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RESEARCH ARTICLE

A Performance Study on the Combination of Available GNSS and Potential LEO-PNT Constellations

KAAN ÇELIKBILEK AND ELENA SIMONA LOHAN, (Senior Member, IEEE)
Electrical Engineering Unit, Tampere Wireless Research Center, Tampere University, 33720 Tampere, Finland

Corresponding author: Kaan Çelikbilek (kaan.celikbilek@tuni.fi)

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ABSTRACT With the reduction in the launch and manufacturing costs of satellites, there has been a surge of interest in Low-Earth Orbit (LEO) satellites from both the industrial and academic sectors in recent years. This heightened interest has led to the growing popularity of the LEO-based Positioning, Navigation, and Timing (LEO-PNT) systems, which are seen either as complementary or standalone alternatives to the current Global Navigation Satellite Systems (GNSS). Studies that explore LEO and GNSS systems together typically do it either from the perspective of LEO-based GNSS augmentation or from the perspective of a standalone LEO system that improves over GNSS. However, there are very few studies that examine the combination of a standalone LEO constellation with GNSS to improve the PNT performances of each. Thus, we take an approach that falls in between the two typical approaches, and we explore the expected performance improvement when standalone LEO and GNSS systems are combined, from a LEO-PNT perspective. For this purpose, we selected three GNSS constellations (GPS, Galileo and BeiDou) as well as two LEO-PNT constellations (Centispace and an experimental design, previously proposed by the Authors), and we analyze their standalone and combined performances in an indoor environment. The simulations are conducted with a MATLAB-based in-house constellation simulator using the QuaDRiGa channel-model library. The results indicate that a combination of two LEO-PNT systems with one or several of the available GNSS constellations can significantly improve the indoor coverage, as well as providing good received signal quality and good geometric configuration quality for indoor positioning when frequency bands similar to GNSS are used for LEO-PNT constellations.

INDEX TERMS Combined constellations, GNSS positioning, LEO-PNT systems, performance analysis.

I. INTRODUCTION

Technological advancements in satellite technology have made it possible to mass-produce cheap satellites, such as CubeSats, shaping the Low-Earth Orbit (LEO)-based applications into an exciting and promising area for business and research. Both academia and industry are keen on designing, launching, and innovating both existing and new LEO satellites, which promise to transform our daily life. Potential LEO system applications include, but are not limited to, providing global broadband connectivity, enabling top scientific research within the space sector, offering Earth-sensing solutions, and complementing existing Global Navigation Satellite Systems (GNSS) for robust and seamless navigation, especially in areas where GNSS use is still challenging, such as indoors. Thousands of satellites are already in LEO (between 200 and 2000 km above Earth), supporting various communication and remote sensing applications.

Current global positioning solutions, namely Positioning, Navigation and Timing (PNT) services, rely heavily on GNSS, which lack high reliability and coverage in challenging environments such as urban canyons or indoors, and are vulnerable to malicious interference. This has created

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a need for complementary or alternative global positioning methods. In this regard, the signals obtained from LEO satellites can effectively supplement and improve global PNT services of GNSS. The obvious benefit, assuming comparable carrier frequencies with GNSS, is the stronger signal power of the LEO satellites due to their proximity to Earth, which, in turn, improves the continuity of the PNT services in the aforementioned challenging environments. In addition, satellites in LEO move faster than those in higher orbits, resulting in a fast change in the spatial geometry, which also accelerates the decorrelation of precise positioning parameters such as ambiguities and positions, leading to rapid convergence [1]. Additional studies focus on developing PNT methods that do not share the same challenges as the code estimation [2], [3], [4]. These benefits of LEO satellites have given rise to the idea of Low-Earth Orbit-based Positioning, Navigation, and Timing (LEO-PNT) systems, which can be designed either as standalone systems or as augmentation systems for the existing GNSS infrastructure.

The current trend in academia focuses mostly on LEO-PNT as an augmentation system. Many scholars have tested LEO satellites' contribution to improve GNSS positioning performance in different scenarios [5], [6], [7], [8], [9], [10], [11], [12], and a particular popularity on Precise Point Positioning (PPP) can be noticed. In [13], the study evaluated the performance improvements of using LEO satellites for GNSS PPP and compared it with solutions using signals from Global Positioning System (GPS) or both GPS and Glonass. The findings revealed that the convergence time is reduced by 51.31% and the positioning accuracy is improved by 14.9% for the LEO-augmented GPS solution compared with the GPS-only PPP scheme, and that, for the same number of satellites, the convergence time is only reduced by 3.93% and the positioning accuracy is improved by 16.4% for the combined GPS and Glonass PPP, again compared with the GPS-only PPP scheme. These numbers indicate that LEO satellites can significantly enhance the PPP convergence speed in comparison to Medium Earth Orbit (MEO) satellites. Similarly, the authors in [14] also investigated the performance of LEO-augmented GNSS PPP, with a focus on harsh environments. Their results show that, compared to BeiDou Navigation Satellite System (BDS)-only, the average time-to-first-fix of BDS+GPS, BDS+LEO, BDS+GPS+LEO combinations can be shortened from 20.0 min to 10.3 min, 4.8 min, and 4.0 min, respectively. More recently, the authors in [15] similarly examined PPP performance of BDS, GPS and Galileo when augmented by Centispace, which revealed an accuracy improvement of up to 18.8% and convergence time reduction of 53%.

There are also a number of studies that examine the augmentation concept without PPP focus. For example, the authors in [16] studied the LEO-augmented GPS case for the Real-Time Kinematic (RTK) solution, using four LEO constellations designed for the study, and showed that faster convergence and fixing can be achieved with a LEO constellation of 192-288 satellites. The authors in [17] instead took an optimization approach, and performed a statistical optimization analysis on the number of orbital planes, satellites, and the orbital inclinations for possible suitable LEO constellations for augmentation purposes, taking Iridium as a base for LEO constellations and examining all four existing GNSS constellations. They concluded that the combination of LEO constellations with different inclinations resulted in better satellite distribution along the latitude for global fast convergent PPP than LEO constellation with singular inclinations, and showed, as an example, that a convergence time of one minute can be achieved globally using a LEO constellation with a total of 240 satellites and with three orbital planes with inclinations at 90°, 60° and 35°.

The above-mentioned studies demonstrate that GNSS can indeed be significantly improved with LEO augmentation. However, the emphasis until now has notably been on LEO constellations designed for GNSS augmentation and on Radio Frequency (RF)-level studies, rather than on developing standalone LEO-PNT constellations. An innovative approach, addressed here, is to also explore the combination of two or more independent constellations to enhance the PNT performance of each, which could be examined from the perspective of signals of opportunity studies. There are very few studies in the literature that takes this approach. One notable example is [18], which shares some similarities with this work. In [18], the authors optimize LEO-PNT constellations and examine their performance in combination with GPS and Galileo, for 3 outdoor scenarios using an elevation angle of 5°. However, the main focus of their study is on optimization, and to show that their constellations are able to maintain good operational conditions. In contrast, this work focuses on a throughout analysis on the performance metrics, focuses on more challenging conditions, (i.e., indoor scenarios, an elevation angle of 10°), and includes additional systems, such as BDS and Centispace. In addition, this work proposes design recommendations for system combinations.

In our study, we simulate the system-level performance of different combinations of selected GNSS and LEO constellations. The GNSS constellations we consider are Galileo, GPS and BDS, and the LEO constellations we consider are Centispace, and an experimental design obtained from an earlier study of ours [19]. The evaluations are made in a MATLAB-based in-house constellation simulator using the QuaDRiGa channel-model library. Thus, we sum up the contributions of this paper as:

- Studying the combined performance of GNSS and LEO systems for positioning purposes under realistic indoor channel models and using an in-orbit constellation simulator;
- Identifying the benefits of using at least one LEO constellation together with existing GNSS constellations for improved coverage and indoor performance;
- Discussing further ways ahead regarding the combined use of LEO and GNSS constellations for future positioning applications.

II. ANALYSIS FRAMEWORK

A. SELECTED LEO-PNT AND GNSS CONSTELLATIONS

Table 1 provides a summary of important parameters for the five selected constellations; GPS, Galileo and BDS are selected amongst the GNSS constellations, and Centispace as well as an experimental LEO-PNT design from the Authors' earlier studies are selected for the LEO-PNT constellations. In order to focus the comparison on the constellation designs as much as possible, we take the L1 base for GPS and Galileo, and the B1I base for BDS, which minimizes the difference in carrier frequencies. All three of these GNSS constellations consist of a single shell (i.e., a single set of constellation parameters). As for Centispace, which consists of 2 shells, there is no publicly available documentation which details its signal properties to the best of the Authors' knowledge, but an educated guess is that it should be similar to BDS as one of the design goals of Centispace is to be used together with BDS. Thus, Centispace's assumed similarity in the physical layer design with BDS, alongside it being one of the few existing LEO-PNT constellations, is cause for it to be included in this study.

Unlike other constellations considered in the study, whose missing parameters in Table 1 can be found in public resources if desired, the experimental design requires a detailed presentation due to being a unique design derived in the Authors' earlier studies [19]. The constellation design consists of 3 shells; the first shell has 133 satellites distributed evenly to 19 orbital planes at 1835 km altitude with 34° orbital inclination, using Walker Star topology, the second shell has 99 satellites distributed evenly to 3 orbital planes at 1550 km altitude with 86° orbital inclination, using Walker Delta topology, and the last shell has 150 satellites distributed evenly to 30 orbital planes at 1477 km altitude with 80° orbital inclination, using again the Walker Star topology. It was designed as a standalone LEO-PNT constellation that can provide good PNT metrics in challenging conditions [19].

During the combination of different constellations, the shells of each constellation are combined separately. For example, while combining GPS and the experimental design, a new hypothetical constellation is created by adding the GPS constellation as a 4^{th} shell to the experimental design, resulting in a 4-shell constellation that captures both geometric properties and the signal properties of both constellations. This method notably ignores the challenges of jointly using different signal designs in the same positioning scheme, which may prove some combinations unfeasible, but such aspects are out of scope for this study due to the fact that the simulator used for this work focuses on system-level modelling, link budget calculations, and receiver processing, rather than on deep RF-level aspects such as generating I/Q samples. The models used to calculate the selected LEO-PNT metrics are detailed in section II-B. The practicality of jointly processing I/Q signals from varying LEO and MEO systems remains a topic of future research.

B. LEO-PNT METRICS UNDER CONSIDERATION

The PNT performance is assessed here through three primary metrics relevant in positioning context: the geometric configuration quality, the received signal quality, and the overall coverage. To evaluate the geometric configuration between satellites and users, two Dilution of Precision (DOP) units were selected: the Position (3D) Dilution of Precision (PDOP), which relates to the positioning accuracy, and the Geometric Dilution of Precision (GDOP), which relates to the combined positioning and timing accuracy. The average path-loss and the Carrier-to-Noise Ratio (C/N_0) are used to measure the quality of the received signal. The coverage, which depends on both the geometric configuration and on the signal quality, is considered crucial, with 4-fold coverage being essential for positioning applications since time-based 3-D positioning requires at least four visible satellites to generate a position estimate. Furthermore, the total number of satellites in the constellation, denoted as n_{sat}, is monitored to provide a rough estimate of the cost to launch and maintain a LEO constellation with n_{sat} satellites.

The DOP metrics can be obtained from the geometry matrix H. The geometry matrix of a single constellation system, assuming code/pseudorange-based positioning and the geocentric coordinate system, can be formed from the unit vectors e_x, e_y, and e_z (corresponding to the X, Y, and Z axes) defined from the receiver to the visible satellites, as a $(n \times 4)$ matrix that corresponds to the 3-D position and the time bias of n visible satellites [24], [25]:

$$H = \begin{bmatrix} e_{x_1} & e_{y_1} & e_{z_1} & 1 \\ e_{x_2} & e_{y_2} & e_{z_2} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ e_{x_n} & e_{y_n} & e_{z_n} & 1 \end{bmatrix} \tag{1}$$

Expanding equation (1) to combine M constellations with each constellation's number of visible satellites given as $(n_1, n_2, \ldots, n_M)$, equation (2) is obtained, where the notation $e_{x_{n_m}}$ refers to the unit vector in X axis, which belongs to the n-th visible satellite of constellation m. The matrix consisting of the 1's and 0's on the right side of equation (2) represents which constellation the satellite signal belongs to, and changing the values of multiple columns to 1 allows for joint processing of corresponding constellation systems. Therefore, the H matrix seen in equation (2) has a size of $(n_{sat_{total}}) \times (3 + M)$, where $n_{sat_{total}}$ is the sum of all visible satellite from all the considered constellations.

$$H = \begin{bmatrix} e_{x_{1_1}} & e_{y_{1_1}} & e_{z_{1_1}} & 1 & 0 & \ldots & 0 \\ e_{x_{2_1}} & e_{y_{2_1}} & e_{z_{2_1}} & 1 & 0 & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ e_{x_{n_1}} & e_{y_{n_1}} & e_{z_{n_1}} & 1 & 0 & \ldots & 0 \\ e_{x_{1_2}} & e_{y_{1_2}} & e_{z_{1_2}} & 0 & 1 & \ldots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ e_{x_{n_M}} & e_{y_{n_M}} & e_{z_{n_M}} & 0 & 0 & \ldots & 1 \end{bmatrix}_{(n_{sat_{total}})\times(3+M)} \tag{2}$$

TABLE 1. Satellite constellation parameters (as of July 2024).

Constellation	Total Number of Satellites	Altitude [km]	Inclination [deg]	EIRP [dBm]	Bandwidth [MHz]	Carrier Frequency [MHz]
*Experimental Design [19]	382	1477-1835	34-86	51.5	10	1575.42
*Centispace [20]	190	975-1100	55-88	**65	**4.092	**1561.098
BDS [21]	27	21528	55	65	4.092	1561.098
Galileo [22]	27	23222	56	59	24.552	1575.42
GPS [23]	30	20200	55	59	24	1575.42

* : These constellations have multiple-shells, and the indicated altitude and inclination ranges mean that individual shells have particular values for that parameter which falls between the given ranges.
** : These parameters are based on our assumptions, as exact values could not be found in public resources.

Above, $e_{x_{s_i}}$ stands for the unit vector in X axis of the s-th considered system, $s = 1, \ldots, M$ and its corresponding i-th visible satellite, $i = 1, \ldots, M_s$, where $\sum_{i=1}^{M_s} i = n_{sat_{total}}$.

After the H matrix is determined, the covariance matrix Q resulting from the least squares solution is calculated as:

$$Q = (H^T \Sigma^{-1} H)^{-1} = \begin{bmatrix} \sigma_x^2 & \sigma_{xy} & \sigma_{xz} & \sigma_{xt} \\ \sigma_{xy} & \sigma_y^2 & \sigma_{yz} & \sigma_{yt} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z^2 & \sigma_{zt} \\ \sigma_{xt} & \sigma_{yt} & \sigma_{zt} & \sigma_t^2 \end{bmatrix} \tag{3}$$

In equation (3), Σ matrix represents the error covariance matrix, which can either be simplified to the identity matrix, assuming an error-free model, or can be modeled separately to include errors such as tropospheric and ionospheric errors, clock errors, etc. In our study, we use a non-unit Σ following the models in [25].

After Q is obtained, its elements are then used to calculate different DOP metrics, which are unitless. The two used in this study are defined as seen in equations (4) and (5). Lower DOP values suggest better accuracy for the PNT solution and typically, a GDOP value below 5 is considered good [26].

$$\text{GDOP} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 + \sigma_t^2} \tag{4}$$

$$\text{PDOP} = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2} \tag{5}$$

The rest of the metrics require detailed link budget calculations. The 4-fold coverage is computed as the percentage of the total number of users that have at least four satellites in view. The path-losses were modeled using the QuaDRiGa link-budget models and were further enhanced with three attenuation models: atmospheric absorption, rain attenuation, and fog/cloud attenuation, calculated via MATLAB's internal functions. We assumed a global rain model with a 60 mm/h rate and a cloud liquid water density of 0.5 g/m^3. Temperature (T), dry air pressure (p), and water-vapor density (ρ) are modeled from the satellite altitude (h), as given in equations (6), (7), and (8) respectively [27].

$$T(h) = 286.8374 - 4.7805\, h - 0.1402\, h^2 \quad [K] \tag{6}$$

$$p(h) = 1008.0278 - 113.2494\, h + 3.9408\, h^2 \quad [hPa] \tag{7}$$

$$\rho(h) = 8.988 \exp(-0.3614\, h - 0.005402\, h^2 - 0.001955\, h^3)[g/m^3] \tag{8}$$

The C/N_0 is calculated for each satellite-user pair via equation (9) given below, where P is the power of the signal indicated in the subscript, B_w is the bandwidth of the channel, and Signal-to-Noise Ratio (SNR) is calculated for each satellite-user pair.

$$C/N_0{}^{dB-Hz} = 10 \log_{10}\left(\frac{P_{carrier}}{P_{noise}}\right) = SNR + 10 \log_{10}(B_w) \tag{9}$$

An ideal constellation would have global 4-fold coverage at 100%, high C/N_0, low values for GDOP, PDOP, and average path-loss, while maintaining a minimal number of satellites in the constellation. Also, it should be noted that the DOP and C/N_0 metrics are averaged over time and over user-satellite pairs to obtain a single value that represents the average performance of the metric for that specific constellation combination at the end of the simulation.

III. RESULTS

A. SIMULATOR DESCRIPTION

In our earlier works [19], [28], a comprehensive LEO constellation simulator was developed by the Authors in MATLAB for LEO-PNT performance analysis. This system-level simulator integrates MATLAB libraries with the external QuaDRiGa[1] channel library [29] for link-budget calculations and calculates the performance metrics explained in section II-B according to the inputs. The simulator emulates a satellite constellation using a set of inputs, including constellation parameters, the start time and duration of the simulation, and user information (such as position and velocity vectors at each time instant, the number of users and their distribution on Earth, etc.), as well as input parameters for QuaDRiGa which includes satellite Effective Isotropic Radiated Power (EIRP), receiver sensitivity, atmospheric attenuation effects, and scenario details. Fig. 1 provides an overview of this simulator.

The simulator employs the SGP4 (Simplified General Perturbation 4) orbit propagator model, which calculates satellite positions and velocities over time, starting from an initial user-defined point. SGP4 takes into account various perturbations, including Earth's shape, solar radiation pressure, and gravitational effects from the Sun and Moon.

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[1] https://quadriga-channel-model.de/

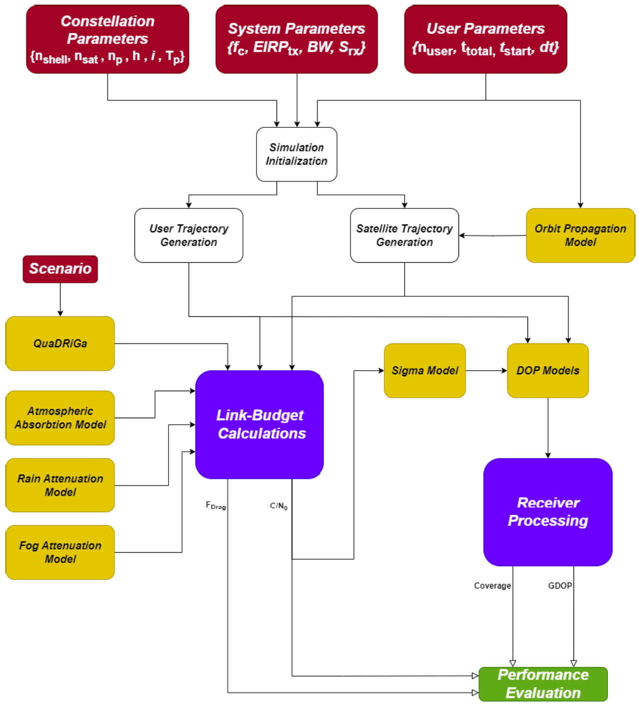

FIGURE 1. Simulator overview - highlighted: input (red), output (green), modifiable model (yellow), main simulation section (blue).

It employs simplified analytical models that balance accuracy and computational complexity effectively. Additionally, the simulator extends the Quadriga channel model with rain and fog attenuation models, adhering to 3GPP specifications.[2] Furthermore, it implements DOP models based on equations (1) - (3), and the non-unit Σ as described in [25].

The performed simulations take into account a rural, indoor Non-Line of Sight (NLOS) environment defined within QuaDRiGa that considers 50 meter signal penetration, a nominal receiver sensitivity value of -155dBm, and stationary users uniformly spread on Earth. Constellations are initialized according to their own parameters, as in Table 1. The duration of each simulation is 1 hour, with 1 minute samples, resulting in 600 Monte-Carlo runs per satellite in the constellation. Summer conditions are assumed for atmospheric models.

B. LEO-PNT PERFORMANCE OF CONSTELLATION COMBINATIONS

The individual performances of the constellations in the selected environment (as detailed in subsection III-A) are presented in Table 2, which shows that GNSS constellations struggle with coverage and signal quality compared to LEO constellations. Centispace is able to achieve the strongest received power by a large margin compared to the other considered constellations, and both LEO constellations achieve approximately 25 dB less path-loss compared to the GNSS constellations. Following this, Table 3 illustrates that the metrics improve already when constellations are combined in pairs. The multi-LEO combination achieves 100% coverage while maintaining relatively good DOP values and signal quality compared to the individual performances. Combining different GNSS systems improves the indoor coverage of GPS by 49.2% to 107.63%, Galileo by 70.47% to 137.17%, and BDS by 17.47% to 30.54%, depending on the combined constellations, while also slightly enhancing both DOP and C/N_0. The benefits of combining the three GNSS constellations and both LEO constellations are visualized in Fig. 2 and Fig. 3 respectively.

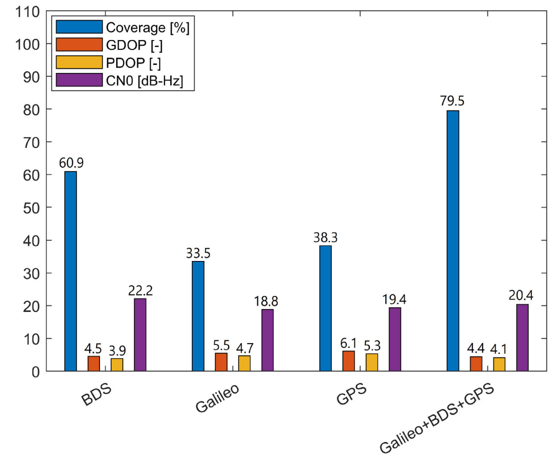

FIGURE 2. Single GNSS versus 3-GNSS combination - indoor performance.

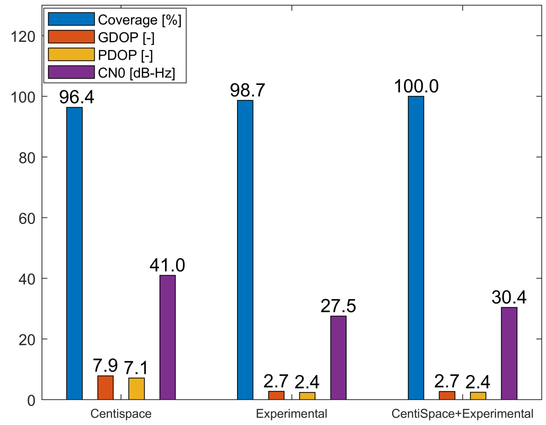

FIGURE 3. Single LEO versus 2-LEO combination - indoor performance.

However, the most significant improvement is seen when GNSS constellations are combined with LEO constellations, resulting in coverage values close to 100% and C/N_0 values approaching those of LEO constellations. Regarding DOP changes in these pairs, combining Centispace with Galileo and BDS slightly worsens GDOP and PDOP in comparison to their standalone GNSS performances, but a slight improvement of both metrics can be seen for GPS. In contrast, combination with the experimental design

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[2] www.3gpp.org

TABLE 2. **LEO-PNT Performance metrics for individual constellations for the considered indoor scenario.**

Type	Constellation	Coverage $[\%]$	n_{sat} $[-]$	GDOP $[-]$	PDOP $[-]$	C/N_0 $[dB-Hz]$	Received Power $[dBm]$	Path-Loss $[dB]$
GNSS	BDS	60.9	27	4.54	3.86	22.16	−146.81	226.08
	Galileo	33.52	27	5.48	4.7	18.85	−150.13	226.83
	GPS	38.29	30	6.1	5.3	19.37	−149.61	225.85
LEO	Centispace	96.38	190	7.88	7.12	40.98	−128	203.72
	Experimental Design	98.67	382	2.75	2.42	27.54	−141.43	200.73

TABLE 3. **LEO-PNT performance metrics for various pair combinations of constellations in the considered indoor scenario.**

Type	Constellation	Coverage $[\%]$	n_{sat} $[-]$	GDOP $[-]$	PDOP $[-]$	C/N_0 $[dB-Hz]$	Received Power $[dBm]$	Path-Loss $[dB]$
Multi-LEO	Experimental + Centispace	100	572	2.71	2.44	30.4	−138.57	203.15
Multi-GNSS	GPS + Galileo	57.13	57	5.12	4.65	19.1	−149.88	226.32
	Galileo + BDS	71.54	54	4.49	4.01	21.01	−147.97	226.46
	GPS + BDS	73.96	57	4.63	4.11	21.06	−147.91	225.96
	Galileo + BDS + GPS	79.5	84	4.43	4.12	20.43	−148.54	226.24
LEO + GNSS	GPS + Experimental	99.06	412	2.76	2.56	26.55	−142.43	209.55
	GPS + Centispace	98.06	220	5.99	5.65	33.83	−135.14	215.83
	Galileo + Experimental	99.06	409	2.76	2.57	26.66	−142.31	209.49
	Galileo + Centispace	97.56	217	6.27	5.98	34.62	−134.35	215.99
	BDS + Experimental	99.44	409	2.72	2.45	26.56	−142.42	209.21
	BDS + Centispace	98.81	217	4.73	4.33	32.71	−136.27	215.42

improves both GDOP and PDOP by about 45% on average for all three GNSS constellations, compared to their individual performances.

Iterating further on the results from Table 3, Table 4 presents the LEO-PNT performances of multi-LEO and multi-GNSS combinations.

In comparison to the multi-LEO case (i.e., Centispace + experimental), combining any of the GNSS constellations with the experimental LEO constellation slightly reduces the average C/N_0, while in the combinations of one GNSS system and Centispace, the average C/N_0 is slightly increased. However, when two or more GNSS systems are combined with at least one LEO system, the average C/N_0 is almost always slightly lower than in the multi-LEO combination; this is likely due to the fact the path losses (and thus the corresponding link budgets) are stronger for GNSS signals than for LEO signals when the carrier frequencies are comparable. However, the most relevant metrics for positioning in our opinion are the DOP metrics; by looking at those, one can find out which LEO+GNSS combinations are the most promising. For example, compared to the multi-LEO case, the combination of multi-LEO and BDS slightly improves the DOP values, while combining multi-LEO with Galileo or GPS slightly worsens GDOP and PDOP instead. In these multi-LEO+GNSS cases, alongside cases where two GNSS systems (e.g., BDS and Galileo) are combined with the two considered LEO constellations, we see the best GDOP values among the considered cases, as well as maintaining a coverage of 100%.

The multi-GNSS+LEO combinations in Table 4 continue these trends for combinations with the experimental design. Compared to the GNSS+LEO combination counterparts from Table 3, slight improvements exists for coverage, but 100% is still not achieved.

Combinations including BDS slightly improve the DOP values while combinations with Galileo and GPS slightly deteriorate them, and the average path-losses increase as more GNSS signals are included in the solution, resulting in decreases in both C/N_0 and average received power.

Further combinations between multi-GNSS and multi-LEO constellations seen in Table 4 again show slight changes compared to multi-GNSS+LEO and multi-LEO+GNSS combinations; the coverage is unsurprisingly at 100% since all combinations in this type of combination include both the experimental design and Centispace, which could reach 100% already, and changes up to 0.11 GDOP, 0.2 PDOP, and 3 dB-Hz C/N_0 can be seen depending on the specific comparison.

Overall, we can state that the improvements on the metrics as a result of combining different constellations are promising, but the particular combinations need analysis. Multiple examples can be seen from Tables 3 and 4 where the combined system provides slightly worse DOP and C/N_0 then a subset of the multi-constellation system, indicating that simply combining more constellations does not equate to an improved geometry or positioning. Indeed, if we are to look at individual metrics, among all the presented results, the combination of both of the considered LEO

TABLE 4. LEO-PNT performance metrics for multi-constellation combinations for the considered indoor scenario.

Type	Constellation	Coverage [%]	n_{sat} $[-]$	GDOP $[-]$	PDOP $[-]$	C/N_0 $[dB-Hz]$	Received Power $[dBm]$	Path-Loss $[dB]$
Multi-LEO + GNSS	Experimental + Centispace + BDS	100	599	2.69	2.47	29.06	−139.92	207.89
	Experimental + Centispace + Galileo	100	599	2.75	2.57	29.44	−139.53	208.12
	Experimental + Centispace + GPS	100	602	2.74	2.58	29.28	−139.69	208.22
Multi-GNSS + LEO	Experimental + GPS + BDS	99.5	439	2.74	2.51	25.83	−143.15	212.78
	Centispace + GPS + BDS	99.19	247	4.34	3.99	29.78	−139.19	219.72
	Experimental + GPS + Galileo	99.25	439	2.78	2.62	25.86	−143.12	212.98
	Centispace + GPS + Galileo	98.5	247	5.24	5.02	30.68	−138.3	220.19
	Experimental + Galileo + BDS	99.5	436	2.73	2.49	25.91	−143.06	212.78
	Centispace + Galileo + BDS	98.94	244	4.46	4.09	30.16	−138.82	219.91
	Experimental + Galileo + BDS + GPS	99.58	466	2.77	2.62	25.3	−143.68	215.1
	Centispace + Galileo + BDS + GPS	99.23	274	4.21	3.99	27.34	−141.64	222.2
Multi-LEO + Multi-GNSS	Experimental + Centispace + Galileo + GPS	100	629	2.8	2.64	28.46	−140.51	211.47
	Experimental + Centispace + BDS + GPS	100	629	2.73	2.6	28.17	−140.8	211.29
	Experimental + Centispace + Galileo + BDS	100	626	2.71	2.51	28.3	−140.67	211.27
	Experimental + Centispace + Galileo + BDS + GPS	100	656	2.76	2.64	27.52	−141.46	213.59

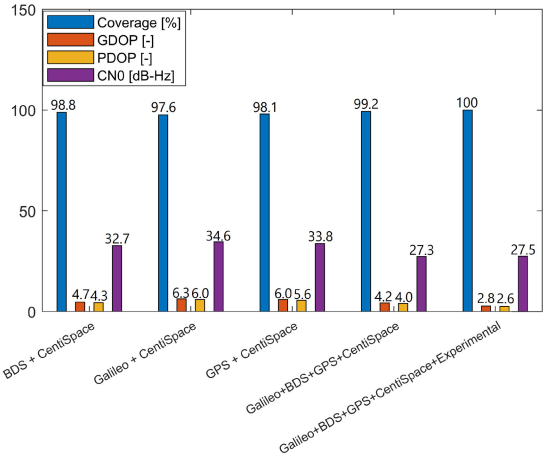

FIGURE 4. Various combinations of GNSS and LEO constellations with centispace - indoor performance.

systems with BDS provides the best GDOP, while the standalone experimental design provides the best PDOP, and the standalone Centispace provides the best C/N_0, best received signal power and the lowest path-loss. However, none of the standalone variants can reach full coverage and only the combinations which include both LEO constellations are able to reach 100% indoor coverage. Thus, it is our design recommendation to include at least two LEO constellations (or one very large LEO constellation with multiple shells, such as a LEO-PNT constellation the size of Starlink) in combination with one or several GNSS systems in order to reach full four-fold coverage for indoor scenarios.

It is important to note that LEO constellations have a high number of satellites, which could lead to feasibility issues. This raises the question of trade-offs: is the performance improvement worth the investment? Figure 4 illustrates the indoor performance of various constellation combinations with Centispace, highlighting the improvements and deteriorations these combinations bring. This visualization is valuable for making informed decisions about combining different constellations with trade-offs in mind.

IV. CONCLUSION

This article provides a comprehensive analysis and discussion on the potential combination of standalone GNSS and LEO constellations from a PNT performance perspective. The study examines three GNSS constellations (Galileo, GPS, and BDS) and two LEO constellations (Centispace and an experimental design from the Authors' previous research). The performance metrics analyzed include four-fold coverage, GDOP, PDOP, average C/N_0, average received power, and average path-loss. An in-house MATLAB simulation, which utilizes the QuaDRiGa channel library for link budget calculations, was used to evaluate these metrics for a rural, indoor NLOS environment. This indoor environment considered a 50-meter signal penetration inside the building, a nominal receiver sensitivity of -155 dBm, and stationary users uniformly distributed on Earth. Tables 2, 3, and 4 detail the impact of various constellation combinations and the resulting changes in performance metrics. The results show that combining two dedicated LEO-PNT systems with one or several of the GNSS constellations now in use in Europe and US results in a significant improvement in coverage for indoor scenarios when L1 frequency bands are used, compared to combined GNSS performance as well as compared with standalone and combined LEO constellations. The increase in coverage and C/N_0 when combining LEO constellations to GNSS constellations is expected, but this study is able to confirm one can achieve significant increases in indoor scenarios and could open new business opportunities and applications for LEO-PNT. On top of the shown performance enhancements, the results also point out what combinations of LEO and GNSS systems are the most promising ones: we have shown that a combination of two small-to-medium sized LEO-PNT constellations (or one mega-LEO-PNT constellation) with at least one GNSS system can also improve the C/N_0 and DOP metrics for the combined system and that combination of additional constellations besides the minimum two small-sized LEO and one GNSS constellations brings in only incremental enhancements.

It is important to acknowledge two primary limitations of this study, which future research could address and build upon. First, the assumptions regarding the signal properties in LEO systems impose specific constraints. For instance, employing a weaker satellite transmitter power or operating on frequency bands other/higher than L1 would yield different outcomes, with substantial implications for potential performance improvements. Secondly, this study assumes that the receiver can reliably construct the geometry matrix (equations (1) and (2)). However, given the varying signal and the system characteristics across different satellite constellations, achieving this may demand unrealistic architectures (if using a single receiver) or may require a combination of multiple user-end receivers, which may be impractical for everyday devices such as cellphones. These elements warrant a more thorough examination before real-life implementation can be realized.

Future research on LEO-PNT holds the potential not only to improve the system performance, but also to unlock a wide range of real-world applications. One promising area is the exploration of code-based versus Doppler-based estimation methods for more accurate and reliable positioning solutions. For example, applications such as autonomous drone navigation and high-speed rail positioning could benefit from Doppler-based positioning, as this method typically requires less detailed knowledge of the signal structure, allowing for real-time, high-speed adjustments with lower latency. Recent research highlights specific challenges in code-based positioning in LEO-PNT systems from a user-segment perspective [30]. Addressing these could enhance the ability of code-based systems to provide precise, high-resolution measurements necessary for applications such as emergency response and precision agriculture, where detailed location accuracy is crucial.

Combining constellations using Doppler-based methods represents another valuable avenue for research. Doppler estimation, which does not rely heavily on prior knowledge of the signal structure, could prove advantages for applications requiring robust velocity and timing data, such as vehicle-to-everything (V2X) communications in smart cities and global logistics for real-time tracking of shipments. The development of hybrid methods that integrate both Doppler and code-based systems could lead to multi-constellation PNT solutions that support a wide array of mobility applications, ensuring uninterrupted positioning even in scenarios where conventional GNSS coverage may be poor.

Integrating machine learning with beamforming is another rich research direction, as machine learning can dynamically optimize the beamforming patterns in order to improve signal quality and broaden the coverage in real-time. This approach is particularly promising for urban navigation and asset tracking in dense urban environments, where optimized beamforming could counteract the signal degradation from buildings and other obstructions. This integration could also support Internet of Things (IoT) deployments for smart city applications, enabling high-precision localization of thousands of connected sensors in complex environments.

Future research could also focus on combined constellation systems, where combining signals from various different LEO and GNSS constellations within a single receiver could offer enhanced reliability and accuracy. Power management strategies, such as duty cycling, as studied in [31], would be critical in these cases, ensuring efficient energy use for applications such as wearable health tracking devices and wildlife monitoring systems, which require long battery life and sustained operation.

Finally, the study in this paper can be taken one step further by investigating the remaining issues that are not addressed in this article. The most likely research direction is to study the process of obtaining the combined position solution; developping the actual positioning method (e.g., PPP or RTK based, or a new method), how to incorporate different clock related issues of LEO (e.g., satellite clock models, clock instabilities, inter-constellation clock biases, clock synchronization frameworks, etc.) with those of GNSS, inclusion of I/Q data generation and the related development of modulation-level methods, and consideration of additional, more challenging scenarios.

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REFERENCES

[1] T. G. R. Reid, A. M. Neish, T. Walter, and P. K. Enge, "Broadband LEO constellations for navigation," *Navigation*, vol. 65, no. 2, pp. 205–220, Jun. 2018, doi: 10.1002/navi.234.

[2] A. Baron, P. Gurfil, and H. Rotstein, "Implementation and accuracy of Doppler navigation with LEO satellites," *NAVIGATION: J. Inst. Navigat.*, vol. 71, no. 2, 2024, Art. no. navi.649.

[3] W. Stock, R. T. Schwarz, C. A. Hofmann, and A. Knopp, "Survey on opportunistic PNT with signals from LEO communication satellites," *IEEE Commun. Surveys Tuts.*, 2024.

[4] J. Kang, P. E. N, J. Lee, H. Wymeersch, and S. Kim, "Fundamental performance bounds for carrier phase positioning in LEO-PNT systems," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Apr. 2024, pp. 13496–13500.

[5] Y. Yang, Y. Mao, X. Ren, X. Jia, and B. Sun, "Demand and key technology for a LEO constellation as augmentation of satellite navigation systems," *Satell. Navigat.*, vol. 5, no. 1, p. 11, Dec. 2024.

[6] Z. Kassas, S. Kozhaya, J. Saroufim, H. Kanj, and S. Hayek. (Aug. 2023). *A Look At the Stars: Navigation With Multi-constellation Leo Satellite Signals of Opportunity*. Inside GNSS. [Online]. Available: https://insidegnss.com/a-look-at-the-stars-navigation-with-multi-constellation-leo-satellite-signals-of-opportunity

[7] X. Li, K. Jiang, P. Li, X. Tang, and X. Guo, "Analysis of navigation augmentation performance based on LEO satellite communication constellation," in *Proc. China Satell. Navigat. Conf.* Springer, 2023, pp. 200–214.

[8] Y. Zheng, H. Ge, and B. Li, "The convergence mechanism of low Earth orbit enhanced GNSS (LeGNSS) precise point positioning (PPP)," *Geo-Spatial Inf. Sci.*, vol. 1, pp. 1–16, Nov. 2023, doi: 10.1080/10095020.2023.2270712.

[9] J. Hong, R. Tu, P. Zhang, R. Zhang, J. Han, L. Fan, S. Wang, and X. Lu, "GNSS rapid precise point positioning enhanced by low Earth orbit satellites," *Satell. Navigat.*, vol. 4, no. 1, p. 11, Dec. 2023.

[10] M. Li, T. Xu, M. Guan, F. Gao, and N. Jiang, "LEO-constellation-augmented multi-GNSS real-time PPP for rapid re-convergence in harsh environments," *GPS Solutions*, vol. 26, no. 1, pp. 1–12, Jan. 2022.

[11] R. Morales-Ferre, E. S. Lohan, G. Falco, and E. Falletti, "GDOP-based analysis of suitability of LEO constellations for future satellite-based positioning," in *Proc. IEEE Int. Conf. Wireless Space Extreme Environ. (WiSEE)*, Oct. 2020, pp. 147–152.

[12] X. Li, F. Ma, X. Li, H. Lv, L. Bian, Z. Jiang, and X. Zhang, "LEO constellation-augmented multi-GNSS for rapid PPP convergence," *J. Geodesy*, vol. 93, no. 5, pp. 749–764, May 2019.

[13] M. Ke, J. Lv, J. Chang, W. Dai, K. Tong, and M. Zhu, "Integrating GPS and LEO to accelerate convergence time of precise point positioning," in *Proc. Int. Conf. Wireless Commun. Signal Process. (WCSP)*, Oct. 2015, pp. 1–5.

[14] Q. Zhao, S. Pan, C. Gao, W. Gao, and Y. Xia, "BDS/GPS/LEO triple-frequency uncombined precise point positioning and its performance in harsh environments," *Measurement*, vol. 151, Feb. 2020, Art. no. 107216. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0263224119310826

[15] W. Li, Q. Yang, X. Du, M. Li, Q. Zhao, L. Yang, Y. Qin, C. Chang, Y. Wang, and G. Qin, "LEO augmented precise point positioning using real observations from two CENTISPACE experimental satellites," *GPS Solutions*, vol. 28, no. 1, p. 44, Jan. 2024.

[16] X. Li, H. Lv, F. Ma, X. Li, J. Liu, and Z. Jiang, "GNSS RTK positioning augmented with large LEO constellation," *Remote Sens.*, vol. 11, no. 3, p. 228, Jan. 2019. [Online]. Available: https://www.mdpi.com/2072-4292/11/3/228

[17] H. Ge, B. Li, L. Nie, M. Ge, and H. Schuh, "LEO constellation optimization for LEO enhanced global navigation satellite system (LeGNSS)," *Adv. Space Res.*, vol. 66, no. 3, pp. 520–532, Aug. 2020. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0273117720302696

[18] L. Marchionne, L. M. Gessato, F. Toni, and S. L. Barbera, "Striking a balance: Performance and cost optimization of LEO-PNT constellation for hybrid users using a meta-heuristic approach," in *Proc. IEEE 10th Int. Workshop Metrol. Aerosp. (MetroAeroSpace)*, Jun. 2023, pp. 609–614.

[19] K. Çelikbilek, E. S. Lohan, and J. Praks, "Optimization of a leo-pnt constellation: Design considerations and open challenges," *TechRxiv*, Jan. 2023, doi: 10.36227/techrxiv.172263277.74357218/v1.

[20] M. Xu, "Centispace system experimental satellites PPP application test," in *Proc. UN/Finland Workshop GNSS*, 2023, pp. 1–21. [Online]. Available: https://www.unoosa.org/oosa/en/ourwork/psa/schedule/2023/2023-un_finland-workshop-on-gnss_presentations.html

[21] C. S. N. Office, "Beidou navigation satellite system signal in space interface control document open service signal b1i (version 3.0)," China Satellite Navigation Office, Beijing, China, Tech. Rep. BDS-SIS-ICD-B1I-3.0, Feb. 2019. http://en.beidou.gov.cn/SYSTEMS/ICD/201902/P020190227702348791891.pdf

[22] E. S. Agency. (2022). *Galileo Satellites*. European Space Agency (ESA). [Online]. Available: https://www.esa.int/Applications/Navigation/Galileo/Galileo_satellites

[23] C. J. Hegarty, *The Global Positioning System (GPS)*. Cham, Switzerland: Springer, 2017, pp. 197–218, doi: 10.1007/978-3-319-42928-1_7.

[24] E. D. Kaplan and C. J. Hegarty, *Understanding GPS, Principles and Applications*, 3rd ed., Norwood, MA, USA: Artech House, 2017.

[25] E. S. Lohan and K. Borre, "Accuracy limits in multi-GNSS," *IEEE Trans. Aerosp. Electron. Syst.*, vol. 52, no. 5, pp. 2477–2494, Oct. 2016.

[26] O. K. Isik, J. Hong, I. Petrunin, and A. Tsourdos, "Integrity analysis for GPS-based navigation of UAVs in urban environment," *Robotics*, vol. 9, no. 3, p. 66, Aug. 2020.

[27] W. Wang, E. S. Lohan, and J. Talvitie, *mmWave Solutions to Cope With the Data Link Challenges in Aviation*, document Deliverable D4.3 within H2020-SESAR-2016-2, EMPHASIS, Jul. 2019.

[28] R. Morales Ferre, J. Praks, G. Seco-Granados, and E. S. Lohan, "A feasibility study for signal-in-space design for LEO-PNT solutions with miniaturized satellites," *IEEE J. Miniaturization for Air Space Syst.*, vol. 3, no. 4, pp. 171–183, Dec. 2022.

[29] S. Jaeckel, L. Raschkowski, K. Börner, and L. Thiele, "QuaDRiGa: A 3-D multi-cell channel model with time evolution for enabling virtual field trials," *IEEE Trans. Antennas Propag.*, vol. 62, no. 6, pp. 3242–3256, Jun. 2014.

[30] B. Eissfeller, T. Pany, D. Dötterböck, and R. Förstner, "A comparative study of LEO-PNT systems and concepts," in *Proc. I_{ON} Pacific (PNT)*, May 2024, pp. 758–782, doi: 10.33012/2024.19646.

[31] P. A. Iannucci and T. E. Humphreys, "Economical fused LEO GNSS," in *Proc. IEEE/ION Position, Location Navigat. Symp. (PLANS)*, Apr. 2020, pp. 426–443.

KAAN ÇELIKBILEK received the B.Sc. (Tech.) degree in electrical and electronics engineering from Bilkent University, in 2018, and the M.Sc. (Tech.) degree in robotics and artificial intelligence from Tampere University, in 2020, where he is currently pursuing the Ph.D. degree in computing and electrical engineering. His research interests include deep learning, reinforcement learning, multi-objective optimization, satellite communication, GNSS, LEO-PNT optimization, and robotics.

ELENA SIMONA LOHAN (Senior Member, IEEE) is currently a Professor and the Leader of TLTPOS Research Group on Signal Processing for Wireless Positioning, Tampere University and a Visiting Professor with Universitat Autonoma de Barcelona. She is the author or co-author of more than 300 international peer-reviewed publications. Her research interests include indoor and outdoor wireless positioning, interference management, and joint sensing and communications. She is a Co-Editor of the first book on *Galileo Satellite System* and *Galileo Positioning Technology* (Springer).

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