Geometry-Interference Trade-off in PRS-Based LEO Positioning for 6G Non-Terrestrial Networks

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***Abstract*—In this paper, we investigate the trade-off between geometric gain and inter-satellite interference in positioning reference signal (PRS)-based low Earth orbit (LEO) positioning for sixth-generation (6G) non-terrestrial networks (NTNs). Dense LEO constellations can provide many simultaneously visible satellites, improving geometry and potentially enhancing accuracy over conventional global navigation satellite systems (GNSSs). However, adding more satellites does not necessarily improve positioning performance. Although the geometric dilution of precision (GDOP) improves with more participating satellites, large relative delay and Doppler offsets degrade PRS orthogonality and increase interference among satellites sharing the same time-frequency resources. To characterize this trade-off, we perform end-to-end simulations with realistic LEO geometry and 3GPP NTN link and channel characteristics. The results show that GDOP improvement rapidly saturates as the number of satellites increases, while PRS interference continues to grow. With reference-point pre-compensation, the additional interference eventually outweighs the marginal geometric gain and increases the positioning error beyond a certain satellite count. Without pre-compensation, the improvement gradually saturates. These results show that high LEO satellite visibility does not necessarily translate into higher positioning accuracy and that the participating satellite count should be determined by jointly considering geometric gain and PRS interference.**

***Index Terms*—6G, non-terrestrial networks (NTNs), LEO satellite positioning, positioning reference signal (PRS), geometric dilution of precision (GDOP).**

I. Introduction

As non-terrestrial networks (NTNs) become increasingly important in sixth-generation (6G) mobile systems, low Earth orbit (LEO) satellites are attracting attention not only for broadband communications but also for positioning, navigation, and timing (PNT) services [1], [2]. Compared with conventional medium-Earth-orbit navigation satellites, LEO satellites operate much closer to ground users, and large-scale constellations with thousands of satellites have already been deployed for broadband access [3], [4]. Such dense constellations can provide many simultaneously visible satellites, and using more satellites generally improves geometry and reduces the geometric dilution of precision (GDOP) [5]. Therefore, LEO-based positioning has the potential to provide favorable geometry and improved positioning accuracy compared with conventional global navigation satellite systems (GNSSs).

A practical approach to extending LEO communication infrastructure to positioning in 6G NTNs is to reuse the New Radio (NR) positioning reference signal (PRS) [6]. The NR PRS separates multiple transmitters in the time-frequency domain through a comb structure. In LEO environments, however, large differential delays and Doppler shifts caused by different propagation paths and satellite velocities degrade PRS orthogonality and introduce inter-satellite interference [7], [8]. Consequently, as more satellites participate, the GDOP improves while interference among satellites sharing the same PRS resources also increases. Previous studies have separately investigated the geometric benefit of additional LEO satellites [5] and PRS interference in LEO environments [7], but the combined impact of these competing effects on positioning performance remains insufficiently characterized.

In this paper, we analyze the trade-off between geometric gain and PRS interference as the number of participating satellites increases using end-to-end simulations with realistic LEO geometry, 3GPP NTN link and channel characteristics, PRS reception, ToA estimation, and position estimation. The results show that GDOP improvement rapidly saturates as more satellites participate, while PRS interference continues to increase. With reference-point pre-compensation, the increasing interference eventually outweighs the marginal geometric gain and increases the positioning error beyond a certain satellite count. Without pre-compensation, the positioning improvement gradually saturates. These results show that high LEO satellite visibility does not necessarily lead to higher positioning accuracy and that the participating satellite count should be determined by jointly considering satellite geometry and PRS interference.

II. System Model

A. Constellation, Link, and PRS Model

We consider a Walker-Delta LEO constellation [9], where satellites above a minimum elevation angle of 30° are regarded as visible. The per-satellite link quality is determined from the link budget, and the small-scale fading follows the 3GPP NTN tapped-delay-line (TDL) channel model [2]. Each visible satellite transmits an NR positioning reference signal (PRS) over the same OFDM time-frequency resources [6]. For a comb size K, satellite k is assigned the comb offset $(k-1) \bmod K$. PRSs with different comb offsets can cause *cross-comb leakage* when relative delay and Doppler shifts displace them from their nominal comb positions, while for $N > K$, reuse of the same comb offset additionally introduces *co-comb collisions*. Detailed constellation, link, and PRS parameters are summarized in Table I.

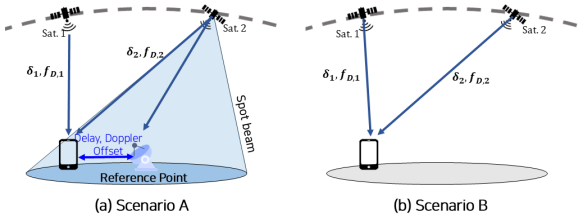

Fig. 1. Transmission scenarios: (a) Scenario A with delay and Doppler pre-compensation to a common ground reference point, and (b) Scenario B without pre-compensation.

B. Superposed Received Signal

Let N co-channel LEO satellites simultaneously transmit their PRSs over the same time-frequency resources. The received baseband signal at the user terminal is modeled as

$$y[n] = \sum_{k=1}^{N} \alpha_k \big(h_k * s_k\big)(nT_{\mathrm{s}} - \tau_k) e^{j2\pi f_{\mathrm{D},k} n T_{\mathrm{s}}} + w[n], \quad (1)$$

where k and n denote the satellite and sample indices, respectively; $s_k(t)$ and $h_k(t)$ denote the PRS waveform and channel impulse response of satellite k, respectively; α_k is the received-signal scaling coefficient determined from the link budget; $f_{\mathrm{D},k}$ is the Doppler shift; T_{s} is the sampling period; and $w[n]$ is additive white Gaussian noise. The propagation delay of satellite k is given by $\tau_k = d_k/c$, where d_k is the satellite-to-user slant range and c is the speed of light.

For a desired satellite k_0, the received components from the remaining $N-1$ satellites act as inter-satellite PRS interference at the matched-filter output, potentially distorting the desired correlation peak or generating false peaks. The same processing is applied to each participating satellite in turn for time-of-arrival (ToA) estimation.

C. Transmission Scenarios and Positioning Metrics

We consider two transmission scenarios, as illustrated in Fig. 1. In Scenario A, each satellite pre-compensates its propagation delay and Doppler shift with respect to a common ground reference point at the center of the serving spot beam. Hence, only the residual delay and Doppler caused by the user offset from the reference point remain. In Scenario B, no pre-compensation is applied, and the receiver experiences the full satellite-dependent delay and Doppler. Accordingly, the co-channel PRSs are relatively aligned in Scenario A, whereas they are more widely displaced in Scenario B.

For each satellite, the time of arrival (ToA) is estimated in two stages: a coarse delay-Doppler cross-ambiguity search followed by fine frequency-domain phase-slope refinement. The estimated ToAs are then passed to a four-state Gauss-Newton solver [10] that jointly estimates the three-dimensional user position and receiver clock bias. Performance is evaluated using the GDOP, positioning error, and post-correlation SIR of a reference satellite k_0, defined as

$$\mathrm{SIR}_{k_0} = 10\log_{10} \frac{|\chi_{k_0,k_0}|^2}{\sum_{k\neq k_0} |\chi_{k_0,k}|^2}, \quad (2)$$

TABLE I
SIMULATION PARAMETERS

Parameter	Value
LEO constellation	Walker-Delta, three shells [11]: 53°:1584/72/1 at 550 km, 53.2°:1584/72/1 at 540 km, and 70°:720/36/1 at 570 km
Minimum elevation	30°
User region	Uniformly distributed within 25 km of the beam reference point
Carrier / channel	2 GHz (S-band) / 3GPP NTN-TDL
PRS configuration	24 RBs, 15 kHz subcarrier spacing, NR Gold sequence
Comb size K	4 and 12
Doppler search	$\pm$60 kHz with 500 Hz resolution
Number of satellites N	4, 6, 8, 10, 12, 14, 16; lowest-GDOP subset
Transmission	Scenario A: pre-compensated; Scenario B: non-pre-compensated

where $\chi_{k_0,k}$ denotes the matched-filter output for satellite k_0, evaluated at its delay and Doppler, for the received component from satellite k. Thus, $k = k_0$ corresponds to the desired signal, while $k \neq k_0$ represents interference.

III. Simulation Results

The simulation parameters are summarized in Table I, and the link budget follows the 3GPP NTN specification [2]. At each epoch, the lowest-GDOP subset of N visible satellites with respect to the beam reference point is selected, and their superposed PRSs are processed according to (1) to estimate the user position.

A. Geometry: GDOP Saturation

Fig. 2 shows the GDOP distribution of the selected satellite set as the number of participating satellites increases. The median GDOP decreases from 3.77 at $N = 4$ to 2.34 at $N = 16$. However, most of the geometric gain is achieved with a relatively small number of additional satellites, with the median GDOP already reaching 2.57 at $N = 10$. Beyond $N = 12$, only marginal improvement is observed, indicating that the geometric benefit of adding more satellites rapidly saturates.

B. Interference: SIR Degradation with Increasing Satellite Count

Fig. 3 shows the median post-correlation SIR versus the number of participating satellites N for different comb sizes and transmission scenarios. In all cases, the SIR decreases monotonically with N, dropping by approximately 9–11 dB from $N = 4$ to 16. Comb-12 maintains a higher SIR than comb-4 over the considered range. Interestingly, for the same comb size, Scenario A with reference-point pre-compensation shows a lower SIR than Scenario B. This is because pre-compensation reduces the relative delay and Doppler differences among satellite PRSs, aligning them more closely in the delay-Doppler domain and increasing mutual interference at the matched-filter output.

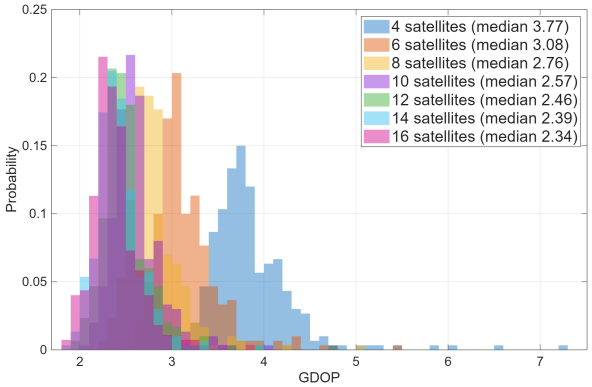

Fig. 2. GDOP distribution of the selected subset versus the number of admitted satellites.

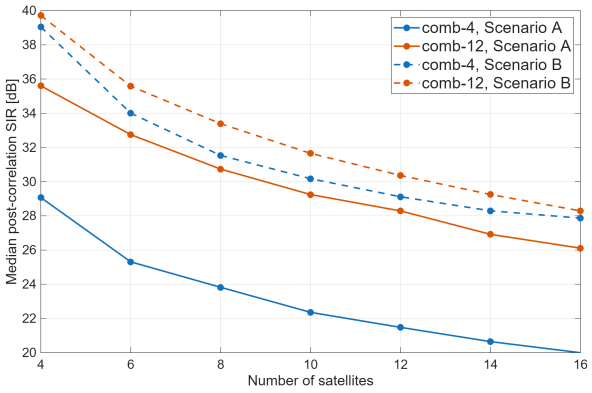

Fig. 3. Median post-correlation SIR versus the number of satellites, for comb-4 and comb-12 under Scenarios A and B.

C. Positioning Error and the Accuracy Reversal

Fig. 4 shows how the geometric gain and increasing PRS interference observed in Figs. 2 and 3 affect the final positioning performance. As the number of participating satellites increases, the GDOP improves with diminishing gain, while the post-correlation SIR continues to decrease. Under Scenario B, the positioning RMSE decreases with N and then gradually saturates. Comb-4 shows little improvement beyond $N = 12$, while comb-12 reaches its minimum around $N = 14$. Under Scenario A, the comb-12 RMSE decreases to 3.89 m at $N = 12$ and then increases to 4.77 m at $N = 16$. This occurs because the marginal geometric gain becomes limited while PRS interference continues to increase and eventually outweighs it. Therefore, the satellite count minimizing positioning error is finite, and the lowest-GDOP satellite set does not necessarily provide the best positioning accuracy. These results indicate that satellite admission should jointly consider geometry, PRS interference, and resource structure.

IV. Conclusion

This paper investigated the geometry-interference trade-off in PRS-based LEO positioning for 6G NTNs. Increasing the number of participating satellites improves the GDOP, but the marginal geometric gain rapidly diminishes while inter-satellite PRS interference continues to increase. Consequently, the positioning error does not necessarily decrease as more satellites are admitted. With reference-point pre-compensation, the positioning RMSE reaches a minimum at a finite satellite count and then increases, while without pre-compensation, the improvement gradually saturates. These results show that high satellite visibility and favorable geometry alone do not guarantee better positioning accuracy. Therefore, satellite admission should jointly consider geometry, PRS interference, and PRS resource structure rather than relying only on GDOP.

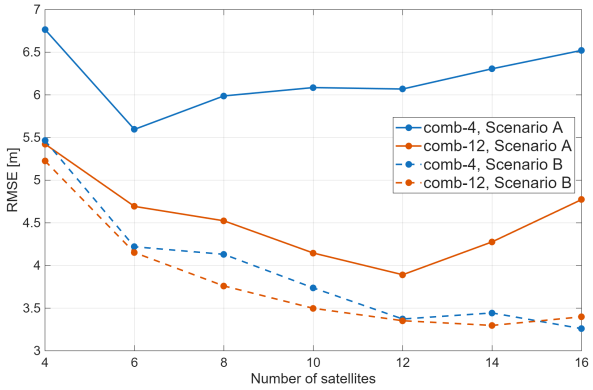

Fig. 4. Positioning RMSE versus the number of satellites, for comb-4 and comb-12 under Scenarios A and B.

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