Implementation and design of the 5G NTN test system

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Abstract

In the progress of 5G/6G, non-terrestrial network (NTN) communication has gained prominence. This paper focuses on presenting a comprehensive hardware and software approach to emulate an experimental model of a Low Earth Orbit (LEO) satellite and ground terminal in regenerative mode [1] [2]. This paper involves the hardware architecture of the test system and configuring the propagation model of the channel simulator which combined with the study incorporates the enhancement of position tracking from the Global Navigation Satellite System (GNSS). Initial access experiments are conducted, exploring different Rach Occasion(RO) and PUSCH Occasion(PO) mapping relationships. The findings reveal trends in selecting mapping relationships, especially in scenarios with constrained satellite communication resources.

1 Introduction

This paper firstly introduces the construction method of the hardware architecture of the test system, including the connection methods of the satellite payload, the ultra wideband satellite-ground channel simulator and the user equipment (UE), and the function of each combined device. The propagation model design of the channel simulator and the application of timing advance(TA) and frequency offset pre-compensation technology combined with GNSS positioning are described. Combined with the above experimental architecture, a competitive initial access simulation experiment about RO-PO mapping relationship is designed. Under this LEO channel model setting, the main factor affecting the initial access success rate after the terminal successfully obtains ephemeris information is the mapping relationship.

2 Test system architecture

As illustrated in Fig. 1, the test system comprises three main components: the satellite payload, simulating the on-board gNodeB; the UE simulator, emulating multiple groups of UEs; and the satellite-ground ultra-wide channel simulator, replicating the wireless propagation effects between the satellite and the terminals. The system operates in regenerative mode within the NTN, where the satellite payload incorporates part or all of gNodeB functions, featuring on-board processing capabilities, so this allows direct connection to the UE. Notably, the satellite payload can directly connect to the UE with on-board processing functions, eliminating the need to account for the delay in the feeder link between the satellite and base station/gateway in TA [3]. Only the delay in the service link between the satellite and UE is considered.

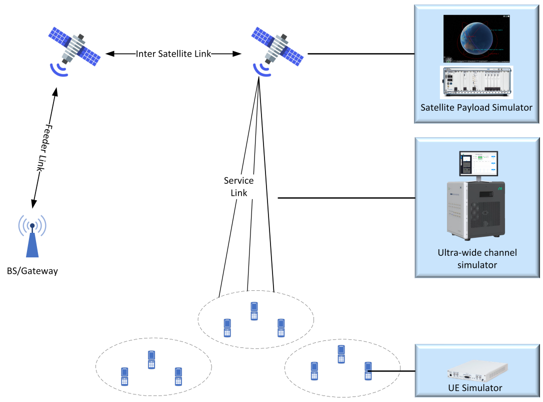


Figure 1. Regenerative mode in NTN.

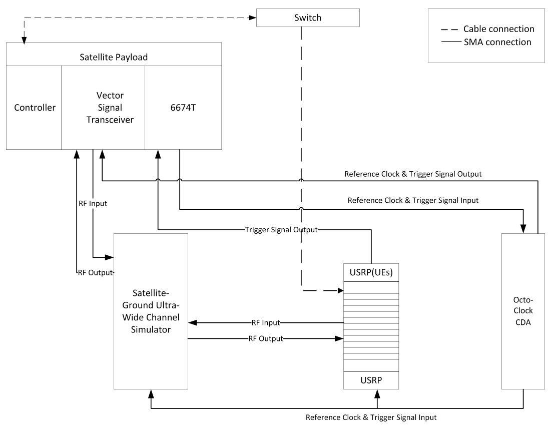


Figure 2. Hardware flow chart.

In Fig. 2, the components of the test system are detailed as follows:

Satellite Payload Simulator: 1. Utilizes a software-defined radio architecture. 2. Core components include embedded controllers, FPGA units, disk arrays, vector signal transceivers (VST), and simulation software based on 5G NTN for satellite payload communication.

User Equipment Simulator: 1. Based on Universal Software Radio Peripheral (USRP). 2. Features main CPU, FPGA, and RF transceiver module.

CDA (Clock and Trigger Distributor): 1. Functions as a reference clock and trigger distributor connected with PXI6674T. 2. Facilitates clock synchronization among different system devices and serves various trigger roles for experimental functions.

Ultra-Wide Channel Simulator: 1. Upper unit provides real-time equipment status display and configuration of channel simulation parameters (frequency, bandwidth, frequency shift, time delay, attenuation, noise, etc.). 2. Supports loading into various channel models and simulators, allowing for cascade combinations of simulations. 3. Satellite channel simulator unit includes modules for ADC and DAC, input and output calibration, delay modeling, amplitude-frequency characteristics, fading characteristics, noise characteristics, spurious characteristics, phase noise characteristics, carrier Doppler simulation, carrier aggregation processing, multipath model simulation, etc. 4. Combines with RF frequency converter unit, consisting of Ka up-converter and Ka down-converter, enabling up-conversion and down-conversion of broadband processing signals for simulating wireless channel characteristics in the Ka-band.

3 Key Technologies

3.1 Timing and frequency pre-compensation with GNSS

3GPP Release 17 enhances UE positioning, minimizing delays and improving efficiency to meet the demands of more complex use cases. This advances time-frequency offset pre-compensation during the initial access LEO satellites [4].

In the initial access process, the satellite transmits a synchronization signal block (SSB) with Primary Synchronization Signal (PSS), Secondary Synchronization Signal (SSS), and Physical Broadcast Channel (PBCH) for time-frequency synchronization and cell search. The UE acquires Physical Cell ID (PCID), decodes PBCH for Minimum Information Block (MIB) acceptance, identifies the PDSCH carrying System Information Block (SIB) to obtain ephemeris. Using orbit ephemeris which including two-line element sets (TLE), satellite orbit hexes parameters or the vector of satellite position and velocity directly. The UE computes time-frequency pre-compensation before random access based on relative position and velocity vectors from the satellite and UE. This transitions the UE from non-Radio Resource Control (RRC) connected to RRC connected during random access.

In the regenerative satellite payload context, focusing on the service link, satellite ephemeris from SIBs calculates position and velocity vectors over time. The UE's position and velocity vectors [5], obtained through GNSS, form the TA and frequency offset computation, when disregarding clock co-clocking errors. The TA and frequency offset is composed by:

$$\boldsymbol{v}(t) = \boldsymbol{v}_s(t) - \boldsymbol{v}_u(t) \tag{1}$$

$$f_{d(t)} = \frac{\boldsymbol{v}(t)}{c} \frac{\boldsymbol{d}(t)}{|\boldsymbol{d}(t)|} f_c \tag{2}$$

where, $\boldsymbol{v}$ denotes satellite and UE relative velocity vector, and $f_{d(t)}$, represents the Doppler shift. f_c is the carrier frequency, and c is the speed of light. $\boldsymbol{d}(t)$ is the distance vector between satellite and UE.

The one way propagation delay is simple to be calculated by:

$$d_0 = \frac{|\boldsymbol{d}(t))|}{c} \tag{3}$$

where, d_0 denotes the one way propagation delay, which is calculated from the position of UE and satellite as a TA for the UL signal.

3.2 Propagation model

The NTN channel model employed in this paper incorporates dynamic delay and Doppler shift resulting from satellite motion, integrates dynamic attenuation attributed to scintillation, rain, and clouds, and the Doppler spread induced by the terrestrial multipath environment. The NTN Tapped Delay Line (TDL) models, following the protocol in 3GPP 38.811, depict multipath parameters at an elevation of 50° have been considered [6]. Rayleigh channel modeling is implemented by applying Gaussian white noise filtering to emulate Doppler expansion in the ground environment. This involves superimposing complex baseband signals with complex monotone signals generated by the Doppler frequency shift module through complex multiplication. The combination of these signals achieves NTN small-scale fading simulation based on a statistical model.

Table 1 outlines simulation parameters for configuring satellite orbit and UE movement. Orbit parameters, including Semi-Major Axis, Eccentricity, Inclination, Right Ascension Of Ascending Node (RAAN), Argument Of Periapsis, and True Anomaly, are defined in relation to the satellite orbit, as Fig3. The UEs' positions are expressed using the Longitude Latitude Altitude (LLA) coordinate system to compute the position and velocity vectors of both the satellite and UEs. Simulation results for attenuation, delay, and Doppler shift are presented in Fig. 4(a), (b), (c), respectively.

Table 1. Simulation parameters of satellite and UE

Parameters Name	Parameter Value
Semi-Major Axis	6727.80 km
Eccentricity	3.4180e-04
Inclination	53.22°
RAAN	71.93°
Argument Of Periapsis	9.97°
True Anomaly	35.28°
UE LLA Position	31.17°, 121.61°, 10m
Carrier Frequency	20 GHz
Simulation Start Time	2022-6-22 11:08:00
Simulation Stop Time	2022-6-22 13:08:00

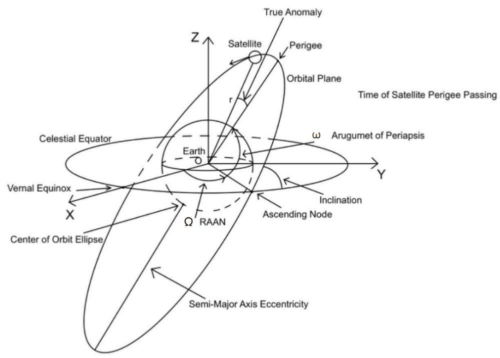
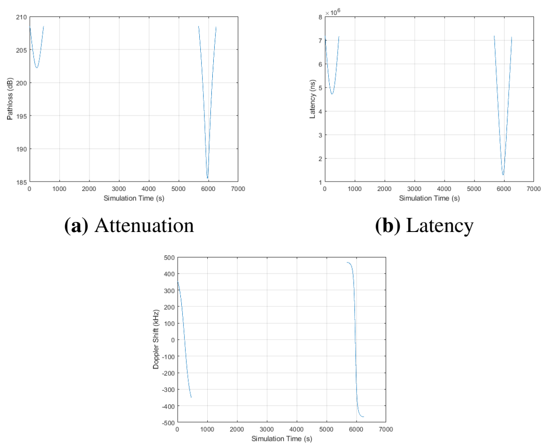


Figure 3. The meaning of orbital parameters.



(a) Attenuation **(b)** Latency **(c)** Doppler Shift

Figure 4. Simulation results of attenuation, delay, and Doppler shift

In this channel mode, the maximum value of the simulation from channel emulator is shown in the Table2., which conforms to the protocol 38.811 model.

Table 2. Maximum value of channel effect parameters

Parameters Name	Parameter Value
Platform orbit	LEO under 600 km
Frequency band	Ka band
Max Doppler shift	467.71 kHz
Max One way propagation delay	7.1806 ms
Max attenuation value	208.479 dB

3.3 Initial Access with RO-PO mapping relationship

To minimize delay in the initial access process post-synchronization Signal Block (SSB) in the non-terrestrial network, a two-step random access(RA) approach is better than four-step RA [7]. All UEs undergo TA and frequency pre-compensation before the RA process. In two-step RA, this involves dividing the process into the uplink Message A (MSGA) comprising the Physical Random Access Channel (PRACH) and Physical Uplink Shared Channel (PUSCH), and the downlink Message B(MSGB). The PO in the uplink MSGA involves Preamble correspondence, which can be one-to-one or one-to-multiple, impacting user access decisions.

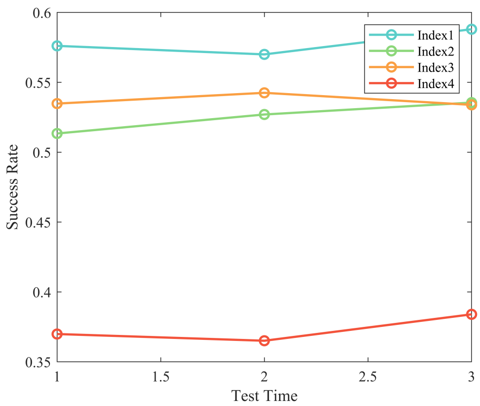
This model utilizes the described model for the construction of simulation equipment and channel model setup. The initial access system resources consist of two RACH Occasions (RO) and 50 POs. Different RO and PO mapping relationships are downlinked at each wave position as the satellite moves in orbit. UEs perform time-frequency offset precompensation after successfully obtaining ephemeris information in SSB. However, if UEs cannot obtain the ephemeris, unsuccessful attempts are counted as initial access failures. Each mapping relationship strategy applies in 100 cells per test, assuming 30 UEs per cell, and the 30 UEs in all cells are assigned mapping resources randomly. We conducted three tests for each strategy, and there are four strategies in this test. The success rate for initial access in different strategies was calculated by counting successful access transitions to the connected state. Instances, where UEs did not receive the ephemeris and resulted in initial access failure, were also included in the count.

Table 3 displays the design scheme of the four mapping relation strategies. The uplink random access resources consist of only 2 ROs and 50 POs. Each RO can have 0 to 64 preamble codes, which are evenly mapped to the corresponding PO resources. Strategy 1 assigns RO1 to the first 25 PO resources, distributing its 64 preamble codes evenly among them in a one-to-many correspondence. RO2 is assigned to the last 25 PO resources, also in a one-to-many correspondence. In Strategy 2, RO2 is allocated to the last 40 PO resources, with leading code correspondence to some in a one-to-many and some in a one-to-one relationship. Strategy 3 shows that RO1 and RO2 share some PO resources, while in strategy 4, RO2 receives significantly more resources than RO1.

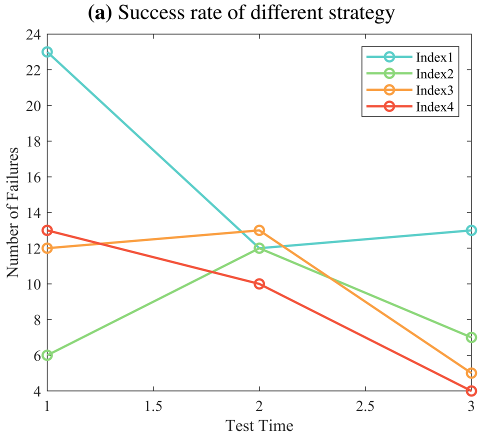
Table 3. Four strategies of RO-PO mapping relationship

Index	***RO1***	***RO2***
1	1-25 POs	26-50 POs
2	1-10 POs	11-50 POs
3	1-30 POs	20-50 POs
4	1-1 POs	2-50 POs

4 Simulation Result



(a) Success rate of different strategy



(b) Initial access failure caused by no ephemeris

Figure 5. Simulation result of four strategy

As shown in Fig. 5(a)(b). Under the current channel model, in the more competitive initial access, the probability that the initial access does not successfully receive ephemeris information is lower than 1% probability under this channel model, considering that the factor is the attenuation problem due to fading, beam misalignment, or synchronization between satellites and UE, but the main influencing factor for the success rate of initial access is the RO-PO mapping relationship matrix. In contrast to the other strategies, strategy 1 is the better one in the experiment, with a more evenly distributed strategy. Since in fact, the satellite has the function of a base station in regeneration mode, the mapping relationship can be adjusted according to the combination of its own moving trajectory, ground area information, or feedback information from the last ground access. This is a follow-up study.

5 Conclusion

This paper presents a simulation methodology that combines satellite, UE, and channel models, as well as initial access experiments applied to this methodology. Further research will follow based on the channel as well as the initial access strategy.

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