Performance Analysis of Integrated 5G-NR Terrestrial and Non-Terrestrial Networks Using System Level Simulations

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***Abstract*—As the momentum for Non-Terrestrial Network (NTN) integration into Terrestrial Network (TN) accelerates, there is an urgent need for performance analysis of these integrated networks to fully grasp their potential benefits and effectively address possible challenges. This paper analyzes the performance of a hybrid 5G New Radio (5G-NR) network using large scale System Level Simulations (SLS), focusing on a scenario with integrated TN-NTN, specifically a Low Earth Orbit (LEO) satellite with a regenerative payload and a conventional terrestrial base station. We perform this analysis utilizing realistic vehicle mobility traces in a real city setting with various network loads. These advanced SLS capabilities, not available in previous state-of-the-art analysis, provide a more accurate representation of real-world conditions. The results demonstrate that the hybrid network significantly enhances overall system performance, particularly in terms of network-level packet loss and data rate. This improvement is attributed to better service coverage, an effective TN-NTN handover mechanism, and stable resource block and bandwidth allocation for all users within the region of interest (ROI).**

***Index Terms*—Integrated TN−NTN, SLS, 3GPP, 5G-NTN, Handover mechanisms, Hybrid networks, LEO satellites**

I. Introduction

The significance of Non-Terrestrial Networks (NTN) is on the rise and gaining traction as the main focus of future mobile networks. By integrating both terrestrial and non-terrestrial elements like satellites or high-altitude platforms, NTN is poised to surmount the challenges faced by conventional Terrestrial Networks (TN), which include inadequate coverage in isolated regions and the struggle to meet the escalating demand for high-speed and dependable mobile communication services [1]. This was emphasized in the liaison statement of Global Satellite Operators Association (GSOA) in 3rd Generation Partnership Project (3GPP) [2]. The statement highlighted that NTN not only addresses these issues with broad coverage and the capability to service areas devoid of terrestrial infrastructure or where deployment is not cost-effective, but also integrates various network components to form a robust infrastructure. This underscores NTN's strategic advantages and expanding role in global connectivity. This trend is reflected in the increasing momentum in 3GPP to introduce various enhancements to support NTN integration in upcoming releases [3, 4, 5].

The convergence of TN-NTN also poses its own set of challenges, such as the need for more dynamic traffic routing and resource allocation techniques to address the uncertainty of traffic flow and transmission demand brought about by the diversity of terminal types in such a complex network [6]. Additionally, integrated TN-NTN networks require effective access control and smooth handover mechanisms to ensure seamless connectivity and uninterrupted service [1]. To address these challenges, numerous studies have been conducted to analyze the performance expectations of these complex systems. For instance, the work done in [7] attempts to model and analyse the performance of an amplify-and-forward hybrid satellite-terrestrial co-operative network where the satellite acts as a relay node in the presence of co-channel interference. Another example is the work done in [8] where the authors attempt to investigate the outage probability performance of a cognitive hybrid satellite–terrestrial network, where the primary satellite communication network and the secondary terrestrial mobile network coexist with an interference constraint.

It is also important to combine such statistical and theoretical bound analysis with accurate and reliable system level simulations that are capable of evaluating and modelling large scale integrated TN-NTN networks with various types of dynamic nodes deployed in a realistic environment. Such simulations provide valuable insights into network performance, help identify risks, optimize resource allocation, evaluate new algorithms or architectures and enable cost-effective decision-making. One example is the work done in [9] where the authors present an open source System Level Simulator (SLS) based on the software Network Simulator 3 (NS-3) capable of simulating Integrated TN-NTN systems. This SLS could support NTN handover decisions, dynamic bandwidth part selection. However, the work in [9] did not analyze TN-NTN handover and could only support static users on the ground with small networks due to the large computational requirements of the simulations. Another example that is presented in [10] analyzes the performance of dynamic mobile users served by a Low Earth Orbit (LEO) based NTN with handover between satellites. However, similar to other works, they do not consider TN-NTN handover nor analyze the system performance of integrated TN-NTN networks.

This paper studies and analyzes the performance of integrated TN-NTN networks with handover and dynamic link conditions. In order to evaluate such a complex system we first present our advanced SLS which enables such an analysis in Section II. We then proceed to describe the integrated TN-NTN use case in Section III with base stations on ground and onboard a LEO satellite, and automotive users on ground in a realistic deployment scenario modeled after the southern German city of Rosenheim. We then analyze and compare the system performance of such a complex scenario with and without the aid of NTN extended coverage as presented in section IV.

II. Simulation Framework

Our simulation framework is implemented in OMNeT++ [11] and uses the implementation of the 5G-NR user plane protocol stack implementation from Simu5G [12] as a baseline. The framework was further extended with the capability to simulate and model NTN as previously presented in [13]. In this section we give an overview of the protocol stack implementation, the enhanced mobility and channel models used for this study.

A. Protocol Stack

Following the simulation architecture of Simu5G, our simulation models only the data plane of a 5G network as shown in Fig.1. This lack of control plane modelling can cause some limitations since we don't consider the impact of signaling overhead in the performance evaluation of the system. However, using this abstraction level allows for a much less computational complexity and enables large scale network simulations with an acceptable error margin [12].

The data flow in the Downlink (DL) direction originates from a remote application server which is then forwarded to the abstract implementation of the 5G-Core (5GC) represented in a User Plane Function (UPF) module which determines the appropriate basestation (gNodeB) to be forwarded to. The gNodeB is then responsible to handle its allocated resources to ensure this traffic is delivered to the designated User Equipment (UE) through the Radio Access Network (RAN). The implementation of the RAN protocol stack in both the gNodeB and the UE consists of 5 layers. From top to bottom, the first is the Service Data Adaptation Protocol (SDAP) layer which is responsible for Quality-of-Service (QoS) flow mappings to the appropriate data bearer. The Packet Data Convergence Protocol (PDCP) layer performs the encryption and numbering of packets and after appending its header to the received Protocol Data Unit (PDU), it sends it to the Radio Link Control (RLC) layer where it is stored in the RLC buffer and retrieved by the underlying Medium Access Control (MAC) when it needs to assemble a transmission block. The MAC layer is responsible for the radio resource allocation to individual UEs based on their respective buffer statuses. When a packet is scheduled and retrieved from the RLC layer, the MAC layer assembles the RLC PDUs into transport blocks, adds a MAC header, and sends everything to the Physical (PHY) layer for transmission. In the PHY layer an air frame is created which encapsulates the MAC transport block and then is sent to the designated receiver, where upon reception applies the channel model calculations to determine the received Signal to Interference and Noise Ratio (SINR) and the corresponding Block Error Rate (BLER) as per the error model implemented in Simu5G [12].

B. Channel Models

The framework includes various channel models representing both terrestrial and non-terrestrial transmission media. These models include both multipath and Line of Sight (LOS) and None Line of Sight (NLOS) propagation models that apply to S-band or Ka-band use cases. For both Terrestrial Networks (TN) and NTN links we use the evaluation parameters defined in [14, 15] as a general reference for the configuration of system level simulations such as antenna gain, transmission power and noise figure for different terminals.

For the TN based links, we use the channel models defined by 3GPP in [16] for the determination of the pathloss and shadowing components to determine the link quality. We also consider the stochastic model given in the same document to determine the existence of a LOS component. In the case of the NTN links we use the propagation models defined by 3GPP in [17] for the modelling of the free space path loss, shadowing and cluster loss components. Additionally, we use International Telecommunication Union (ITU) recommendations for the modelling of atmospheric (including gaseous, cloud and rain components) and scintillation losses as defined in [18, 19, 20].

C. Mobility Models

Ground users follow vehicle mobility models, with vehicle tracks being defined using the Simulation of Urban Mobility (SUMO) library [21] which is interfaced with our simulation model through the use of the Veins framework [22]. For airborne gNodeBs, flight paths can be defined based on orbital parameters in NORAD-TLE format. For simplicity, the mobility model could also be based on a linear/circular trajectory initialized based on latitude, longitude, altitude, and Euler angles to update the direction of movement [13].

III. Use Case and Scenario Description

In order to evaluate the benefit of a hybrid TN−NTN network, we design a hypothetical evaluation scenario as shown in Fig.2. In this scenario we first define a Region of Interest (ROI) on Open Street Map (OSM) which for this analysis is assumed to be based on the German city of Rosenheim. Based on this OSM data, different vehicular routes are generated using the SUMO tool for a fixed number of ground users. The UEs are assigned hand-held transmission characteristics as defined in [16]. These automobile users are referred to as vehicles in the remainder of the paper. The terrestrial gNodeB is positioned around the edges of the ROI and assumed to be the the primary candidate for providing 5G services to the deployed ground

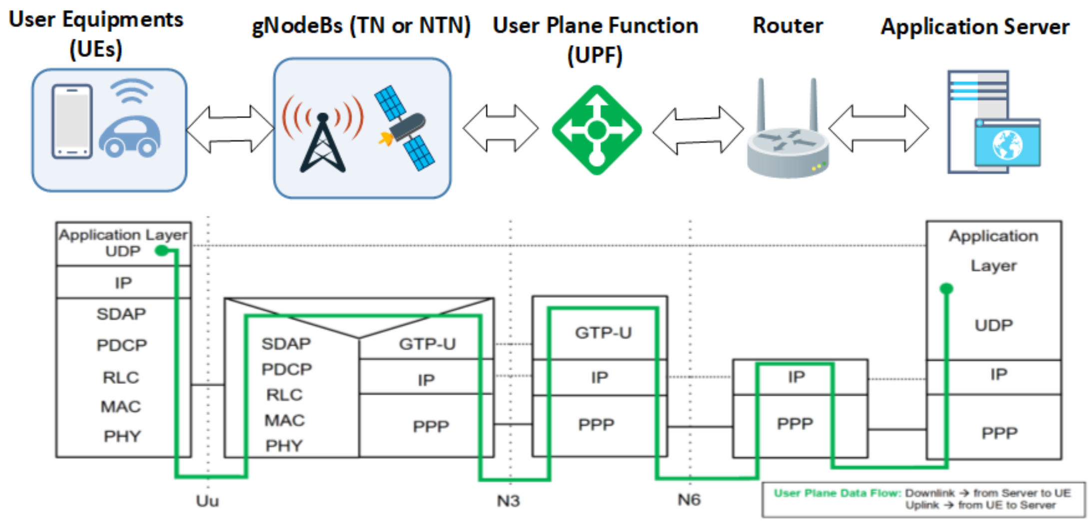


Fig. 1: User plane data flow in simulation

vehicles. Lastly, the LEO satellite trajectories are defined using the INET's mobility framework, such that these satellites fly approximately over the centre of the ROI. We assume the satellites are equipped with regenerative payloads, acting as a NTN gNodeB to the ground vehicles. In the current version of the simulator, the satellites do not support beam steering or beam switching resulting in Earth-moving beams. The beam projection on Earth is based on the antenna specifications of the payload, which is assumed to be of Bessel type [17] with the beam coverage controlled by the Half Power Beam Width (HPBW) configuration of the antenna. The resulting dual mobility, one associated with the vehicular movement and the other with the movement of LEO satellite leads to dynamic link conditions. For the analysis performed in the next section, it is assumed that the connection between vehicles and the NTN gNodeB is (LOS) type with clear sky conditions. However, for terrestrial links i.e., between vehicles and the TN gNodeB, the probability of being in a LOS or NLOS is based on the stochastic models defined by 3GPP in [16] for the urban macro cell channel model.

The bandwidth used by the TN and the NTN gNodeBs is defined in terms of Resource Blocks (RBs) in the SLS. The NTN and TN gNodeBs use a different set of RBs belonging to different frequency bands which results in no interference between the two networks. Additionally, to ensure a fair comparison we assume the same overall system bandwidth allocation that is either entirely allocated to the TN or divided between the TN and NTN when we evaluate the integrated network. Hybrid Automatic Repeat Request (HARQ) is switched off in this scenario for both TN and NTN. Inclusion of HARQ for TN may increase the user connectivity albeit at a cost of increased latency. This will be addressed in future studies along with the impact of advanced physical layer abstraction error models. The different parameters that are fixed for the scenario are summarized in Table I.

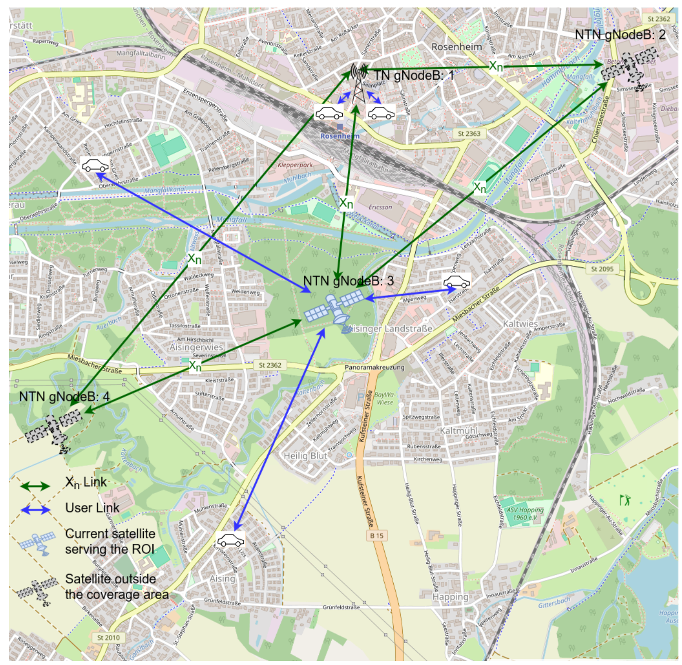


Fig. 2: Schematical simulation scenario layout

For evaluation purposes, the scenario is observed over a period of 24 seconds. The LEO satellites are flying at a speed of 7.5 km/s with a dwell time over the ROI of approximately 6 seconds. In order to ensure constant illumination of ROI by a LEO satellite, a multi-plane constellation comprising of five satellites is simulated. These five satellites are assumed to have identical antenna/beam configuration and have limited coverage overlap. In this scenario the network topology of the gNodeBs is a combination of star and ring type, where the connection between the gNodeBs is established using the Xn interface. Each NTN gNodeB is connected to the TN gNodeB on ground forming a star network whereas each NTN node is

TABLE I: Parameter Configuration

Parameter	Value
Frequency	2.6 GHz
System Bandwidth	40 MHz
Duplex Type	Frequency Division Duplex (FDD)[1]
TN Bandwidth (bw_{tn})	40 MHz (TN only) 20 MHz (Integrated TN-NTN)
NTN Bandwidth (bw_{ntn})	20 MHz (Integrated TN-NTN)
Sub-carrier spacing	15 KHz
HARQ, target BLER	Disabled, 0.01
Scheduling algorithm	Proportional Fair
Satellite altitude	600 km
Satellite antenna pattern	Bessel type
Equivalent satellite antenna aperture	2 m
Satellite transmit power (p_s)	46.8 dBm
Satellite antenna gain (g_s)	30 dBi
3dB beamwidth (HPBW)	4.4127 deg
Satellite beam diameter	50 km
Satellite receiver noise figure (nf_s)	4.276 dB
TN gNodeB antenna pattern	Omni
TN gNodeB antenna gain (g_t)	8 dBi
TN gNodeB transmit power (p_t) [2]	46 dBm (TN only) 43 dBm (Integrated TN-NTN)
TN gNodeB receiver noise figure (nf_t)	5 dB
vehicle antenna pattern	Omni
vehicle antenna gain (g_u)	0 dBi
vehicle transmit power (p_u)	23 dBm
vehicle receiver noise figure (nf_u)	7 dB
Channel characteristics for vehicle to TN gNodeB	3GPP 38.901 [16]
Channel characteristics for vehicle to Satellite	3GPP 38.811 [17]

[1] This means the allocated network BW is divided between DL and UL, i.e. in case of "TN only" we have 20 MHz for each DL and UL.
[2] The power level is adapted to the amount of available BW to ensure the same Power Spectral Density (PSD) for a fair comparison between the TN network in both scenarios.

connected to only two neighboring NTN gNodeBs resulting in a ring network.

The handover procedure is similar to the baseline Simu5G implmentation as shown in Fig.3. The logic is in part similar to the Conditional Handover (CHO) logic detailed in release 16 to 18 [23]. Every gNodeB periodically sends a handover control packet to all the vehicles that are within its range. The maximum range determined by the validity distance of the used channel models are 5 km for a TN link and 25 km (from beam center) for the NTN link . Once a vehicle receives such a control packet then it measures the link quality for the gNodeB sending the control packet. Each vehicle has a serving gNodeB which is termed as the master gNodeB and the other gNodeBs from which it receives the handover control packets are the secondary gNodeBs. When the vehicle measures a better link quality from one of the secondary gNodeBs, the vehicle will trigger a handover from the current master gNodeB to the secondary gNodeB.

IV. Results and Analysis

The results displayed in this section compare the performance of the scenario described above with and without the presence of NTN gNodeBs, which is represented as "TN Only" and "Integrated TN-NTN" respectively in the figures below.

The geographical distribution of the type of coverage in the integrated TN-NTN scenario can be observed in Fig.4. The ROI is divided into equidistant blocks of 100 squared meters and a block is determined to be covered by TN or NTN if more than 50% of the received packets in it are from the respective network type. Areas without data-points are areas where no measurements were done due to absence of vehicular movement in the area.

Fig.5 showcases how many vehicles are connecting with a particular gNodeB over the period of simulation. Fig.5(a) is the case when only the TN gNodeB is deployed in the ROI. It is observed that not all the 50 vehicles (total no of vehicles are indicated using the red line) can be served by this one TN gNodeB, as some of the vehicles are outside the coverage range of the TN gNodeB. When the same scenario is complemented with a NTN gNodeB, as shown in Fig.5(b), that all the deployed vehicles can be served. The vehicles connecting with the NTN gNodeB are not only the ones that are outside the coverage range of the TN gNodeB but also those vehicles that were previously connected to the TN in Fig.5(a) are now connected to the NTN due to better link quality.

The benefit of using a NTN gNodeB in addition to a TN gNodeB in this case does not only improve coverage but also improves the overall system performance. Fig.6 demonstrates the system performance in terms of probability of packet loss across all vehicles over time. The blue area indicates the probability of a packet loss due to poor channel quality. As expected the probability of packet loss is much higher when the ROI is served by the TN gNodeB only.

The Signal-to-Noise Ratio (SNR) shown in Fig.7 is evaluated on the vehicle side for the DL direction, which is the average of all the SNR measured across the occupied RBs. Fig.7 compares the SNR measurement of selected vehicles in the DL between the two scenarios. Fig.7a shows the distribution of recorded SNR at vehicles 0, 1, 2 and 3 which drive at different distances from the TN gNodeB with the higher the ID value the closer the vehicle is to the TN gNodeB. Amongst them, vehicles 0, 1, 2 always connect to a NTN gNodeB in the "Integrated TN-NTN" scenario, whereas vehicle 3 is always connected to the TN gNodeB because of its close proximity to the TN gNodeB. It can be observed from Fig.7a that for vehicles 0, 1 and 2 the mean SNR measurement is at least 5 dB higher for the scenario "Integrated TN-NTN", due to the presence of NTN gNodeB that results in a better link quality. However it is also observed that for vehicle 3 which always connects to a TN gNodeB in the "Integrated TN-NTN" scenario experiences the same average SNR since the power spectral density is maintained in the TN network in both scenarios and there is no interference assumed in this evaluated use case. Fig.7b compares the SNR measurement of vehicle 1 over time, where the blue line corresponds to "TN only" and the orange line corresponds to "Integrated TN-NTN" scenario respectively. As the vehicle 1 always connects to one of the NTN gNodeBs in "Integrated TN-NTN", the SNR performance in Fig.7b displays a sinusoidal behaviour. This is representative of the satellite rising and setting over the ROI. The blue line which indicates the SNR performance when connected to a TN gNodeB shows a gradual degradation in performance before improving again. This is due to the vehicle's mobility model that leads to increasing and then decreasing distance to the TN gNodeB respectively. The blue

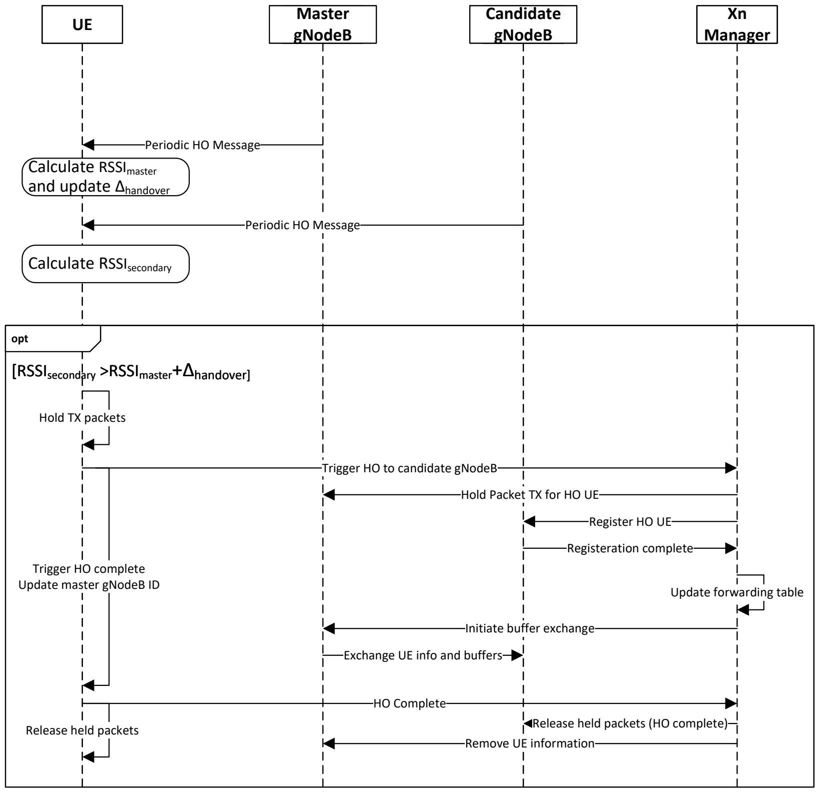


Fig. 3: Simulated UE-triggered Handover (HO) Procedure

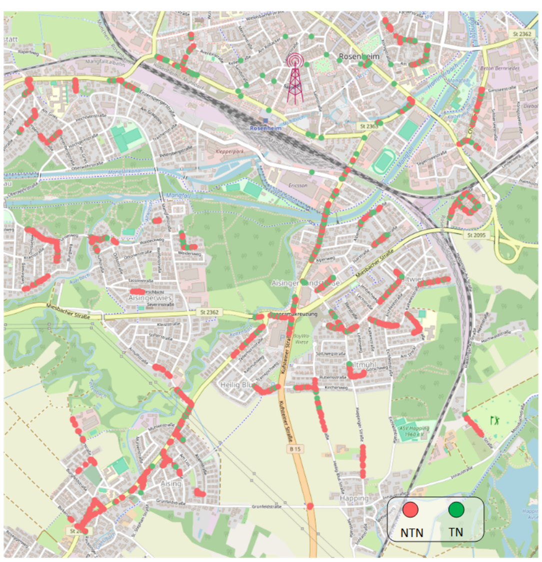


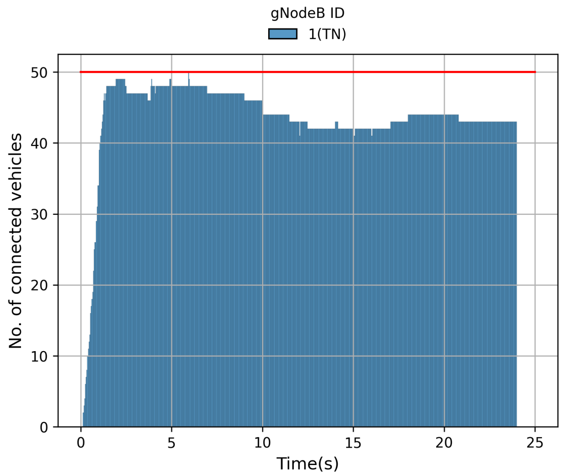
Fig. 4: Geographical distribution of TN-NTN coverage where a position is determined to be served by either network when more than 50% of the UEs within 10 m radius of a point report being served by it.

line also demonstrates that the SNR performance remains constant for a certain period of time, which is because the channel coefficients are static for every 10 meters traveled by the vehicle.

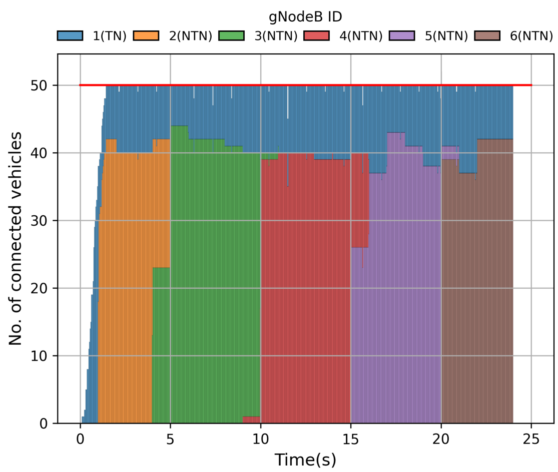
The system performance for the two scenarios ”TN only” and ”Integrated TN-NTN” was also analyzed by varying the system load. Fig.8 shows the variation in sumrate over the ROI between the two scenarios for different system loads. The system load is varied by changing the total number of vehicles that are deployed in the ROI. The sumrate is the sum of the received throughput of all the vehicles measured in the DL. It is observed that with increasing system load the difference in the network sumrate between the two scenarios increases. One reason for this overall improvement in system performance, is the improvement in signal strength for those vehicles that are far away from the TN gNodeB and can connect to a NTN gNodeB instead. Second, is because of load sharing between the two gNodeBs, as it enables the two gNodeBs serving the ROI to maintain the required bandwidth allocation.

V. Conclusion

In this paper, we conducted a comprehensive analysis of the system performance within an integrated TN-NTN scenario with realistic mobility traces in a real city setting. We outlined the simulation model in Section II and detailed the scenario setup and underlying assumptions in Section III, which served as the basis for our findings discussed in Section IV. Our analysis demonstrated that the integration of TN and NTN networks significantly enhances the overall system performance.

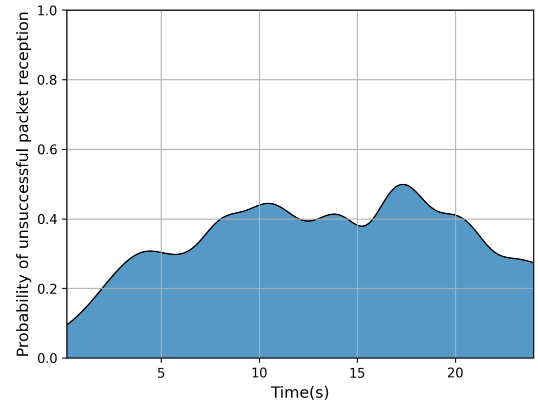


(a) TN only

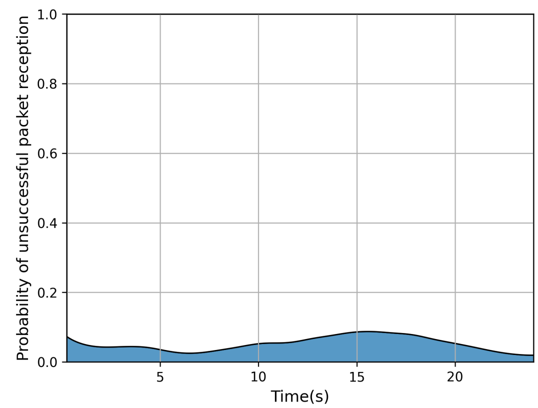


(b) Integrated TN-NTN

Fig. 5: Comparison of serving cell distribution stacked over simulation time. 1 refers to the terrestrial gNodeB and 2, 3, 4, 5, 6 refer to the six consecutive NTN gNodeBs that fly over the ROI. The red line indicates the total number of vehicles.



(a) TN only



(b) Integrated TN-NTN

Fig. 6: Comparison of the probability density of packet loss across all vehicles in the DL over simulation time. The blue area in the graph indicates the probability of no packet loss and the orange area represents the probability of packet is lost.

Specifically, we evaluated network-level packet loss and data rate metrics to gauge performance improvements.

Our results indicate that the observed enhancement in system performance can be attributed to several key factors. Firstly, the integration of TN and NTN networks leads to better service coverage, thereby extending connectivity to previously underserved areas. Additionally, the implementation of an efficient TN-NTN handover mechanism ensures seamless transitions between network segments, further bolstering performance. Moreover, stable resource block and bandwidth allocation strategies within the Region of Interest (ROI) contribute to improved network efficiency and user experience.

Our study assumed no interference between TN and NTN nodes by dividing the available system bandwidth between the two networks in accordance with the current 3GPP specifications up to Release 19. Future research endeavors will explore more complex scenarios, such as instances where both gNodeBs share the same pool of resource blocks, potentially leading to interference. This extension will provide valuable insights into the network's behavior under more realistic conditions. Subsequent work will also focus on refining handover mechanisms by evaluating conditional handover mechanisms as introduced by 3GPP, and analyzing the implications of this hybrid network on Quality of Service (QoS) fulfillment. Additionally, further analysis on the impact of NTN links on session continuity at the transport level, particularly due to high latency and frequent handovers, should be considered in future work analyzing these types of networks.

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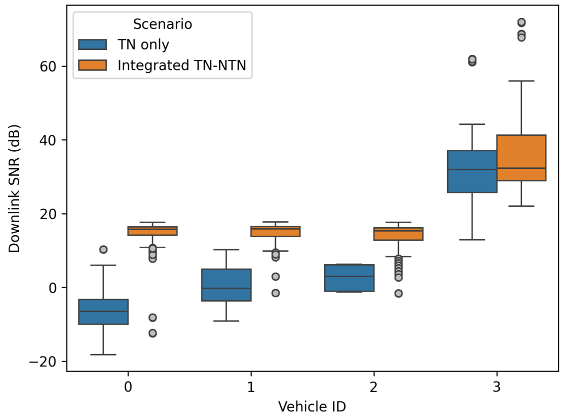
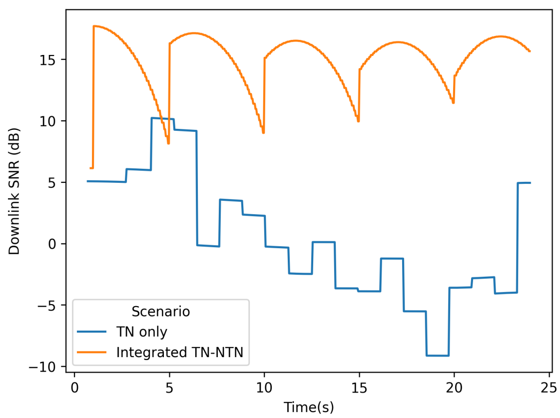


(a) Overall measured SNR values at different vehicles



(b) Measured SNR vs simulation time at vehicle 1

Fig. 7: Comparison of recorded SNR measurements in different terminals in DL. The chosen vehicles drive at various distances from the TN gNodeB namely: 2700, 1600, 1300, 300 meters for IDs 0,1,2,3 respectively.

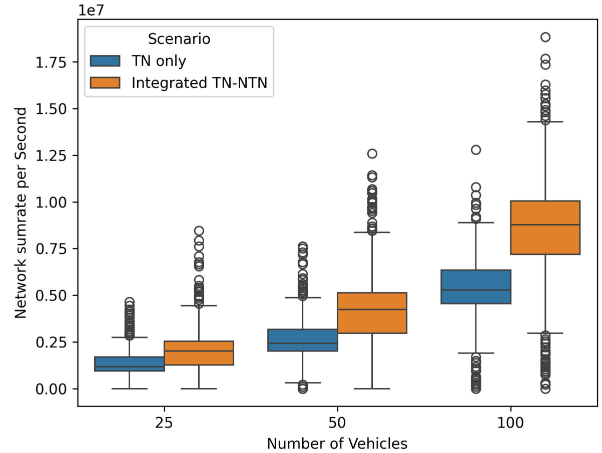


Fig. 8: Achieved network sumrate in bits per second over the ROI per second in case of ”TN only” and ”Integrated TN−NTN” in DL

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