Selection of PRACH Detection Interval for 5G NR-Based LEO NTN

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***Abstract*— In a non-terrestrial network (NTN) environment using low earth orbit (LEO) satellites, the rapid movement of the satellites induces time-varying propagation delays and channel characteristics. To compensate for the time-varying propagation delays, the user equipment (UE) periodically calculates the timing advance (TA) using the orbital information from System Information Block 19 (SIB19), the common TA parameters, and Global Navigation Satellite System (GNSS) coordinates. However, if the SIB19 update is unavailable, the UE continues to calculate the TA using outdated information, leading to pre-compensation errors that may result in either overcompensation or undercompensation of the timing advance. In this paper, we analyze the impact of the PRACH detection intervals on PRACH detection performance under TA error conditions. To this end, we perform simulations emulating a LEO NTN environment and compare the performance of different detection interval designs under both TA over- and under-compensation conditions.**

***Keywords*— NTN, LEO, PRACH, NR, TA**

I. INTRODUCTION

The non-terrestrial network (NTN) has gained significant attention as a key technology for extending the coverage of terrestrial infrastructure and providing enhanced communication services. In particular, low earth orbit (LEO) satellites can provide efficient communications with lower transmission delays compared to geostationary orbit satellites. The 3GPP has standardized the 5G New Radio (NR)-based NTN specifications, which use the Physical Random Access Channel (PRACH) for initial access between the user equipment (UE) and the base stations (gNB) [1]. Due to the rapid movement of the satellite in NTN environments, propagation delays vary continuously over time. To compensate for this propagation delay, the UE periodically calculates the timing advance (TA) using the orbital information in System Information Block (SIB) 19, the common TA parameters, and Global Navigation Satellite System (GNSS) coordinates [2][3]. The calculated TA is applied as pre-compensation during PRACH transmission. However, if SIB19 is not updated periodically, the UE will continue to calculate TA based on the previously received SIB19, which may result in insufficient or excessive pre-compensation. This can cause the PRACH detector to estimate incorrect cyclic shifts (CS), resulting in false alarms. If the TA estimate becomes inaccurate, the received signal timing can shift relative to the expected detection window, potentially causing detection failures. This paper focuses on designing a PRACH detection interval to handle these timing variations caused by TA errors. The appropriate detection interval can be adaptively selected based on whether the TA is too large (overcompensation) or too small (undercompensation). The results demonstrate that this adaptive approach can significantly improve PRACH detection reliability in practical LEO NTN deployments.

II. PRACH DETECTION INTERVAL DESIGN

In this paper, we consider the C2-format PRACH, which is one of the PRACH preamble formats defined in 5G NR, as shown in Fig. 1[1]. The preamble consists of a cyclic prefix (CP), four Zadoff–Chu (ZC) sequence symbols (SEQ), and a guard period (GP). In the C2 format, the CP length is defined to be identical to that of a single SEQ symbol, and the guard period (GP) is configured to be longer than in other preamble formats. This structure can support the long propagation delays encountered in LEO NTN environments. In particular, since the CP length is identical to that of a useful symbol, the receiver can exploit the CP region as an additional detection interval.

In LEO NTN environments, the satellite's high mobility causes significant time-varying propagation delays [2]. As the satellite approaches the UE, the propagation delay decreases, while as the satellite moves away, the propagation delay increases. Even if the UE pre-compensates for the potential propagation delay using the calculated TA at a given time and transmits a signal, a mismatch between the pre-compensated TA and the actual propagation delay may occur due to satellite movement during propagation. Fig. 2 shows how this TA error

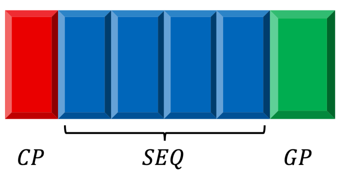

Fig 1. C2-Format PRACH Structure

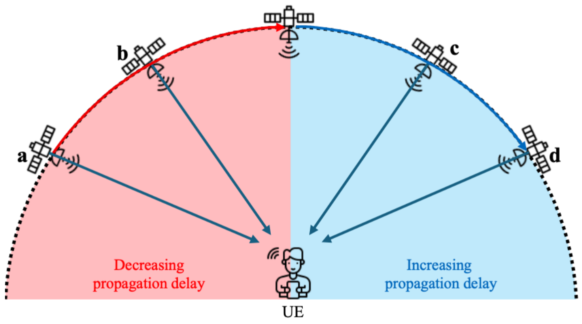

Fig 2. Propagation Delay Variation in LEO NTN Environments

can occur in LEO NTN environments. As the satellite moves from point '**a**' to point '**b**', the propagation delay gradually decreases. If the UE pre-compensates by calculating the TA based on the SIB19 information received at point '**a**', but the satellite has already moved to point '**b**', the TA value used for pre-compensation will be larger than the actual propagation delay at point '**b**', resulting in TA overcompensation. Conversely, if the satellite moves from point '**c**' to point '**d**', the propagation delay increases. In this case, if the TA value calculated by the UE based on the SIB19 information obtained at point '**c**' may be smaller than the actual propagation delay at point '**d**', potentially resulting in TA undercompensation. This TA overcompensation and undercompensation advances or delays the arrival time of the PRACH preamble signal, causing timing misalignment at the receiver.

As the preamble reception timing changes, the receiver can anticipate TA overcompensation and undercompensation situations and set appropriate detection intervals to perform preamble detection. For example, in a TA overcompensation condition, the preamble is received earlier in time, allowing the receiver to advance the preamble detection interval earlier than originally expected. Conversely, in a TA undercompensation condition, the preamble is received later in time, allowing the receiver to delay the preamble detection interval.

Meanwhile, since the C2-format PRACH has the same CP length as the SEQ symbol, the CP region can also be utilized for detection. This structural property enables predicting TA overcompensation or undercompensation due to satellite movement. It thus allows different detection intervals to be considered depending on whether the preamble is advanced or delayed. Fig. 3 shows the impact of TA overcompensation and undercompensation on two detection intervals in the receiver. As shown in Figure 3, in a TA overcompensation scenario, the preamble is received temporally advanced, causing the leading portion of the preamble to fall outside the detection interval. In this case, setting the detection interval to the length of four consecutive SEQ symbols includes the signal received following the preamble. Therefore, setting the detection interval to the length of the CP plus three consecutive SEQ symbols would be a better selection. Conversely, in a TA undercompensation scenario, the preamble is received temporally delayed, causing the trailing portion of the preamble to fall outside the detection interval. In this case, setting the detection interval to the length of four consecutive SEQ symbols would be appropriate, since the signal received before the preamble is included in the detection interval. Therefore, leveraging the structural characteristics of the C2-format PRACH can effectively mitigate partial symbol distortion caused by TA overcompensation and undercompensation, depending on the selection of the

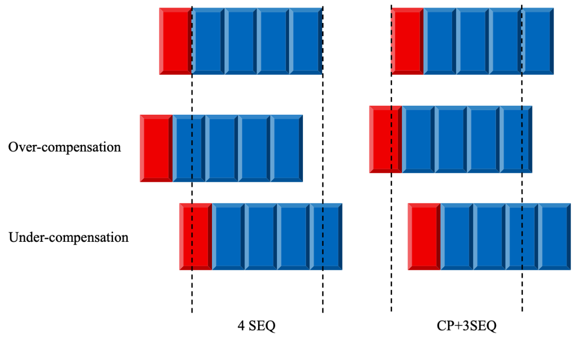

Fig 3. Impact of TA Overcompensation and Undercompensation on Detection Intervals

detection interval. In this paper, we consider these two detection intervals and evaluate the operation and performance under TA overcompensation and undercompensation conditions.

III. SIMULATION CONFIGURATION

In this study, we evaluate the performance of a detection interval that includes the CP and three consecutive SEQ symbols, and a detection interval consisting of four consecutive SEQ symbols, using a MATLAB-based PRACH transceiver simulator[5]. To evaluate these two configurations, we implemented TA overcompensation and undercompensation scenarios in a LEO NTN environment. The TA overcompensation scenario occurs when the satellite moves closer to the UE after the initial SIB19 update, reducing the propagation delay before the next update. In contrast, the TA under-compensation scenario occurs when the satellite moves away from the UE, increasing in the propagation delay.

The receiver employs a window-based PRACH detection method. This method multiplies the received signal in the frequency domain by the ZC sequence used in the preamble, then transforms it back to the time domain to obtain the power delay profile (PDP). The PDP is windowed based on the CS spacing used during PRACH generation, and the receiver searches for the window with the maximum PDP value. If this maximum value exceeds a predefined threshold, the preamble is declared present. This simulator uses a distance-based detection method that calculates the distance between the PDP peak and the adjacent CS boundaries, then selects the CS closest to the peak[6]. The PRACH transmission and reception parameters used in the simulator are summarized in Table 1. Since this simulation aims to compare the impact of accumulated propagation delay between successive SIB19 updates, it does not consider fading effects other than propagation delay. Furthermore, the propagation delay is assumed to be perfectly compensated for at the time of the initial SIB19 update, and subsequent delays accumulate over time.

TABLE I. SIMULATION PARAMETER

Parameter Name	**Value**
Subcarrier Spacing	120[kHz]
Zero Correlation Zone	15
Root sequence Length	139
FFT size	4096
Preamble format	C2

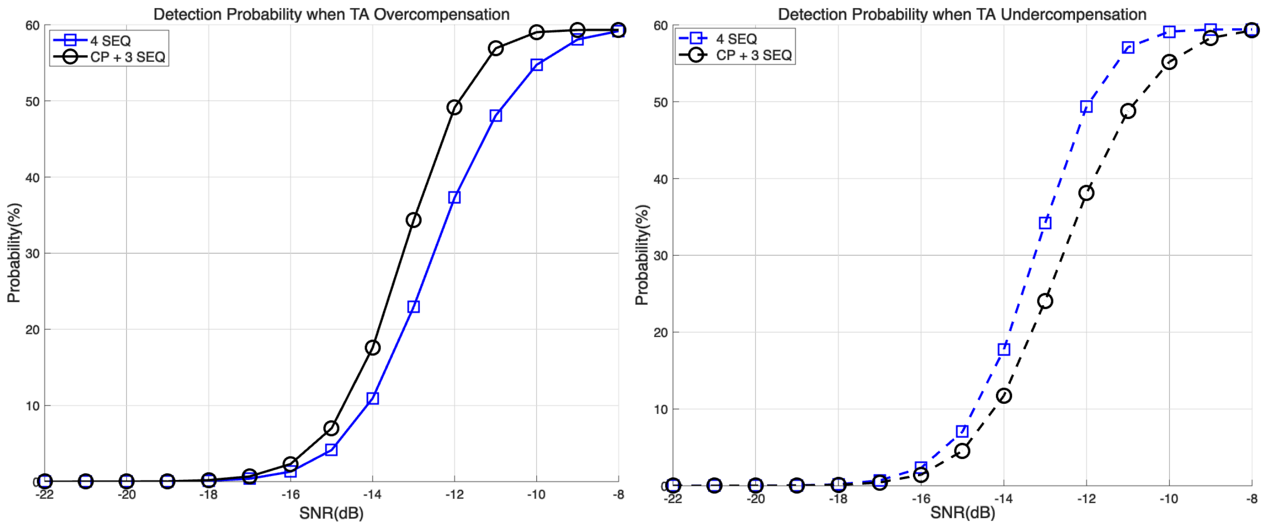

Fig.4. PRACH Detection Performance for Different Detection Intervals Under TA Overcompensation and Undercompensation

IV. SIMULATION RESULT

Fig. 4 compares PRACH detection performance for two detection intervals under the TA overcompensation and undercompensation scenarios in a LEO NTN environment. The simulation results show that under the TA overcompensation scenario, setting the detection interval to the length of the CP plus three consecutive SEQ symbols achieves a higher detection probability. As explained in Section II, when the preamble is received temporally advanced, it is advantageous to set the detection interval so that the received signal following the preamble is not included in the detection interval. In contrast, under the TA undercompensation scenario, setting the detection interval to four consecutive SEQ symbols results in better detection performance. As explained in Section II, when the preamble is received temporally delayed, it is advantageous to set the detection interval so that the received signal preceding the preamble is not included in the detection interval.

V. CONCLUSION

In this study, we analyzed the impact of the PRACH detection intervals on PRACH detection performance under TA error conditions. The simulation results showed that, in the TA overcompensation scenario, setting the detection interval to the length of the CP plus three consecutive SEQ symbols achieved better detection performance, whereas in the TA undercompensation scenario, setting the detection interval to the length of four consecutive SEQ symbols results in higher detection performance. This indicates that when a TA pre-compensation error exists in a LEO NTN environment, PRACH detection performance can be effectively improved by predicting a TA overcompensation or undercompensation situation and selecting an appropriate detection interval.

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