{PL_{in}} \quad (2)$$

which depends on the following parameters:

- Free-Space Path Losses (FSPL), defined as $\mathrm{FSPL}(d, f_c)[\mathrm{dB}] = 32.45 + 20\log_{10}(f_{c,\mathrm{GHz}}) + 20\log_{10}(d)$ [16], with d the satellite-receiver distance.
- Shadow fading (SF), with SF$\sim \mathcal{N}(0, \sigma^2_{\mathrm{SF}})$, whose values for Non-Terrestrial-Networks (NTN) are found in [27].
- Outdoor Clutter Losses ($\mathrm{CL_{out}}(\theta_{\mathrm{el}})$) coming from the signal colliding with outdoor buildings and structures, which depend on θ_{el} and the scenario at hand [27].
- Path losses due to the atmosphere ($\mathrm{PL_g}$), defined in [27].
- Path losses due to the scintillation in the ionosphere and troposphere ($\mathrm{PL_s}$), defined in [27].
- Indoor path losses, defined as [27]–[30] [31, Section 22]:

$$\mathrm{PL_{in}}(\theta_{\mathrm{el}}, f_c) = \mathrm{PL_{wall,ext}}(\theta_{\mathrm{el}}, f_c) + 0.212 \cdot |\theta_{\mathrm{el}}| + \mathrm{nL}(\theta_{\mathrm{el}}) \cdot \mathrm{PL_{wall,in}} + 0.5 d_{\mathrm{in}}(\theta_{\mathrm{el}}) + \mathrm{CL_{in}}(\theta_{\mathrm{el}}, f_c) \quad (3)$$

where:

  - $\mathrm{PL_{wall,ext}}(\theta_{\mathrm{el}}, f_c)$ represents the external wall penetration path losses with normal incidence, which depend on the building materials, which in turn will be different depending on θ_{el} and on f_c. [16] [31, Section 22].
  - the term $0.212 \cdot |\theta_{\mathrm{el}}|$ accounts for the non-normal signal incidence through the external wall [30].
  - $\mathrm{nL}(\theta_{\mathrm{el}})$ is the number of interior walls the signal penetrates, which will depend on the scenario.
  - $\mathrm{PL_{wall,in}}$ represents the path losses caused by one indoor wall, and is defined as $\mathrm{PL_{wall,in}} = 4.9 + 0.05 \cdot f_{c,\mathrm{GHz}}$ [28].
  - The term $0.5 d_{\mathrm{in}}(\theta_{\mathrm{el}})$ accounts for other objects that mitigate the signal indoors [16], [28], such as furniture or people, with $d_{\mathrm{in}}(\theta_{\mathrm{el}})$ the distance traveled by the signal indoors.
  - $\mathrm{CL_{in}}(\theta_{\mathrm{el}}, f_c)$ represents the Clutter Losses caused by indoor reflections, which are non-zero for the indoor NLoS component [29].

Most notably, the Line-of-Sight (LoS) and NLoS components of the signal have different path losses, with the NLoS typically entering the building through the external wall material with the fewer losses [31, Section 22], but with added clutter losses. The NLoS component with the lower penetration loss is herein assumed to be always available, whose power depends also on f_c through the material-specific losses.

D. Indoor scenario definition

In this work, the placement of a user inside two different buildings is simulated, located in three distinct outdoor environments, namely in rural 'R', urban 'U', or dense urban 'DU' conditions, given the dependence of the path losses on the outdoor clutter losses outlined previously, whose probability and value are defined in [16] and depend on θ_{el}. Two indoor scenarios are defined as follows:

- Indoor 1 'I1': It constitutes a 1-story building with a height of 3 m, length of 10 m and width of 10 m, with the user placed in the middle of the building. The path losses will mainly come from the external wall, since nL $= 0$ for all values of θ_{el}. This building is representative of the softest indoor scenario, such as a warehouse.
- Indoor 2 'I2': Representative of a shopping mall, an office, or a more complex industrial structure, it comprises a 3-story building, with a height of 9 m, and length and width of 10 m, with the user placed in the middle of the lowest floor.

Notably, both buildings are considered to be thermally-efficient, which have higher path losses than the traditional ones [31, Section 22] [30], and are made out of IIR glass windows and concrete. Fifty different time instances are simulated for 400 users uniformly distributed throughout Europe, meaning that we compute statistics over $20,000$ points.

III. Simulation Results

The simulated performance results for the framework in Section II are presented herein. First off, the C/N_0, PDOP, and coverage values are shown for scenario 'Indoor 1' in Table II, placed in rural (I1R), urban (I1U), or dense urban (I1DU) environments, along with the lower-bound positioning accuracy $\sigma_{\mathrm{3D,LB}}$ presented in Eq. (1).

'Indoor 1' is the simplest indoor scenario among the two considered indoor scenarios; the results in Table II show that the GNSS constellations do manage to achieve a positioning solution in most instances, though with a clearly reduced C/N_0. Particularly, when using the four main GNSS constellations that most commercial receivers can process, a relatively high coverage is achieved, with fairly decent accuracy.

However, the gain in using LEO satellites is substantial compared to GNSS. Most LEO constellations present both higher C/N_0 and coverage values, and better accuracy than GNSS up to a carrier frequency of 4 GHz when using an EIRP of 67 dBm, as shown in Fig. 1, and until 1.5 GHz for an

TABLE III: Performance of the constellations of analysis at the "Indoor 1" one-floor, soft-indoor scenario.

Constellation	Fc (GHz)	$\mathbf{C/N_0}$ **(dB-Hz)**			**PDOP (-)**			**Coverage (%)**			$\sigma_{\mathrm{3D,LB}}$ **(m)**		
		I1R	I1U	I1DU	I1R	I1U	I1DU	I1R	I1U	I1DU	I1R	I1U	I1DU
GNSS													
GPS	L1	23.7	19.7	15.0	1.9	1.9	1.9	94.8	82.9	64.4	8.5	8.3	8.2
Galileo	E1	21.5	15.1	10.1	2.0	2.0	2.0	93.5	71.3	52.7	10.7	10.8	10.8
4 GNSS	L1	22.2	16.7	12.2	1.4	1.5	1.6	99.7	98.1	89.9	7.0	7.2	7.6
LEO satellite EIRP of 67 dBm													
Çelikbilek	0.3	66.5	62.1	57.8	1.1	1.1	1.1	100	100	100	2.5	2.5	2.5
	1.5	53.0	48.0	43.6	1.1	1.1	1.3	100	100	100	2.5	2.5	2.5
	4.0	35.8	31.2	26.8	1.1	1.4	1.6	100	98.0	90.9	2.8	3.3	3.9
	7.0	20.8	16.1	11.5	1.3	1.5	1.9	99.7	97.7	89.5	4.7	8.5	10.2
Marchionne	0.3	67.8	62.1	58.3	1.6	1.6	1.6	100	100	100	3.4	3.4	3.4
	1.5	53.7	48.0	44.2	1.6	1.6	1.6	100	100	100	3.4	3.4	3.5
	4.0	37.3	31.3	27.4	1.6	2.1	2.6	100	91.7	81.3	3.7	4.7	6.0
	7.0	22.5	16.4	12.4	1.7	2.1	2.5	97.2	90.7	77.9	8.3	10.0	11.6
Iridium-Next -like	0.3	70.4	64.5	60.2	3.7	3.7	3.7	18.8	18.8	18.8	5.4	5.4	5.4
	1.5	56.3	50.4	46.0	3.7	3.7	3.7	18.8	18.8	18.8	5.4	5.5	5.6
	4.0	39.7	33.6	29.1	3.7	3.7	3.5	18.8	14.7	10.8	6.0	5.8	5.6
	7.0	24.7	18.5	13.9	3.7	3.7	3.5	18.0	14.6	10.6	14.6	13.8	13.0
OneWeb-like	0.3	67.2	61.9	57.2	0.9	0.9	0.9	100	100	100	2.0	2.0	2.0
	1.5	53.1	47.8	43.1	0.9	0.9	1.0	100	100	100	2.0	2.1	2.1
	4.0	36.5	31.0	26.1	1.0	0.9	1.0	100	73.6	59.0	2.3	2.2	2.4
	7.0	21.4	15.7	10.7	1.0	1.0	1.0	93.4	72.5	55.4	5.5	5.2	5.2
OneWeb-like @ 500 km	0.3	73.5	68.8	64.7	1.9	1.9	1.9	100	100	100	4.2	4.2	4.2
	1.5	59.4	54.6	50.5	1.9	1.9	1.9	100	99.7	99.8	4.2	4.2	4.2
	4.0	42.7	37.8	33.6	1.9	1.9	2.0	99.6	79.8	73.5	4.3	4.2	4.5
	7.0	27.6	22.5	18.1	1.9	1.9	1.8	93.4	72.5	57.5	6.4	6.1	6.0
LEO satellite EIRP of 50 dBm													
Çelikbilek	0.3	49.4	45.1	40.8	1.1	1.1	1.1	100	100	100	2.5	2.5	2.6
	1.5	35.4	30.9	26.6	1.1	1.4	1.6	100	98.2	91.4	2.7	3.2	3.8
	4.0	18.8	14.2	9.8	1.4	1.6	1.9	99.7	97.5	88.8	8.4	9.6	11.4
	7.0	3.8	-0.9	-5.5	-	-	-	0.0	0.0	0.0	-	-	-
Marchionne	0.3	50.8	45.1	41.3	1.6	1.6	1.6	100	99.8	99.8	3.4	3.5	3.5
	1.5	36.7	31.0	27.2	1.6	2.1	2.8	100	92.6	84.4	3.7	4.7	6.4
	4.0	20.3	14.3	10.4	1.8	2.2	2.6	96.7	90.0	76.5	9.5	11.2	13.0
	7.0	5.5	-0.6	-4.6	-	-	-	0.0	0.0	0.0	-	-	-
Iridium-Next -like	0.3	53.4	47.5	43.2	3.7	3.7	3.7	18.8	18.8	18.8	5.4	5.5	5.6
	1.5	39.3	33.4	29.0	3.7	3.7	3.5	18.8	14.8	11.0	5.9	5.8	5.6
	4.0	22.7	16.6	12.1	3.8	3.7	3.5	17.8	14.5	10.4	16.2	15.1	14.2
	7.0	7.7	1.5	-3.1	-	-	-	0.0	0.0	0.0	-	-	-
OneWeb-like	0.3	50.2	44.9	40.2	0.9	0.9	0.9	100	100	100	2.1	2.1	2.1
	1.5	36.1	30.8	26.1	0.9	1.0	1.5	99.9	77.5	66.6	2.2	2.4	3.6
	4.0	19.5	14.0	9.1	1.1	1.0	1.0	93.4	72.5	55.4	6.4	6.0	6.0
	7.0	4.4	-1.3	-6.3	-	-	-	0.0	0.0	0.0	-	-	-
OneWeb-like @ 500 km	0.3	57.5	51.8	47.7	1.9	1.9	1.9	100	99.3	99.4	4.2	4.2	4.2
	1.5	42.4	37.6	33.5	1.9	1.9	2.0	99.7	83.2	78.8	4.3	4.3	4.6
	4.0	25.7	20.8	16.6	1.9	1.8	1.8	92.7	72.5	57.5	6.8	6.4	6.4
	7.0	10.6	5.5	1.2	8.1	8.1	8.1	15.3	14.3	12.6	70.4	70.3	70.3

EIRP of 50 dBm. Hence, in order to achieve decent soft-indoor accuracy, these results show that LEO satellites transmitting with an EIRP of 67 dBm or higher can be employed with f_c values up to 4 GHz. For smaller EIRPs (e.g., 50 dBm), more likely to be used on small-sized LEO satellites such as CubeSats, only carrier frequencies equal or smaller than GNSS carrier frequencies can be used to reach soft-indoor users.

Between the compared LEO constellations, the big-sized 'OneWeb-like' constellation reaches the highest accuracy levels. Nonetheless, the medium-sized 'Marchionne' and 'Çelikbilek' constellations reach the highest coverage, particularly the latter for the case of $f_c = 4$ GHz with an EIRP of 67 dBm, as shown in Fig. 2, and for the case of $f_c = 1.5$ GHz with an EIRP of 50 dBm, while keeping acceptable accuracy. This can be explained by the fact that, unlike OneWeb-like, both 'Marchionne' and 'Çelikbilek' constellations were optimized for good positioning accuracy and coverage.

Most notably, while 'OneWeb-like @ 500 km' operates at a much lower altitude than 'OneWeb-like', it is the latter which performs better for 'Indoor 1'. This is due to the fact that, while lower-flying constellations generally deliver more power, higher constellations have more visible satellites,

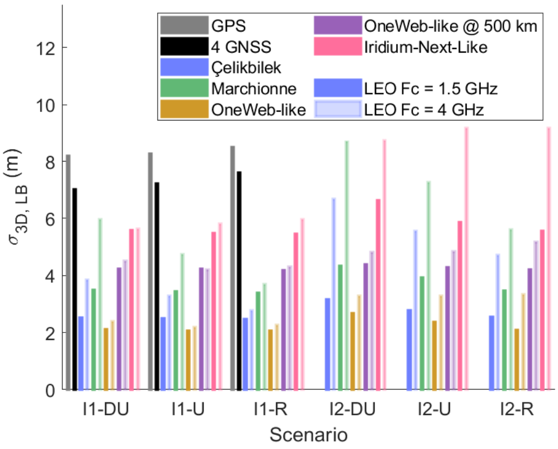

Fig. 1: $\sigma_{3D,LB}$ for indoor scenarios, comparing GNSS and LEO systems operating at f_c of 1.5 and 4 GHz and with an EIRP of 67 dBm.

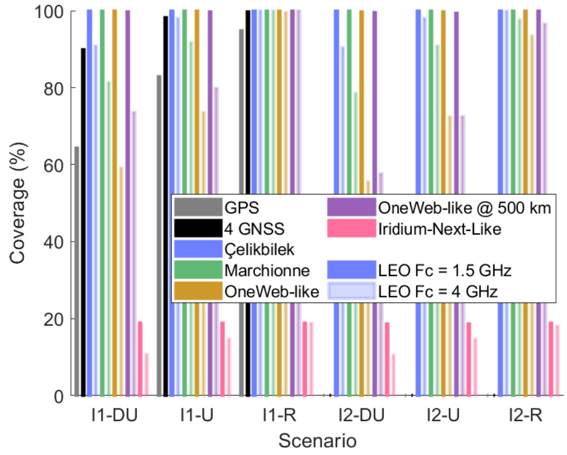

Fig. 2: Coverage for indoor scenarios, comparing GNSS, and LEO systems operating at f_c of 1.5 and 4 GHz and with an EIRP of 67 dBm.

which is particularly important for indoor scenarios where very specific θ_{el} values may have a strong impact on the positioning accuracy, since the signal may be entering the building through the path with the fewer losses. The probability of a satellite flying at these particular θ_{el} is higher with higher altitudes, which proves to be more useful than putting the same amount of satellites at a lower orbit. This conclusion is even clearer and more notable for the more complex case of 'Indoor 2'.

Another point for analysis is the use of the UHF carrier frequency. These results indicate that, when using the EIRP of 50 dBm, indoor accuracy at somewhat higher levels than open-sky GNSS can be achieved in the 'Indoor 1' scenario, with all constellations reaching very close to maximal accuracy and coverage. Meanwhile, if operating with an EIRP of 67 dBm, the gain with respect to GNSS is very substantial, which would lead to improved interference robustness indoors [18], [19].

In terms of the 'Indoor 2' scenario, similar conclusions can be reached for LEO, while GNSS ceases to work completely. As mentioned earlier, operating at $f_c \geq 4$ GHz decreases considerably the coverage and positioning accuracy, proving that even an EIRP of 67 dBm might not suffice to operate at these bands. Notably, however, the 'Çelikbilek' constellation still offers quite decent coverage and accuracy for $f_c \leq 1.5$ GHz, proving again to be the best medium-sized LEO constellation.

As per the use of the $f_c = 0.3$ GHz for the 'Indoor 2' scenario, the evaluated EIRP of 50 dBm already provides a performance close to that of GNSS in open-sky, and thus a $f_c = 0.3$ GHz proves to be the best option for hard indoor scenarios (e.g.. multi-floor, many concrete walls, etc.).

IV. System Design Takeaways and Conclusions

These results lead us to some concise system design takeaways for LEO-PNT operating indoors:

- Operating in bands higher than GNSS, such as $f_c = 4$ GHz, is shown to be relatively compatible with indoor positioning, as long as a sufficiently high EIRP is offered by the LEO satellites. From the tested EIRP values, the 67 dBm choice shows some coverage and accuracy, but a higher EIRP would be needed for more demanding applications (e.g. a coverage of 99%). An f_c of 7 GHz is shown to be clearly unusable for indoor positioning.
- If operating at the L1 band, an EIRP of 50 dBm suffices to provide decent results for most constellations, showing a good trade-off between indoor positioning performance, and satellite design complexity. Nonetheless, if using the higher-end EIRP of 67 dBm, the average LEO performance indoors is nearly that of GNSS in open sky.
- As per the choice of 0.3 GHz, outstanding performance is achieved when operating with an EIRP of 67 dBm, reaching values between 50 and 70 dB-Hz of C/N_0 indoors, depending on the scenario and the constellation. However, a far more approachable design lies on using an EIRP of 50 dBm, which provides good performance.
- The constellations providing the best trade-off between performance and number of satellites are 'Çelikbilek' and 'Marchionne'. They provide the best coverage and accuracy, surpassed only by the big-sized 'OneWeb-like'. Between the two, 'Çelikbilek' does outperform 'Marchionne', due to its multi-shell configuration.
- Notably, when comparing the same constellation operating at different altitudes, such as OneWeb-like at 1200 km or at 500 km, there is a trade-off between coverage and accuracy which depends on the complexity of the indoor scenario. For the softer 'Indoor 1' scenario, the lower satellite altitude offers better coverage, as observed in Fig. 2 for f_c = 4 GHz and an EIRP of 67 dBm, or for f_c = 1.5 GHz with an EIRP of 50 dBm. However, its accuracy is worse since a lower amount of satellites are visible at each point in time, as depicted in Fig. 1. For the more complex scenario 'Indoor 2', the coverage for both

TABLE IV: Performance of the constellations of analysis at the "Indoor 2" three-floor, hard indoor scenario.

Constellation	Fc (GHz)	$\mathrm{C/N_0}$ **(dB-Hz)**			**PDOP (-)**			**Coverage (%)**			$\sigma_{\mathrm{3D,LB}}$ **(m)**		
		I2R	I2U	I2DU	I2R	I2U	I2DU	I2R	I2U	I2DU	I2R	I2U	I2DU
GNSS													
GPS	L1	13.1	9.2	4.5	-	-	-	0.0	0.0	0.0	-	-	-
Galileo	E1	14.2	7.8	2.8	-	-	-	0.0	0.0	0.0	-	-	-
4 GNSS	L1	13.5	8.1	3.0	-	-	-	0.0	0.0	0.0	-	-	-
LEO satellite EIRP of 67 dBm													
Çelikbilek	0.3	56.2	51.8	47.5	1.1	1.1	1.1	100	100	100	2.5	2.5	2.5
	1.5	42.1	37.6	33.3	1.1	1.2	1.4	100	100	100	2.5	2.8	3.1
	4.0	25.6	21.0	16.6	1.2	1.4	1.7	99.9	98.0	90.4	4.7	5.6	6.7
	7.0	11.7	7.0	2.4	155.3	138.3	156.4	19.4	9.0	7.8	1010.3	958.5	-
Marchionne	0.3	57.5	51.9	48.1	1.6	1.6	1.6	100	100	100	3.4	3.4	3.4
	1.5	43.5	37.7	33.9	1.6	1.7	1.9	100	100	100	3.4	3.9	4.3
	4.0	27.2	21.3	17.4	1.6	2.0	2.5	97.7	90.9	78.5	5.6	7.3	8.7
	7.0	14.0	7.9	3.8	3.0	3.0	2.9	31.1	14.6	12.5	18.6	20.5	19.3
Iridium-Next -like	0.3	60.8	54.9	50.6	3.7	3.7	3.7	18.8	18.8	18.8	5.4	5.4	5.5
	1.5	46.7	40.8	36.4	3.7	3.7	3.7	18.8	18.7	18.6	5.5	5.8	6.6
	4.0	30.2	24.2	19.7	3.7	3.7	3.5	18.0	14.6	10.6	9.2	9.2	8.7
	7.0	16.7	10.5	5.8	-	-	-	1.1	0.5	0.4	-	-	-
OneWeb-like	0.3	57.7	52.4	47.7	0.9	0.9	0.9	100	100	100	2.0	2.0	2.0
	1.5	43.6	38.3	33.6	0.9	1.0	1.1	100	99.8	99.7	2.1	2.4	2.7
	4.0	27.0	21.5	16.7	0.9	0.9	0.9	93.4	72.5	55.4	3.3	3.3	3.3
	7.0	12.9	7.2	2.2	14.3	15.7	15.3	49.2	36.3	27.1	120.5	138.3	134.3
OneWeb-like @ 500 km	0.3	63.5	58.7	54.7	1.9	1.9	1.9	100	100	100	4.2	4.2	4.2
	1.5	49.4	44.6	40.4	1.9	1.9	1.9	100	99.4	99.5	4.2	4.3	4.4
	4.0	32.8	27.9	23.7	2.0	1.8	1.8	96.6	72.5	57.5	5.2	4.8	4.8
	7.0	18.8	13.7	9.4	2.3	2.3	2.3	92.5	72.5	57.5	16.3	17.0	16.8
LEO satellite EIRP of 50 dBm													
Çelikbilek	0.3	39.2	34.7	30.5	1.1	1.3	1.5	100	100	100	2.6	2.9	3.4
	1.5	25.1	20.6	16.3	1.2	1.4	1.7	99.9	98.1	90.4	4.5	5.3	6.4
	4.0	8.6	4.0	-0.4	-	-	-	0.0	0.0	0.0	-	-	-
	7.0	-6.7	-10.9	-14.6	-	-	-	0.0	0.0	0.0	-	-	-
Marchionne	0.3	40.5	34.9	31.1	1.6	1.9	2.2	100	99.2	98.3	3.5	4.3	5.1
	1.5	26.5	20.7	16.9	1.6	2.0	2.5	97.6	90.9	78.5	5.5	7.0	8.4
	4.0	10.2	4.3	0.4	4.0	3.8	4.0	3.6	1.2	1.2	33.4	33.6	35.2
	7.0	-3.0	-9.1	-13.2	-	-	-	0.0	0.0	0.0	-	-	-
Iridium-Next -like	0.3	43.8	37.9	33.6	3.7	3.7	3.7	18.8	17.3	16.7	5.6	5.8	6.6
	1.5	29.7	23.8	19.4	3.7	3.7	3.5	18.0	14.6	10.6	8.9	8.8	8.4
	4.0	13.2	7.2	2.7	-	-	-	0.0	0.0	0.0	-	-	-
	7.0	-0.3	-6.5	-11.2	-	-	-	0.0	0.0	0.0	-	-	-
OneWeb-like	0.3	40.7	35.4	30.7	0.9	1.2	1.5	100	99.2	99.1	2.1	2.8	3.5
	1.5	26.6	21.3	16.6	0.9	0.9	0.9	93.5	72.5	55.4	3.2	3.1	3.1
	4.0	10.0	4.5	-0.3	6.4	6.4	6.5	1.9	0.9	0.7	63.0	63.7	64.5
	7.0	-4.1	-9.8	-14.8	-	-	-	0.0	0.0	0.0	-	-	-
OneWeb-like @ 500 km	0.3	47.0	41.7	37.7	1.9	2.0	2.0	100	99.0	99.1	4.2	4.4	4.6
	1.5	32.4	27.6	23.4	2.0	1.8	1.8	97.0	72.8	57.8	5.1	4.8	4.7
	4.0	15.8	10.9	6.7	3.7	3.7	3.7	89.7	70.3	55.7	28.5	28.6	28.2
	7.0	1.8	-3.3	-7.6	10.5	10.1	10.0	0.9	0.3	0.3	84.2	81.6	80.4

altitudes is very similar, while the accuracy of the prior is substantially better. The explanation for this effect is that, in more complex indoor scenarios, the propagation losses will be low for some particular θ_{el} values, such as an θ_{el} where the impinging signal is coming through a window and does not go through many interior walls. Hence, using a constellation where the probability of having satellites at these particular θ_{el} values is higher might become more useful than a constellation whose average delivered power is higher. Ultimately, it is better to design a constellation at 1200 km rather than at 500 km for complex indoor scenarios, while there is a trade-off between coverage and accuracy for simpler scenarios.

- The smaller 'Iridium-Next-like' constellation, proves to be a good stepping stone for larger systems, since it already delivers some indoor coverage in all scenarios.

A. *Future work*

Future work may include the derivation of system design takeaways that depend on the applicability of the LEO-PNT system, since the prospective applications of LEO-PNT go beyond the case of indoor positioning presented in this work. The definition of an optimal system that considers both the performance of the multiple applications it is meant to be used for and the overall complexity is still needed. Another line for future research is an assessment of indoor performance when combining signals from various LEO constellations.

References

[1] W. W. Baber and A. Ojala, "New Space Era: Characteristics of the New Space Industry Landscape," in *Space Business: Emerging Theory and Practice*. Springer Nature Singapore Singapore, 2024, pp. 3–26.

[2] D. Egea-Roca, M. Arizabaleta-Diez, T. Pany, F. Antreich, J. A. Lopez-Salcedo, M. Paonni, and G. Seco-Granados, "GNSS user technology: State-of-the-art and future trends," *IEEE Access*, vol. 10, pp. 39 939–39 968, 2022.

[3] G. Seco-Granados, J. Lopez-Salcedo, D. Jimenez-Banos, and G. Lopez-Risueno, "Challenges in indoor global navigation satellite systems: Unveiling its core features in signal processing," *IEEE Signal Processing Magazine*, vol. 29, no. 2, pp. 108–131, 2012.

[4] A. Ojala, S. Fraccastoro, and M. Gabrielsson, "Internationalization of indoor positioning platform firms: Insights from loose coupling theory," in *Proceedings of the 57th Hawaii International Conference on System Sciences*. Hawaii International Conference on System Sciences, 2024.

[5] "WiFi-based indoor positioning, author=Yang, Chouchang and Shao, Huai-Rong," *IEEE Communications Magazine*, vol. 53, no. 3, pp. 150–157, 2015.

[6] F. Liu, J. Liu, Y. Yin, W. Wang, D. Hu, P. Chen, and Q. Niu, "Survey on WiFi-based indoor positioning techniques," *IET communications*, vol. 14, no. 9, pp. 1372–1383, 2020.

[7] R. Jurdi, H. Chen, Y. Zhu, B. L. Ng, N. Dawar, C. Zhang, and J. K.-H. Han, "WhereArtThou: A WiFi-RTT-Based Indoor Positioning System," *IEEE Access*, vol. 12, pp. 41 084–41 101, 2024.

[8] A. Alarifi, A. Al-Salman, M. Alsaleh, A. Alnafessah, S. Al-Hadhrami, M. A. Al-Ammar, and H. S. Al-Khalifa, "Ultra wideband indoor positioning technologies: Analysis and recent advances," *Sensors*, vol. 16, no. 5, p. 707, 2016.

[9] F. Wang, H. Tang, and J. Chen, "Survey on NLOS identification and error mitigation for UWB indoor positioning," *Electronics*, vol. 12, no. 7, p. 1678, 2023.

[10] S. G. Kumar, S. Prince, and B. M. Shankar, "Smart tracking and monitoring in supply chain systems using RFID and BLE," in *2021 3rd International Conference on Signal Processing and Communication (ICPSC)*. IEEE, 2021, pp. 757–760.

[11] P. S. Farahsari, A. Farahzadi, J. Rezazadeh, and A. Bagheri, "A survey on indoor positioning systems for IoT-based applications," *IEEE Internet of Things Journal*, vol. 9, no. 10, pp. 7680–7699, 2022.

[12] S. Hayward, K. van Lopik, C. Hinde, and A. A. West, "A survey of indoor location technologies, techniques and applications in industry," *Internet of Things*, vol. 20, p. 100608, 2022.

[13] E. Domínguez, A. Pousinho, P. Boto, D. Gómez-Casco, S. Locubiche-Serra, G. Seco-Granados, J. López-Salcedo, H. Fragner, F. Zangerl, O. Peña *et al.*, "Performance evaluation of high sensitivity GNSS techniques in indoor, urban and space environments," in *Proceedings of the 29th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2016)*, 2016, pp. 373–393.

[14] F. Van Diggelen, *A-GPS: Assisted GPS, GNSS, and SBAS*. Artech house, 2009.

[15] K. Çelikbilek and E. S. Lohan, "A Performance Study on the Combination of Available GNSS and Potential LEO-PNT Constellations," *IEEE Access*, 2024.

[16] 3GPP, TR 38.901 v14.1.1, "Study on channel model for frequencies from 0.5 to 100 GHz," Tech. Rep., 2017.

[17] P. Zheng, X. Liu, J. He, G. Seco-Granados, and T. Y. Al-Naffouri, "LEO satellite and RIS: Two keys to seamless indoor and outdoor localization," *arXiv preprint arXiv:2312.16946*, 2023.

[18] G. Foreman-Campins, J. A. López-Salcedo, and E. S. Lohan, "A Comparative Study on Ranging Accuracy and Interference Robustness of LEO-PNT Systems in Outdoor Scenarios," *Submitted to IEEE Access*, 2025.

[19] E. Kaplan and C. Hegarty, *Understanding GPS/GNSS: Principles and Applications, 2nd Edition*, 2006.

[20] L. Marchionne, L. M. Gessato, F. Toni, and S. La Barbera, "Striking a Balance: Performance and Cost Optimization of LEO-PNT Constellation for Hybrid Users Using a Meta-Heuristic Approach," in *2023 IEEE 10th International Workshop on Metrology for AeroSpace (MetroAeroSpace)*. IEEE, 2023, pp. 609–614.

[21] K. Çelikbilek, E. Simona Lohan, and J. Praks, "Optimization of a LEO-PNT Constellation: Design Considerations and Open Challenges," *International Journal of Satellite Communications and Networking*, 2025.

[22] L. Ries, M. C. Limon, F.-C. Grec, M. Anghileri, R. Prieto-Cerdeira, F. Abel, J. Miguez, J. V. Perello-Gisbert, S. D'addio, R. Ioannidis *et al.*, "LEO-PNT for augmenting Europe's space-based PNT capabilities," in *2023 IEEE/ION Position, Location and Navigation Symposium (PLANS)*. IEEE, 2023, pp. 329–337.

[23] GPS, "GPS L1 Link Budget," 2007. [Online]. Available: https://apps.fcc.gov/els/GetAtt.html?id=110032x=

[24] T. G. Reid, T. Walter, P. K. Enge, D. Lawrence, H. S. Cobb, G. Gutt, M. O'connor, and D. Whelan, "Navigation from low earth orbit: part 1: concept, current capability, and future promise," *Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications*, vol. 2, pp. 1359–1379, 2020.

[25] Iridium, "Iridium Next Engineering Statement," 2016. [Online]. Available: https://fcc.report/IBFS/SAT-MOD-20131227-00148/1031348.pdf

[26] S. Kozhaya, S. Joe, and Z. Z. M. Kassas, "Unveiling Starlink for PNT," *NAVIGATION: Journal of the Institute of Navigation*, vol. 72, no. 1, 2025.

[27] 3GPP, TR 38.811 v15.4.0, "Study on New Radio (NR) to support non-terrestrial networks," Tech. Rep., 2020.

[28] I. Rodriguez, H. C. Nguyen, I. Z. Kovács, T. B. Sørensen, and P. Mogensen, "An empirical outdoor-to-indoor path loss model from below 6 ghz to cm-wave frequency bands," *IEEE antennas and wireless propagation letters*, vol. 16, pp. 1329–1332, 2016.

[29] ITU-R, P.2108-1, "Prediction of clutter loss,," Tech. Rep., 2021.

[30] ITU-R, P.2109-2, "Prediction of building entry loss,," Tech. Rep., 2023.

[31] ITU-R, P.2346-5, "Compilation of measurement data relating to building entry loss,," Tech. Rep., 2023.