Empowering User Capabilities via Non-Orthogonal Multiple Access in 3GPP Non-Terrestrial Networks

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***Abstract*— In this paper, we propose a novel technique for enhancing the initial access capacity of users in a 3GPP non-terrestrial network (NTN) by utilizing the non-orthogonal multiple access (NOMA) technique. The conventional initial access scheme standardized in 3GPP LTE or NR employs a contention-based approach, leading to frequent collisions among preambles transmitted by users in the 5G NTN. To overcome the drawbacks of the conventional approach and to enhance the user's initial access capacity in the future 6G NTN, we incorporate the NOMA scheme into the conventional initial access scheme. More specifically, we apply the NOMA scheme to Msg3 of the initial access procedure, thereby significantly reducing the collision probability. Simulation results verify the validity of our proposed scheme, and we also present potential directions for future research.**

Keywords—3GPP, Initial access, non-terrestrial network, non-orthogonal multiple access

I. Introduction

Many wireless research institutes and global large corporations have focused on the usage of satellite communication in cellular networks to achieve global coverage. Starlink, renowned as the world's premier satellite service provider, already offers high-speed wireless communication services with a downlink data rate of 200 Mbps and an uplink data rate of 25 Mbps [1]. While the 3GPP specifications in LTE were initially focused on terrestrial cellular networks, the organization has been actively developing specifications for non-terrestrial networks (NTN) to integrate them into cellular networks [2].

Starting from 3GPP Release 15, study items related to NTN were initiated, and the simulation results from these studies were contributed by various companies. As of 3GPP Release 17, the working items for incorporating NTN into cellular networks are actively being pursued. In most cases, specifications related to NTN align with those of terrestrial networks (TN) if they function effectively in an NTN environment. However, due to differing channel characteristics between TN and NTN, some modifications to the TN standards may be necessary.

Recently, ITU-R WP 5D has reached an agreement on the IMT-2030 framework, also referred to as 6G [3]. IMT-2030 introduces several potential key performance indicators (KPIs). One of these indicators is connection density, which is specified to range from by 10^6 to 10^7 devices per square kilometer. This density is more than ten times greater than that of 5G.

In a terrestrial network (TN), this level of device density can be accommodated by deploying small cells. However, when considering a non-terrestrial network (NTN) scenario, challenges arise. For instance, satellite gNBs with beam radii ranging from 50 to 500 kilometers can provide cellular services to devices within their coverage area. In this context, a maximum of 800 billion devices could be served. However, the current specifications are inadequate to support such a high device count in an NTN scenario. Further enhancements and adaptations would be necessary to address this substantial increase in device density.

Initial access in a non-terrestrial network (NTN) is a critical research area due to the necessity of establishing connections for data transmission to satellite gNBs. Maintaining data transfer in the presence of connection outages is challenging. The existing specification for initial access relies on a contention-based approach, leading to a significant number of collisions among users utilizing the same preamble sequence.

To mitigate collision issues and improve the user capacity of NTN by enhancing the initial access success probability, the authors of this paper propose the application of the non-orthogonal multiple access (NOMA) scheme to Msg3 of the initial access procedure.

The paper is structured as follows. First, in Section 1, an overview is provided. The introduction discusses the significance of initial access in NTN and introduces challenges stemming from connection outages and collision-related issues. In Section 2, the conventional initial access procedure is examined, along with its limitations when applied to the NTN scenario within the context of 6G's key performance indicators (KPIs). Section 3 presents a system model, outlining the integration of the NOMA scheme into Msg3 of the initial access procedure. Finally, the paper concludes with simulation results and future prospects. The concluding section shows simulation results that validate the proposed approach and outlines potential avenues for future research to expand upon the current work.

By addressing the shortcomings of the existing initial access method and leveraging the NOMA scheme, the paper aims to improve initial access success rates and enhance the overall performance of NTN for 6G communication systems.

II. Conventional Initial Access and Challenges

A. 4-Step RACH

In the context of the 3GPP standard, cellular devices operating in the RRC-Idle state typically follow a 4-step RACH (Random Access Channel) [4] initial access procedure as the default method. When a device aims to transition from an idle RRC connection state to a connected state, it initiates a process involving the synchronization signal block (SSB) within the synchronization raster.

Upon locating the essential information for the initial access procedure, the device randomly selects a preamble and transmits it to a pre-configured RACH-Occasion (RO). If the gNB (gateway NodeB) successfully receives the preamble during the designated RO, it responds with a random access response (RAR). This RAR contains crucial parameters such as RAPID (Random Access Preamble ID), TA (Timing Advance), UL_Grant (Uplink Grant), TC_RNTI (Temporary C-RNTI), and others, all transmitted over a preconfigured control channel.

Subsequently, the device opens its receive window for a specified duration known as ra-ResponseWindowSize. During this window, the device attempts to detect the RAR and, upon successful detection, transmits Msg3 (Message 3) using the UL_Grant provided in the RAR. Upon receiving Msg3, the gNB decodes its content and responds with Msg4 (Message 4), which includes the user's identity information extracted from Msg3.

The device then verifies whether the identity in Msg4 matches the one transmitted in Msg3. If there is a match, the initial access procedure is considered successful and concludes at this point. This sequence of steps ensures a coordinated and efficient approach to establishing the connection between cellular devices and the network infrastructure.

B. Problems of RACH in NTN scenario with 6G KPI

In the current specification, the maximum number of devices for initial access per beam at a single SSB timing is limited to 64. When we take into account the default SSB transmit period of 20ms and the velocity of a Low Earth Orbit (LEO) gNB at an altitude of 1,200km with a beam radius of 50km, the calculation for the maximum number of devices that can successfully access the network simplifies to 44,800. This calculation is based on an ideal scenario without considering any handover scenarios. However, this figure is significantly small when compared to the requirements set by the 6G key performance indicators (KPIs).

III. System Model and NOMA-Applied Msg3

To surpass the constraints of the current specification and enhance the user capacity of future NTN, the authors suggest the adoption of a NOMA-based approach. This approach aims to alleviate collisions that arise from contention-based access methods.

A. System model

Let's consider a scenario involving a non-terrestrial gNB based cellular network, comprising a single LEO satellite gNB and a total of N NTN devices located within the satellite's coverage area. Assume that block fading channel and perfect timing and frequency synchronization between LEO gNB and devices. The primary objective is to enable these N NTN devices to establish network access while they remain within the satellite's coverage zone. In this particular setup, let's assume the following parameters: satellite altitude 1,200km, satellite beam radius 50km, moving beam configuration (the beam moves along with the satellite), LEO satellite velocity 7.2km/s, and time in satellite coverage 14 seconds. Given these parameters, it is crucial for NTN devices to initiate the process of accessing the network within the 14-second while they are within the coverage area of the moving satellite beam. This ensures a successful initial access procedure for each NTN device.

B. NOMA-Applied Msg3

To simplify the problem, let's assume that devices utilizing the same preambles successfully receive a Random Access Response (RAR) and transmit Message 3 (Msg3) to the specified time-frequency resource as indicated by the UL_Grant.

Within the context of the terrestrial network, numerous NOMA schemes have been proposed by various companies for standardization within 3GPP Release 16 [5]. However, achieving consensus on specific schemes has proven challenging. From these options, we have chosen to adopt a bitwise scrambling-based NOMA scheme, similar to schemes like LCRS, RSMA, and LSSA. These schemes employ a scrambling mechanism to enhance the efficiency and performance of NOMA in the network.

Devices that transmit Msg3 employ a scrambling process on their Msg3 bit sequence using their designated NOMA signature. Specifically, for the RSMA scheme, the NOMA signature takes the form of a W-CDMA scrambling sequence. Conversely, the LCRS scheme utilizes a scrambling sequence based on gold sequences. Let's represent the transmitted symbol sequence for user i as $s_i[k]$, physical channel to the satellite as h_i, AWGN as n. Assuming that index for users are assorted by descending order of channel quality without loss of generality, the received signal of LEO gNB at time k is given by

$$y[k]=\sum_{i=1}^{N}h_i s_i[k]+n. \quad (1)$$

Let's consider a scenario where the NOMA signature (scrambling sequence) of each user is known by the gNB. After the received signal is demodulated and decoded, the first decoded message undergoes re-encoding and re-modulation. Subsequently, the estimated channel is applied to the re-modulated message, which is then subtracted from the received signal. This entire process is referred to as successive interference cancellation (SIC). The SIC process continues iteratively until the last user's message is decoded.

However, it's important to note that if an error occurs during the decoding process for one of the users, the messages of the remaining users may become corrupted by this error. Nonetheless, if the target block error rate is sufficiently low to allow for the successful decoding of all users' messages, this process is expected to result in a significant increase in user capacity.

Assume that SIC is successfully performed for the previous user's signal. The signal-to-interference-plus-noise ratio (SINR) of kth symbol of user i is given by

$$SINR_k^i=\frac{P\,|\,h_i\,|^2}{N_0+\sum_{j=1}^{i-1}P\,|\,h_j\,|^2} \quad (2)$$

where P is the transmit power of each symbol and N_0 is the variance of AWGN. The outage occurs when the received SINR goes below target SINR which is related to the target symbol rate. The block error rate of user i is given by

$$BLER_i=1-\left(1-\Pr\left(\mathrm{SINR}_k^i<\gamma_{\mathrm{th}}\right)\right)^{\lceil K/M\rceil} \quad (3)$$

where K is the size of Msg3 and M is the modulation order. $\lceil K/M\rceil$ means that additional bits are added to process desired modulation.

IV. Simulation results and Future Works

A. Simulation results

Let's consider a Rayleigh fading channel with a channel variance of 1. We have 4 users in this scenario. To simplify our analysis, we will focus on the Symbol Error Rate (SER) performance. The Block Error Rate in equation (3) can be easily calculated using the SER. We will plot the SER performance of users employing Orthogonal Multiple Access (OMA) for comparison with the NOMA scheme.

Figure 1 illustrates the SER performance of each user. The 'Best user' refers to the user with the highest channel quality. The second, third, worst user has the similar meaning. Figure 1 illustrates the SER performance of each user. The term 'Best user' designates the user with the highest channel quality, while the 'second best,' 'third best,' and 'worst' users have similar connotations. Figure 1 shows that the best, second, and third users exhibit superior Symbol Error Rate (SER) performance compared to the OMA user. This indicates that NOMA allows more users to access the network simultaneously in comparison to OMA.

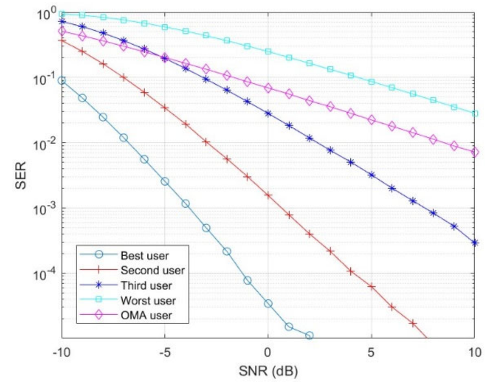

Figure 1. Symbol error rate of NOMA users

B. Future works

In this paper, only Msg3 enhancement are considered for mitigate collision probability. However, in order to comply with the current standard, there should be some modifications of Msg2 and Msg4. For example, some fields of Msg2 RAR is not needed or useless for NOMA scenario. Timing advance field for conventional RAR is 12bit and this field is for one target user. Considering NOMA scenario, this field is useless for others. Also, PUSCH field for Msg4 should be modified. The existing standard for Msg4, contention resolution process, allocates resources at most one chosen user. To utilize our Msg3 structure, Msg4 contains the information for all users using NOMA.

Additionally, we have applied the NOMA scheme from the terrestrial network to Msg3. However, the NOMA scheme is highly sensitive to time/frequency synchronization issues. Hence, development of robust NOMA scheme is left as a future work.

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