Evaluation for Elevation Angle-Dependent Beam Size in NR NTN Systems

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***Abstract*—Appropriate beam design plays a vital role in satellite-based Non-Terrestrial Networks (NTN) towards beyond 5G. In this paper, we propose an evaluation for elevation angle-based major-semi axis beam radius. To deal with this, we calculate beam major semi-axis radius with elevation angle and differential delay in NTN, based on 3rd Generation Partnership Project (3GPP) New Radio (NR) standards. Using the evaluation method, within NR standards, the differential delay-based beam major semi-axis radius can be independent of the elevation angle in some elevation angle intervals. Furthermore, we compare the differential delay-based beam results with the 3dB beamwidth results. The comparison shows that the differential delay-based beam major semi-axis radius can be more critical according to the preamble structure, subcarrier spacing, and elevation angle.**

***Index Terms*—Low Earth Orbit (LEO) satellite networks, differential delay, elevation angle-based beam, beam size, preamble, OFDM numerology**

I. INTRODUCTION

Low Earth Orbit (LEO) satellites are well-suited for achieving low-latency communication performance due to their low altitude. This feature makes the LEO satellite communications system compatible with 5G New Radio (NR) communication systems, which aim for low-latency communication. The 3rd Generation Partnership Project (3GPP) has also been focusing on Non-Terrestrial Networks (NTN), especially the LEO satellites, as a key means of communications since 2017 [1]. Also, starting from Rel. 18 in 2022, 3GPP has initiated the standardization process about the keyword, *NR NTN enhancement* [2]. In the *NR NTN enhancement*, *beam coverage enhancement* is one of the work items. Physically, beam illumination leads to the implementation of not only circular but also elliptical beams based on elevation angles. However, previous discussions in 3GPP just considered circular beams scenario. Thus, beam design for *NR NTN* has emerged as a critical topic for 3GPP discussion.

This paper presents an analysis of beam size variation, focusing on elliptical beams whose size changes according to the elevation angle. To achieve this, the maximum differential delay is evaluated with 3GPP NR standards like Random Access, preamble structure, and subcarrier spacing (SCS) numerology in Orthogonal Frequency Division Multiplexing (OFDM). By combining the differential delay and NR standards, a reliable elevation angle-based beam methodology for NR NTN systems is proposed. Furthermore, a comparison between the proposed beam radius results and 3dB beamwidth-based beam radius results is conducted, offering an engineering guide for beam size selection based on specific elevation angle and NR scenario.

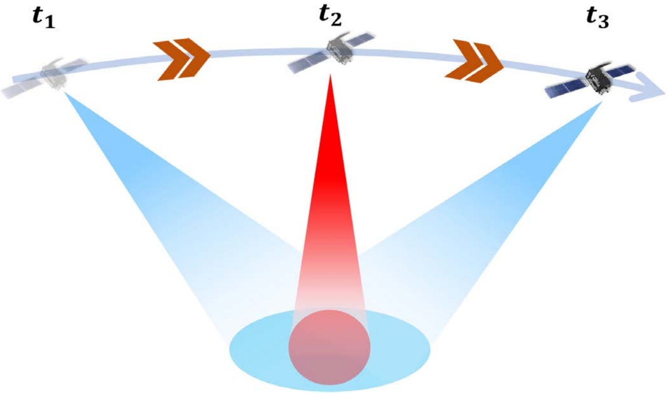

Fig. 1. Circular and elliptical beam footprints under the beam spread mode.

II. SYSTEM MODEL

A. Beam Spread in NTN

When a transmitter illuminates its beam directly beneath its *nadir* point, without employing specialized beam techniques, then the beam's footprint at the *nadir* becomes almost circular. However, when the beam is steered away from the *nadir*, the beam's footprint becomes an ellipse. This is an essential physical result, so the same phenomenon results in the LEO satellite beam's footprint and it is called as *beam spread.* As Fig. 1, when the LEO satellite illuminates its beam on the *nadir* point (at t_2), then the beam's footprint becomes almost circular. On the other hand, when the LEO satellite's beam is steered away from the *nadir* (at t_1 and t_3), the beam's footprint becomes an ellipse which has its major semi-axis radius in the direction of the satellite orbit. In this context, one of the main items for discussion about *NR NTN enhancement* is *beam coverage enhancement* [2]. Especially, an elevation angle (θ)-dependent coverage concept is also proposed [3].

B. Differential Delay in NTN

The differential delay (ΔD) means the distance difference between different positions of each user equipment (UE) and a base station. In LEO satellite networks, the ΔD means

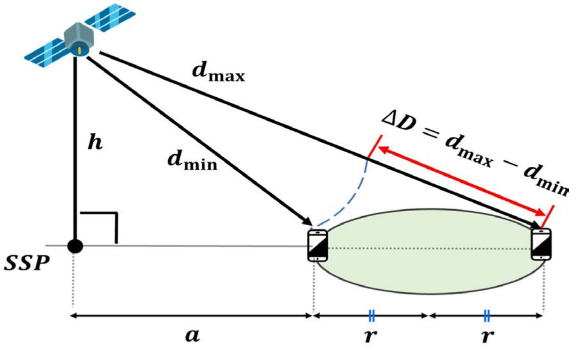

Fig. 2. Differential delay (ΔD) in NTN.

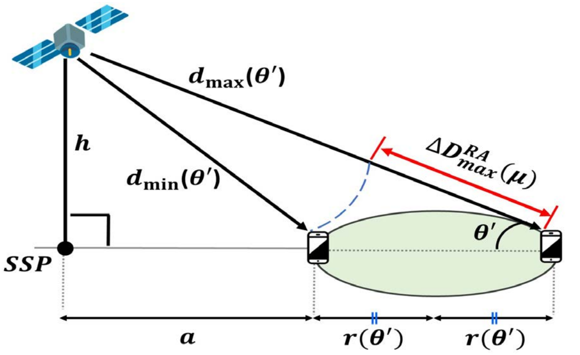

Fig. 3. The proposed elevation-dependent beam design.

the distance difference between a satellite and UEs located on different positions in the same beam [4]. In Fig. 2-(a), particularly when direct access is considered, the maximum differential delay occurs when d_{max} is the largest distance (where the minimum elevation angle in the same beam occurs) and d_{min} (where the UE is closest to the satellite) is the shortest distance. The ΔD in the LEO satellite networks is larger than that in TN, and it should be considered when implementing NR NTN.

III. ΔD-BASED ELEVATION ANGLE DEPENDENT BEAM SPREAD METHODOLOGY

TABLE I
SIMULATION PARAMETERS

Parameters	Values
The Earth's mean radius	6,371 km
LEO satellite altitude	550 km
Minimum elevation angle	10 °
Beamwidth in 3GPP set 1 for satellite parameters	4.4127 °
Beamwidth in 3GPP set 2 for satellite parameters	8.832 °
Short preamble formats	A1, A2, A3, B1, B2, B3, B4, C0, C2

In this section, we derive a θ-based beam major semi-axis radius methodology based on [4]'s methodology for direct access. Procedures which affect to the ΔD in the NR specification are Timing Advance (TA) and Random Access (RA), and [4] proves the major element between them for ΔD in NTN is RA. The RA procedure is performed based on RA sequences, and they are divided into a RA preamble. The RA preamble has a time duration with Cyclic Prefix (CP) (T_{CP}) and a random sequence with duration (T_{SEQ}). Both are dependent to the RA preamble format with short-sequence length (A1, A2, A3, B1, B2, B3, B4, C0, C2), but they are independent to the OFDM numerology μ (= 0, 1, 2, 3). The μ determines the time slot $T_{slot}(\mu)$ ($T_{slot}(\mu)$ =1, 0.5, 0.25, 0.125 ms with μ's order) [5]. Since the preamble format fit into an integer number of $T_{slot}(\mu)$, the maximum distance based on RA procedure can be calculated as follows:

$$\Delta D^{RA}_{max}(\mu) = c\frac{N_{slot}(\mu)T_{slot}(\mu) - T_{CP} - T_{SEQ}}{2}, \qquad (1)$$

where $N_{slot}(\mu) = \lceil (T_{CP}+T_{seq})/T_{slot}(\mu) \rceil$, and c is the speed of the light. $\Delta D^{RA}_{max}(\mu)$ is divided by two because of the Round Trip Delay (RTD).

As the Fig. 2-(b), $d_{min}(\theta')$ is able to be calculated by $d_{max}(\theta')$ and $\Delta D^{RA}_{max}(\mu)$. On the position with $d_{max}(\theta')$, the elevation angle becomes the minimum value in the same beam while the distance becomes the largest one. Assuming the elevation angle with the largest distance as θ', the $d_{max}(\theta')$ is determined by:

$$d_{max}(\theta') = \sqrt{(R_E + h)^2 - \cos\theta'} - R_E \sin\theta', \qquad (2)$$

where R_E and h are the Earth mean radius and the satellite's altitude. Based on the above equation, the $d_{min}(\theta')$ is derived by:

$$d_{min}(\theta') = d_{max}(\theta') - \Delta D^{RA}_{max}(\mu). \qquad (3)$$

When focusing on varying footprint with θ', the $d_{min}(\theta')$ should be higher than the h. In other words, if $d_{min}(\theta') < h$, then we don't have to consider the differential delay in implementing NR NTN systems. Therefore, the θ-based beam coverage is meaningful until a condition ($d_{min}(\theta') > h$) satisfies. Using the $d_{min}(\theta')$, in the Fig. 2-(b), the distance a between the satellite's sub-satellite point (SSP) and the the closest UE is determined by the equation, $a = \sqrt{d^2_{min}(\theta') - h^2}$. Under the inequation and a conditions, the maximum θ-based footprint major semi-axis radius $r(\theta')$ can be simply calculated as follows:

$$r(\theta') = \frac{d_{max}(\theta')\cos\theta' - \sqrt{d^2_{min}(\theta') - h^2}}{2}. \qquad (4)$$

IV. PERFORMANCE EVALUATION

In this section, we present simulation results using the previous section's method. As the table I, R_e is fixed by 6,371 km. The altitude h is set at 550 km since this value is now the most used altitude value for NTN [7]. We use the minimum elevation angle (θ_{min}) as 10 °. Even though the θ_{min} is fixed by 10 °, the beam radius results include all proposed θ_{min}, e.g., 3GPP's proposed θ_{min} (10 °) and the STARLINK's θ_{min} (25 °) since this paper's method produces results varying θ' [7]. We also derive beam major semi-axis radius results using the LEO satellite 3dB beamwidth in Rel. 16 to compare the ΔD based results with the beamwidth based results [6]. There are two sets for satellite system level simulator in Rel. 16, and the 3dB beamwidth in set 1 is 4.4127 ° and that in set 2 is 8.832 °. The short preamble structures in the table I for NR are used because of assuming better communication performance. Also, the OFDM numerology values used in this paper are zero and one (SCS = 15, 30 kHz) for handheld NTN scenario [6].

In Fig. 3 and Fig. 4, results for the 3dB beamwidth-based maximum beam major semi-axis radius and the ΔD-based maximum beam major semi-axis radius with $\mu = 0, 1$ $(r(\theta'))$ are plotted by the θ' using the preamble structures [5]. The 3dB beamwidth-based maximum beam major semi-axis radius in these figures shows that the maximum major semi-axis radius decreases as the θ' increase. This consequence is the expected result as the Fig. 1. However, the $r(\theta')$ usually changes few in low θ', and after specific θ', it increases rapidly. The $r(\theta')$ is plotted until the condition $d_{min}(\theta') > h$ satisfies. In the interval with $d_{min}(\theta') < h$, the $r(\theta')$ is independent to the ΔD. The reason for the occurrence of some intervals that the radius decreases even though the θ' increases is believed to be due to the influence of $\cos$ and root terms in the equation (4). Also, results of the preamble B4 have always the smallest beam major semi-axis radius in preambles since the B4 format's duration is always the largest one [5].

Considering both ΔD and 3dB beamdwith for beam design, the beam radius should be formed by the method with smaller beam radius. Therefore, based on results of the Fig. 3 and 4, the beam radius cannot be an extreme ellipse in lower θ within NR standards. For example, if we use the preamble as A3 with $\mu = 0$ and beamwidth as 4.4127 °, then the maximum beam major semi-axis radius is dependent to the 3dB beamwidth in higher θ' interval ($\theta' \geq 26$ °). In another interval ($\theta' \leq 26$ °), the maximum beam major semi-axis radius is determined by the $r(\theta')$ method. Furthermore, if we use the preamble as B4 with $\mu = 1$ and 3dB beamwidth as 4.4127 °, then the maximum beam radius is determined by the $r(\theta')$ method when $\theta' \leq 67$ °, and becomes almost constant in all θ' intervals.

V. Conclusion

In this paper, we have evaluated the elevation angle-based beam major semi-axis radius. To use NR in NTN, NR's Random Access specifications are used without modification. Based on the Random Access specifications and the differential delay equation, the differential delay-based beam major semi-axis radius has been derived. Given the 3dB beamwidth radius, the derived results have shown that the elevation angle-based beam major semi-axis radius is varied with the preamble structure and the elevation angle. Furthermore, the proposed method reveals that severe elliptical footprints in lower elevation angle cannot be formed within NR standards.

In future works, we deeply investigate why the occurrence of some intervals that the radius decreases as the elevation angle increases, and propose optimal the elevation angle-based beam major semi-axis radius.

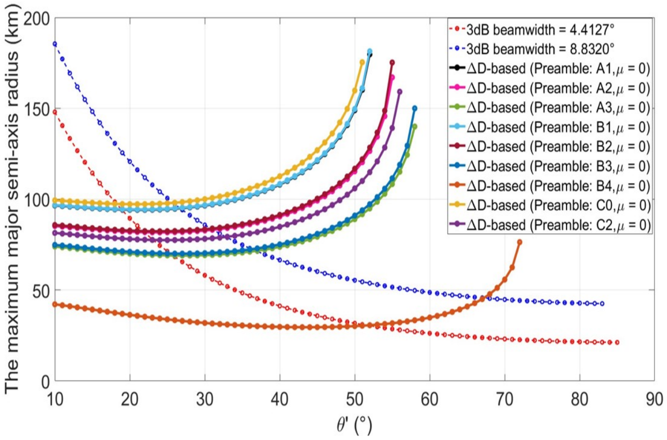

Fig. 4. Results for 3dB beamwidth-based beam major semi-axis radius and ΔD-based major semi-axis radius with $\mu = 0$.

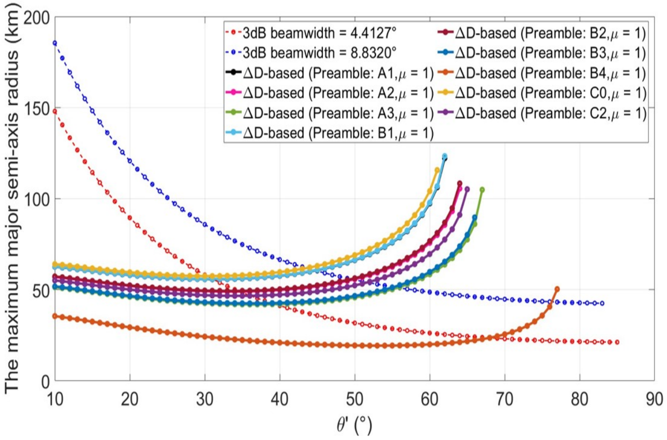

Fig. 5. Results for 3dB beamwidth-based beam major semi-axis radius and ΔD-based beam major semi-axis radius with $\mu = 1$.

VI. Acknowledgment

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References

[1] 3GPP TR 38.811 v15.4.0, "Study on New Radio (NR) to support non-terrestrial networks (Release 15)," Sep. 2020.

[2] 3GPP TSG RAN Meeting #97-e, "NR NTN (Non-Terrestrial Networks) enhancements(Release 18)," Sep. 2022.

[3] 3GPP TSG RAN WG2 #121bis-e, "NTN mobility enhancements for earth-moving cell scenario in terms of measurement initiation, cell reselection and handover," April. 2023.

[4] A. Guidotti, "eam size design for new radio satellite communications systems," *IEEE Trans. Veh. Technol.*, vol. 68, no. 3, pp. 11379-11383, Nov. 2019.

[5] A. Chakrapani, "On the design details of SS/PBCH, signal generation and PRACH in 5G-NR," IEEE Access, vol. 8, pp. 136617–136637, Jul. 2020

[6] 3GPP, TR 38.821 v16.1.0, "Solutions for NR to support non-terrestrial networks(NTN) (Release 16)," May 2021.

[7] N. Pachler, et al., "An Updated Comparison of Four Low Earth Orbit Satellite Constellation Systems to Provide Global Broadband," *in Proc. 2021 IEEE international conference on communications workshops (ICC workshops)*, Montreal, Canada Jun. 2021, pp. 1-7.